Highway Economic Requirements System

TECHNICAL REPORT

U.S. Department
of Transportation

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Administration**

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1 Introduction

The Highway Economic Requirements System (HERS) is a computer model designed to simulate improvement selection decisions based on the relative benefit-cost merits of alternative improvement options. HERS is intended to estimate national level investment requirements which assume state highway improvement selection decisions that consider the relationship between benefits accruing to highway users and agencies, and the initial improvement cost of a potential improvement option. Output from the HERS model is used in preparation of the Department of Transportation's (DOT) biennial *Status of the Nation's Surface Transportation System • Condition and Performance • Report to Congress* (*C&P Report*).

The HERS model is the result of the efforts to examine more carefully the costs, benefits and national economic implications associated with highway investment options.

This Technical Report is the fourth volume of HERS documentation. It is labeled Version 3.26 (v3.26) because it corresponds to program Version 3.26 which was used to evaluate 1997 data in preparation of the 1999 *C&P Report*. It consists of detailed technical discussions of the procedures, assumptions, algorithms, and inputs of the HERS model. The first three volumes are intended to provide a non-technical introduction to a general audience interested in using and interpreting model generated results:

- Volume I - Executive Summary

  This document provides a non-technical presentation of the model.

- Volume II - System Overview

  This volume offers a procedural summary of the model's logic structure and the analytical, economic and engineering procedures it implements.

- Volume III - User's Guide

  This volume provides "hands-on" assistance to the analyst interested in using HERS to evaluate alternative highway program and policy scenarios.

Each volume is updated independently of the others. This Technical Report is the first of the four volumes to be updated to Version 3.26.

HERS is designed to estimate the benefits resulting from potential improvements, distinguishing three types of benefits to highway users (travel time, operating costs, and safety), two types of benefits to highway agencies (maintenance costs and the "residual value" of an improvement at the end of the analysis period), and one "external" benefit (reduction in damage caused by vehicle emissions). The HERS model uses benefit-cost analysis to differentiate between potential improvements when selecting improvements for implementation. HERS v3.26 further includes the effects of "induced traffic" and "induced demand," reflecting user response to changes in the generalized price over the short and long term, respectively.

HERS was developed for the Federal Highway Administration (FHWA) by Jack Faucett Associates, and is maintained and operated by the Volpe National Transportation Systems Center. The development of HERS has benefited substantially from the FHWA's Highway Performance

Monitoring System (HPMS) database and its associated simulation, the Analytical Process (AP). HERS uses the description of the current state of the highway system contained in the HPMS database as the basis of all analyses. This database contains a detailed description of a stratified random sample of over 100,000 sections of non-local roads. The descriptions are updated annually by State highway departments in accordance with FHWA specifications set forth in the HPMS *Field Manual*.[1]

Each of these “sample sections” represents a relatively large number of actual highway sections. The total mileage of these sections (but not their number) is known and can be obtained by multiplying the length of each sample section by its “expansion factor.” All HERS estimates of costs and benefits are obtained by analyzing individual sample sections and multiplying the results by the appropriate expansion factor.

HERS starts with the base-year description of the highway system contained in the HPMS database and forecasts changes to the system and analyzes potential improvements for each of several “funding periods.” The number and length of the funding periods can be specified by the user, but computation-time considerations generally allow for only a small number of funding periods. A common HERS application uses four five-year funding periods.

For each funding period, HERS forecasts the condition of each sample section and determines which improvements should be made. HERS considers resurfacing or reconstruction, possibly combined with alignment improvements and/or four alternative types of widening. To the extent that funds are reserved for this purpose, appropriate improvements may be made to eliminate any “unacceptable” conditions that can be corrected. Additional improvements to correct “deficiencies” are then selected on the basis of a benefit-cost analysis (BCA) procedure until available funds for the period are used up or some user-specified characterization of the highway system has been achieved. If sufficient funds are not available to correct all unacceptable conditions, the B/C procedure is used to select which of these conditions should be corrected. The unacceptability and deficiency criteria used by HERS are user specified.

An outline of the HERS model structure is presented in Chapter Two of this report. At a more general level, it also presents the HERS processing cycle along with its several major variants.

The next three chapters are arranged to mirror the HERS processing cycle. Chapter Three discusses the procedures used within the model to identify potential improvements for any given section. Chapter Four then elaborates on the methods HERS uses in evaluating the candidate improvements. The selection of improvements as performed for the several HERS processing options is explained in Chapter Five.

The HERS model incorporates several interior models which it uses to determine traffic growth, pavement wear, etc. These are discussed in Chapter Six. Chapter Seven presents the methods used by HERS to convert quantities such as vehicle speed, pavement condition, and potential improvements into dollars for use in benefit-cost analysis.

The effects of the various HERS improvements on highway conditions is presented in Chapter Eight, and Chapter Nine provides an overview of the output from the HERS program.

This report contains eight appendices. Appendix A, ”Benefit-Cost Analysis,” describes in detail the benefit-cost evaluation procedure that controls the selection of improvements. Appendix B,

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[1] U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System *Field Manual*, Washington, D.C., December 1993.

”Induced Traffic and Induced Demand,” is a paper discussing the theoretical underpinnings of induced traffic and induced demand related to the concept of elasticity. The derivation of the values used by HERS for short and long run elasticity is presented in Appendix C, ”Demand Elasticities for Highway Travel.” Appendix D, ”Basic Theory of Highway Project Evaluation,” places the HERS model within a wider context.

Appendix E, ”Operating Cost Equations,” contains the equations used by HERS to determine operating costs. Appendix F, ”Detailed Description of Procedures for Incorporating Air Pollution Costs in HERS,” presents the derivation of the HERS emissions cost equation, constants, and factors. The constants and factors used in calculating emissions costs are presented in Appendix G, ”Factors For Emissions Equations.” And Appendix H, ”A Numerical Example,” walks through the processing of a single section during a funding period, illustrating many of the algorithms documented in the body of this Report.

2 An Outline of the Model Structure

This section provides an overview of the structure of the HERS system; that is, the ordering of computational events by which the model performs its analysis. The sequencing of events is referred to as the HERS process; the program entities which perform specific modeling functions are referred to as the HERS models. Each is introduced below, with more detailed discussion in the sections which follow.

2.1 HERS Analytical Objectives

In any given run, HERS is designed to perform one of three types of analysis as specified in the user input field "Objective." The user-specified objective may be in any of three possible forms:

1. Maximize the net present value of all benefits of highway improvements subject to specified constraints on funds available during the period;
2. Minimize the cost of improvements necessary to achieve a specified goal for the performance of the highway system at the end of the funding period; or
3. Implement all improvements with a benefit-cost ratio (BCR) greater than some specified threshold value.

The three forms are also referred to as Constrained Fund, Performance Constrained, and Minimum BCR, respectively.

When Objective is set to "1", HERS will solve for highway conditions and performance when improvements are constrained by available funds (referred to as a "constrained fund" run). When Objective is set to "2", HERS will solve for the funding levels required to bring the system to a specified level of performance (referred to as a "performance constrained" run). When Objective is set to "3", HERS will solve for both the required funding level and the resultant performance levels when improvements are constrained to return a minimum ratio of benefits relative to their cost (a "minimum benefit-cost ratio (BCR)" run). The model recognizes two special cases. The first is an "engineering needs" run (sometimes referred to as "full needs"), which is a minimum BCR run with the minimum BCR set to a very low negative number so that all sections with deficiencies are selected for improvement. The second is a "maintain current conditions" run in which the model first determines the level of system performance at the beginning of the run based on user-specified parameters (for example, current highway-user costs), and selects the least costly mix of improvements to maintain that level of performance. Each of the special cases can be selected via a dedicated input field. Finally, while a minimum BCR run where the minimum BCR is set to 1.0 is referred to as an "economic efficiency" run, this is not a different type of analysis, but a specific and often used Objective 3 scenario, and was used as the Maximum Economic Investment scenario in the 1999 *C&P Report*.

Objective 2 scenarios, such as the Maintain User Costs scenario of the 1997 *C&P Report,* can be specified as a goal for a single type of highway-user cost or highway agency cost per vehicle-mile (e.g., number of fatalities per vehicle-mile); or it can be specified as a dollar-valued composite of all net user and agency costs estimated by HERS (travel time costs, operating costs, fatality costs, injury costs, property damage, and maintenance costs). The dollar-valued composite can be obtained as a simple sum of the component costs or as the sum of two or more components with different weights. (The run specification file provides one set of weights used in balancing components of the incremental benefit-cost ratio, and another set for balancing components of the performance goal.) In the latter event, it is recommended (but not required) that the components of the IBCR be given weights that are consistent with the specified goal; e.g., the goal might be that the sum of user costs plus two times agency costs should not exceed $0.50 per vehicle-mile, in which case it is recommended that agency costs be weighted twice as heavily as user costs in the IBCR as well.

2.2 The HERS Process

The basic process is agreeably straightforward: forecast section condition; identify deficiencies and potential improvements; evaluate and select improvements; and implement improvements (or, for unimproved sections, implement the unimproved condition forecast for the end of the period). Output statistics are accumulated, and the process is repeated for each subsequent funding period. However, the model has two features (alternative improvement selection procedures, and mandatory correction of unacceptable conditions) which complicate the structure. Each feature offers a pair of alternatives, which, selected independently, define four distinct logical structures.

2.2.1 The Improvement Selection Procedures

The first feature is that the model supports two improvement selection procedures. Both procedures use benefit-cost analysis to choose between potential improvements, but one procedure chooses among improvement options for a single section at a time, while the other selects from all potential improvements to all sections in the system.

The “minimum BCR” alternative (Objective = 3) instructs the model to implement, for each deficient section, the most ambitious improvement which meets a minimum benefit-cost ratio. Under this option, all deficient sections with an “economically justifiable” candidate improvement are improved. An improvement is considered “economically justifiable” if its benefit-cost ratio is greater than or equal to the user-specified minimum. (For the “Economic Efficiency” scenario, the minimum BCR is set to 1.0.) Benefit-cost analysis is used first to determine if a section will be improved, and second to identify the most attractive of the potential improvements. (The improvement with the greatest BCR is considered more attractive.) The model is under no budget or performance constraints, but will implement the most attractive improvement for each qualifying section.

The “constrained” alternative (Objective = 1 or 2) effectively compels the model to rank all potential improvements, for all sections, in order of economic desirability (that is, ranked by BCR). The model then selects improvements in order of decreasing BCR until a specific constraint (available funds or system performance level) has been reached. While not all economically attractive improvements may be selected, those selected will all be more economically attractive than those not selected for implementation. When the constraint is available funds, the program selects the set of improvements which return the maximum benefit for the capital expenditure. When the program is constrained to attain a specific level of performance for the highway system, it selects the set of improvements which will achieve those goals at the lowest cost.

Exhibit 2-1 shows flow diagrams for these two selection procedures. In the minimum BCR version, the model selects a section’s improvement immediately after evaluating the possible improvements. In the constrained run, the model “pre-selects” a section’s most attractive improvement and places it on a list of potential improvements. After all sections have been evaluated, the model initiates a second selection procedure which selects improvements from the potential list (which is ordered by BCR) until the constraint, whether a budget limit or a performance goal, has been met.

The processes for identifying potential improvements are presented in Chapter 3, “Identifying Candidate Improvements.” The evaluation of potential improvements, including benefit-cost analysis, is presented in Chapter 4, “Evaluating Improvements.” And the process of choosing improvements for implementation is presented in Chapter 5, “Selecting Improvements.”

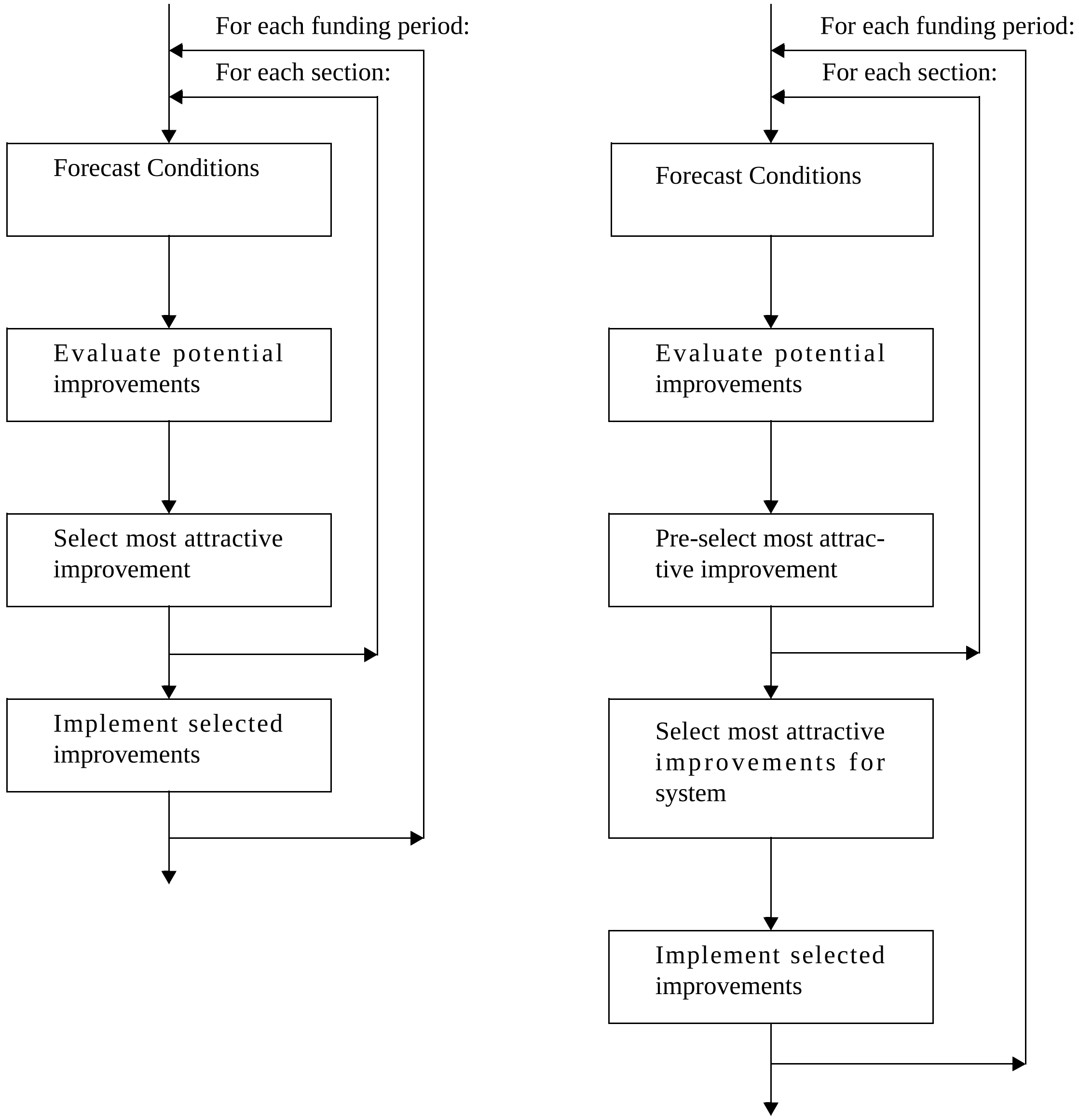
2.2.2 Addressing Unacceptable Conditions

The second feature which can complicate the HERS selection process is the provision of a “safety-net” to force the model to improve unacceptably deficient sections without regard for the economic desirability of the improvement. If this option is selected, HERS will make a special pass through all sections prior to the normal evaluation to identify low-cost improvements to correct unacceptable conditions. Improvements selected on this basis are referred to as “mandatory improvements.” For most purposes, such as preparation of data for the Conditions and Performance Report, the model is run without selecting this option, so no mandatory improvements are implemented.

The processing flow after the identification of mandatory improvements varies depending upon the analytical objective. The simplest case is illustrated in Exhibit 2-2, “Minimum BCR Run with Mandatory Improvements.” In this case, after identifying mandatory improvements for sections with unacceptable conditions, the program re-examines each section to identify economically attractive improvements. On a section for which a mandatory improvement has been identified, the model will implement either the mandatory improvement or an economically attractive improvement which also corrects all unacceptable conditions. On sections without mandatory improvements, the economically most attractive improvements will be implemented.

The processing flow for a performance constrained run with mandatory improvements is shown in Exhibit 2-3. In this type of run, the program forecasts the unimproved condition of the system at the end of the funding period, then implements improvements until the level of system performance reaches the specified goal. If implementing the mandatory improvements alone achieves the performance goal, no additional improvements are considered during this funding period. If the goal has yet to be achieved, the program loops through the sections again to identify economically attractive improvements, which are ordered by BCR and selected until the goal is attained.

Exhibit 2-4 shows the processing flow for a constrained fund run with mandatory improvements. For this scenario, the analyst specifies two funding levels: the total amount of funds to be expended per funding period, and the amount of the total funds which are to be used for more



Minimum BCR run (without Mandatory Improvements)

Constrained Run (without Mandatory Improvements)

Exhibit 2-1. HERS Process Flow Without Mandatory Improvements

aggressive (that is, non-mandatory) improvements. For example, the analyst might specify that 100 million dollars be allocated for the first funding period, of which 70 million dollars is reserved for non-mandatory improvements. After identifying mandatory improvements for all sections, the program checks whether the cost of all mandatory improvements exceeds the 30 million dollars allocated for mandatory improvements.

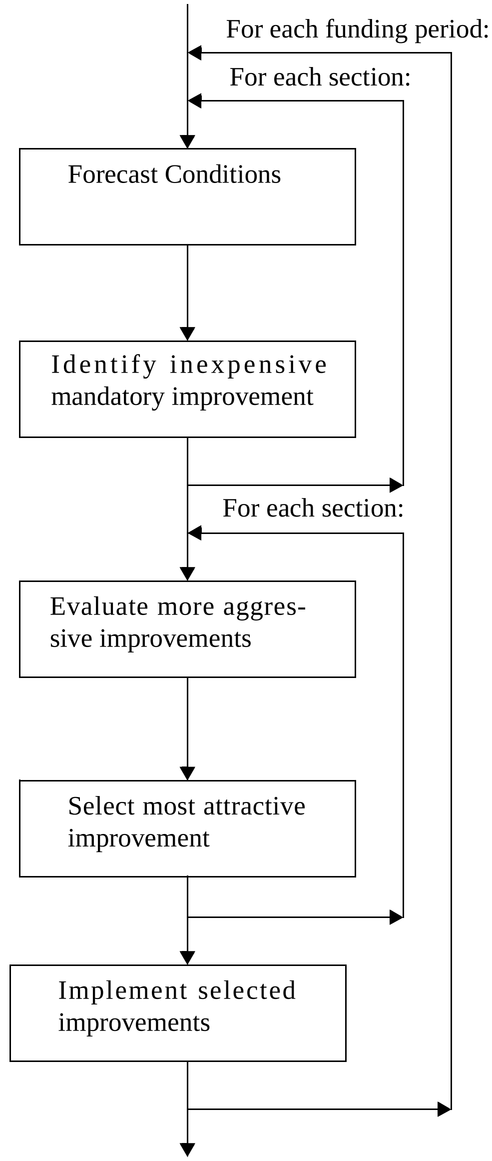


Exhibit 2-2. Minimum BCR Run with Mandatory Improvements

If the mandatory improvements cost more than the funds allocated for them, the program selects from the mandatory improvements in order of their BCRs until it has expended all the available funds on the economically most attractive improvements. It then checks whether additional funds have been reserved for more aggressive (non-mandatory) improvements. If not, it implements the selected improvements and advances to the next funding period.

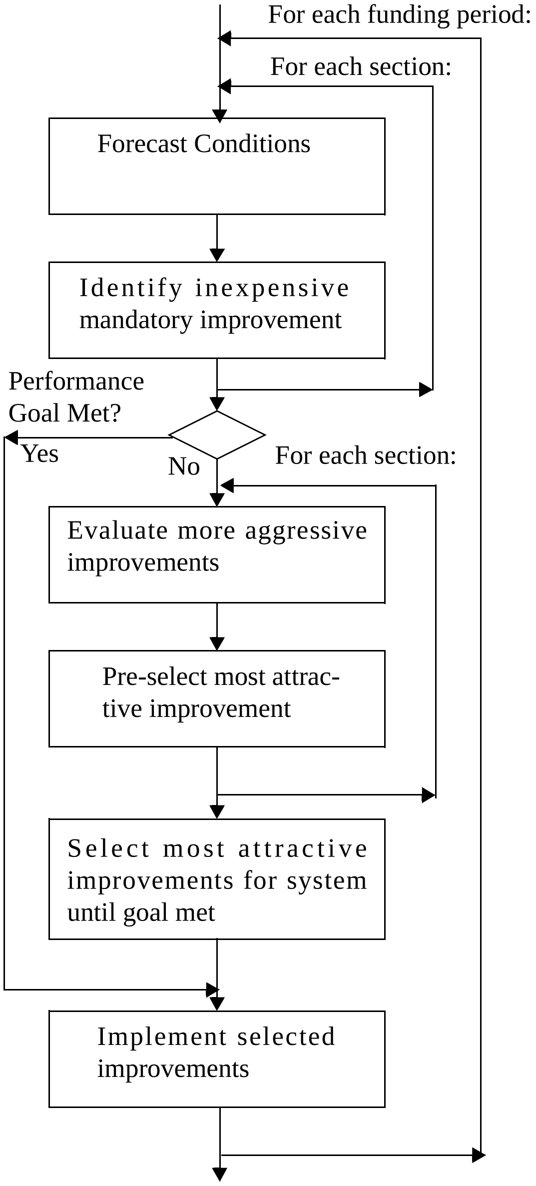


Exhibit 2-3. Performance Constrained Run With Mandatory Improvements

However, if funds were reserved for non-mandatory improvements, or if the mandatory improvements cost less than the funds allocated for them, the program loops through all the sections again to identify more aggressive improvements for implementation with the remaining funds. These improvements are selected in BCR order.

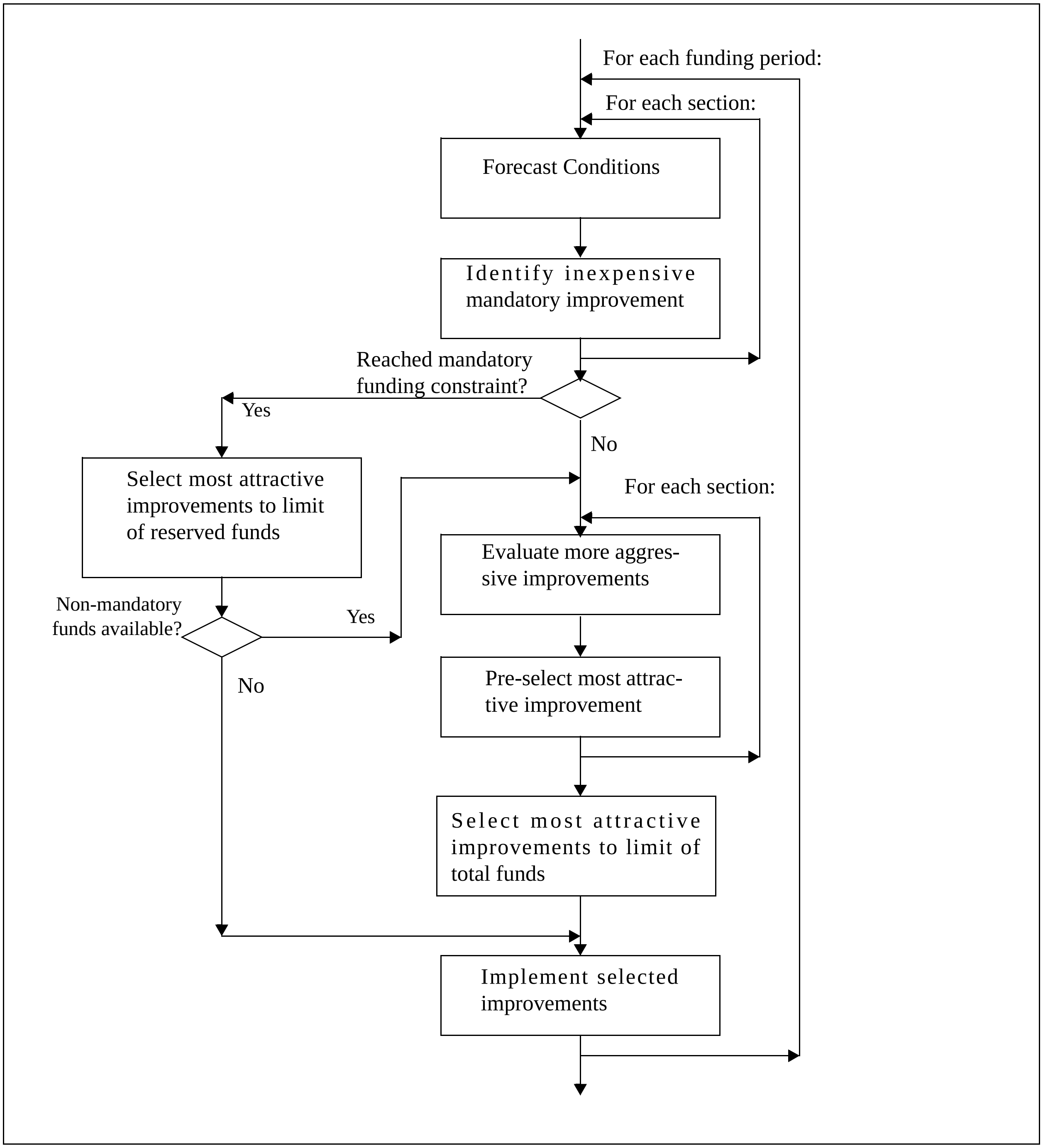


Exhibit 2-4. Constrained Fund Run With Mandatory Improvements

Note that in all cases, it is possible for the model to identify a mandatory improvement for a section, and subsequently replace it with an economically more attractive improvement which corrects all the unacceptable conditions which existed on the section.

The identification of potential improvements to correct sections in unacceptable condition is discussed in paragraph 3.3.2, "Addressing Unacceptable Conditions: the Optional First Pass." The process of selecting mandatory improvements, or of replacing a mandatory improvement with a more aggressive improvement, is presented in paragraph 5.2, ”Selecting Mandatory Improvements.”

2.3 The HERS Prediction and Calculation Models

For each funding period, for each sample section, for each of the logical sequences, the program performs the same set of predictions:

- predicts future traffic volume
- predicts future pavement conditions
- predicts current and future speeds
- predicts section capacity after improvement.

These predicted conditions are then used to calculate costs:

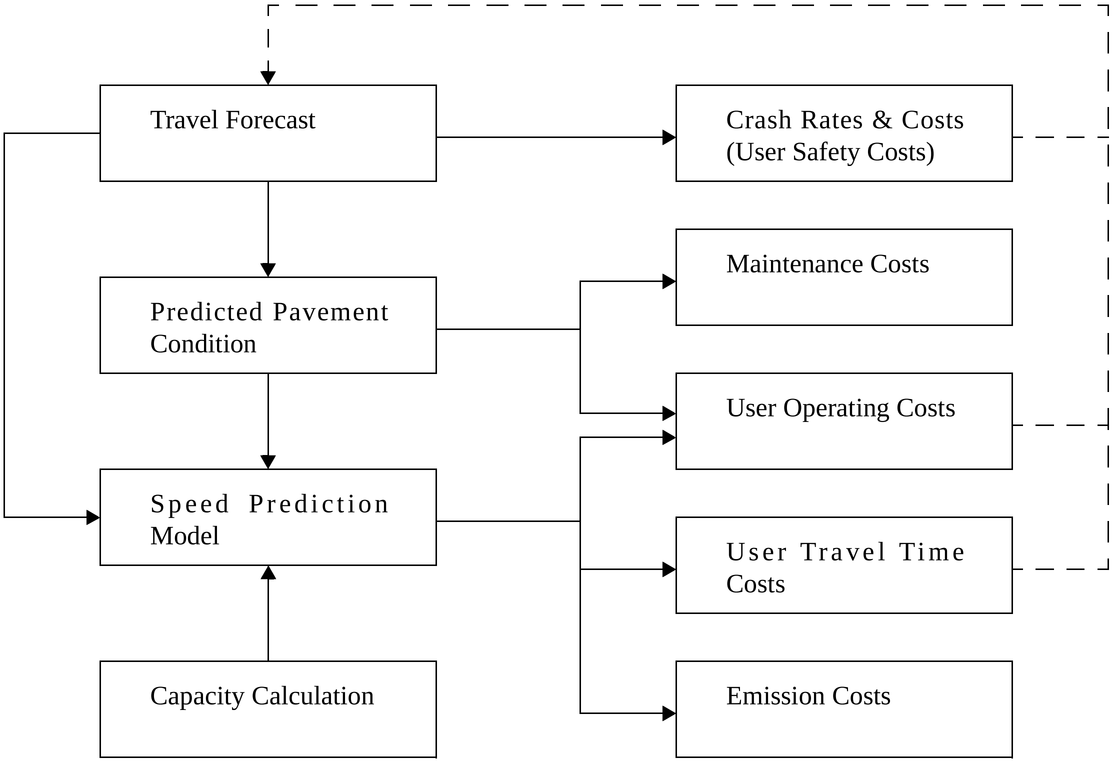
- costs to users of the highway system:
  - operating costs
  - travel time costs
  - safety costs
- agency costs:
  - capital improvement costs
  - maintenance costs
- costs associated with vehicle emissions.

The information generated by the prediction and calculation models are used within the logic structure to evaluate and select improvements. The relationships between the prediction and calculation models are shown in Exhibit 2-5, “Prediction and Calculation Model Linkages.” The prediction models are discussed in detail in Chapter 6, “HERS Internal Models,” and the calculation models are presented in Chapter 7, “Cost and Benefit Calculations.”

2.4 Implementation and Output

The condition of each section is maintained in a set of data items which are originally populated from the HPMS database. While many of these items are not changed during analysis (for example, section identification and location), others (such as traffic volume and pavement condition) can be expected to change with each passing funding period. Improvements are implemented through changes to applicable data items (notably pavement condition and number of lanes).

At the beginning of each funding period, the model forecasts the condition of each section at the end of the funding period. This basic forecast consists of predicting future traffic volume, then calculating the effect of this traffic on the pavement condition. For sections which are unimproved during the funding period, this becomes the condition of the section at the beginning of the subsequent funding period. Because HERS treats improved sections as receiving their



Notes: The dashed line reflects the influence of user costs on travel forecasts due to demand elasticity. The Capacity Calculation is entered only after implementing an improvement.

Exhibit 2-5. Prediction and Calculation Model Linkages

improvements at the midpoint of the funding period, determining the end of period condition of an improved section consists of upgrading the section's condition to reflect the improvement and then forecasting it's condition at the end of the period.

At this point, the program accumulates the statistics which will be used to generate the output pages. See Chapter 9, "Model Output," for more details.

2.5 The HERS Milieu

2.5.1 HERS Time Frames

The HERS program operates over a set of time frames known as funding periods (FPs), as shown in Exhibit 2-6, "HERS Time Periods." These funding periods are equal in length, and combine to form the overall analysis (OA) period. The set of all funding periods form a sequence, with the first one beginning at the start of the OA period, and each succeeding funding period starting at the end of the preceding one. HERS defines additional funding periods which start after the end of the OA period. These “post analysis period” funding periods are the same length as the funding periods within the OA period, and extend far enough beyond the end of the OA period to permit benefit-cost (B/C) analyses to be performed on all improvements that might be implemented during the OA period. Exhibit 2-6 depicts an overall analysis period consisting of four five-year funding periods.

HERS performs B/C analyses on all improvements that might be implemented during the OA period, but not on improvements that might be implemented after the OA period. For purposes of the B/C analyses, HERS treats all improvements as if they were implemented at the midpoint of the funding period. Accordingly, every benefit-cost analysis period (BCAP) extends from the midpoint of a funding period to the midpoint of a subsequent funding period (which can extend beyond the end of the OA period). Additionally, because of the impact of an improvement upon the price to the user of the section, the time-frame for the elasticity calculations (shown in the exhibit as ELAS) also run from funding period midpoint to funding period midpoint.

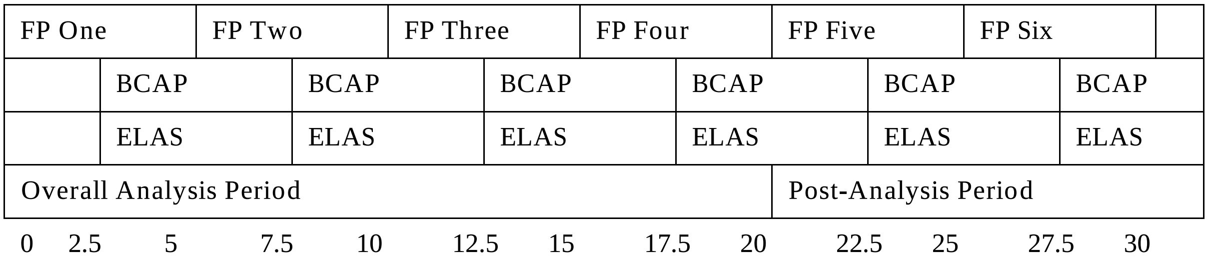


Exhibit 2-6. HERS Time Periods

2.5.2 Functional Classes

The HERS program recognizes nine functional classes of highways, including all of the urban arterial and collector classes, and all of the rural arterial and major collector classes. Rural minor collectors and roads functionally classified as local are not recognized by HERS.

A large number of HERS parameters can be specified by the user with different values for each of the nine functional classes. These include:

- Deficiency Levels
- Serious Deficiency Levels
- Unacceptability Levels
- Minimum Tolerable Conditions
- Design Standards
- Improvement Costs
- Truck Growth Factors
- Cost of Non-Fatal Injuries
- Property Damage Cost per Crash

- Funds Available for Improvements (Fund Constrained Run)
- Highway Performance Goals (Performance Constrained Run)
- Weights for Highway Performance Goals
- Weights for Benefit-Cost Ratio Calculation.

The Fleet Composition model also relies on functional class. (See paragraph 6.4, ”The Fleet Composition Model.”)

When performing a constrained fund run or a performance constrained run, HERS allows the user the options of setting separate budget constraints or performance goals for each functional class, or for certain combinations of functional classes. These combinations are shown in Exhibit 2-7, “Highway Functional System Groupings.” The user can set targets for:

- 1 group (for all functional systems combined);
- 2 groups (for the urban system and for the rural system);
- 2 groups (for the principal arterials and for the minor arterials and collectors);
- 4 groups (for urban principal arterials, for rural principal arterials, for urban minor arterials and collectors, and for rural minor arterials and collectors); or
- 9 groups (for each of the nine functional classes distinguished by HERS).

The flow charts in Exhibits 2-1 through 2-4 are based upon the standard case where the set of sample sections is treated as a single system (one group). However, if the user elects to use multiple functional class groups in setting performance goals or budget constraints, then during initialization, HERS takes the additional step of separating the sample sections into the component groups, and maintains a separate section file for each group. During processing, the model processes each group in turn in a loop nested between the loops for funding periods and sections. The structure then becomes:

```
Loop through each funding period...
    Loop through each functional class group...
        Loop through all sections in the class group...
            Process a section (forecast conditions, identify potential improve-
            ments, pre-select an improvement)
        End loop (all sections)
        Select improvements until constraint is satisfied for the class group
        Implement selected improvements for the class group
    End loop (functional class group)
End loop (funding period)
```

Code:	Description:	Single System	Rural and Urban	Princ. Art. & Other	Princ. Art. & Other by Rural/Urban	By Functional Class
	Number Of Groups >>>	1	2	2	4	9
	Rural					
01	Principal Arterial – Interstate	1	1	1	1	1
02	Other Principal Arterial	1	1	1	1	2
06	Minor Arterial	1	1	2	2	3
07	Major Collector	1	1	2	2	4
	Urban					
11	Principal Arterial – Interstate	1	2	1	3	5
12	Principal Arterial – Other Freeways and Expressways	1	2	1	3	6
14	Other Principal Arterials	1	2	1	3	7
16	Minor Arterial	1	2	2	4	8
17	Collector	1	2	2	4	9

Exhibit 2-7. Highway Functional System Groupings

3 Identifying Candidate Improvements

The highway improvements analyzed by HERS v3.26 consist of various combinations of pavement, widening and alignment improvements. The first part of this chapter presents definitions of these improvement types. The second portion identifies the section characteristics and types of deficiency levels that HERS utilizes in determining whether potential improvements should be evaluated. The third part presents the procedures used for identifying these potential improvements. The fourth portion lists the default values for the different types of deficiency levels. The fifth part discusses the implications of using the default deficiency level settings, and of using values that are more or less stringent.

3.1 HERS Improvement Types and Kinds

The highway improvements considered by HERS v3.26 consist of resurfacing or pavement reconstruction, possibly combined with some type of widening and/or alignment improvement. Schematically, these improvement types can be viewed as being obtained by selecting one “improvement option” from each of the columns of Table 3-1, “Improvement Options.” There are 32 possible combinations for the options in the three columns of the table, and eight possible combinations for the options in the first two columns. However, as HERS corrects shoulder deficiencies when reconstructing pavement, it makes no distinction between pavement reconstruction with or without shoulder improvements. The result is 28 different “types” of improvement, or, if the third column is ignored, seven different “kinds” of improvement.

Table 3-1. Improvement Options

Pavement	Widening	Alignment
0. Resurface	0. None	0. No change
1. Reconstruct	1. Improve shoulders	1. Improve curves
	2. Widen lanes	2. Improve grades
	3. Add lanes	3. Improve curves and grades

Table 3-1 shows three distinct alignment options: improve curves, improve grades, or improve both. In HERS 3.26, if curves (respectively, grades) are in “unacceptable” condition (as defined later in this chapter) but grades (respectively, curves) are not, then an improvement that improves curves (respectively, grades) to the design standard but does not modify grades (respectively, curves) may be selected. Otherwise, only alignment improvements that result in improving both curves and grades to the design standard are considered.

Each of the seven kinds of improvement are described briefly in Exhibit 3-1, “Kinds of Improvement.” Within each group, the improvements are listed in decreasing degree of aggressiveness.

HERS uses an additional set of extra-cost options to improve substandard urban freeways to design standards. The four options are: surface shoulders; improve access control to full; upgrade median type to positive barrier; and widen median to design standard. The appropri-

A. Reconstruction
  1. Reconstruction with More Lanes - Complete reconstruction with the addition of lanes to the existing section. Lanes added in excess of the state-coded widening feasibility code are added at high cost – otherwise, lanes are added at normal cost. Shoulder and drainage deficiencies are corrected.
  2. Reconstruction to Wider Lanes - Complete reconstruction with wider lanes than the existing section. No additional lanes are added. Shoulder and drainage deficiencies are corrected.
  3. Pavement Reconstruction - Complete reconstruction without adding or widening lanes. Shoulder width increased to design standard if feasible, and any other shoulder or drainage deficiencies are corrected.

B. Resurfacing
  1. Major Widening - The addition of lanes to an existing facility. Lanes added in excess of the state-coded widening feasibility code are added at high cost – otherwise, lanes are added at normal cost. This improvement includes resurfacing the existing lanes and other minor work such as shoulder and drainage work.
  2. Minor Widening - This improvement is similar to major widening except that the added width yields wider lanes or shoulders, but no additional lanes.
  3. Resurfacing with Shoulder Improvements - The overlay of existing pavement plus the widening of shoulders to design standards if feasible or the complete reconstruction of shoulders to provide additional strength. A minor amount of additional right-of-way may be acquired.
  4. Resurfacing - The overlay of existing pavement including bringing the shoulders up to grade including minor drainage work.

Exhibit 3-1. Kinds of Improvement

ate improvements are only implemented on substandard urban freeways undergoing pavement reconstruction; sections being resurfaced are not upgraded in this manner.

The HERS model differentiates between lanes added at “Normal” and “High” cost. New lanes are added at normal cost when they do not violate the state-supplied Widening Feasibility code (WDFEAS) for the section. The user has the option of setting the Federal Override (WDFOVR) value to add lanes beyond those permitted by the state code up to the maximum lane limit (MAXLNS). These lanes are added at high cost. It is possible for a section to be improved by the addition of lanes at both cost levels: HERS reports these improvements as high cost lanes in the output statistics.

3.2 Deficiency Criteria

HERS recognizes a section’s need for improvement by comparing its characteristics to user-specified deficiency levels. HERS distinguishes up to three degrees of deficiency that might exist for eight characteristics of each highway section. The eight characteristics are:

1. Pavement condition;
2. Surface type;
3. Volume/Capacity (V/C) ratio;
4. Lane width;
5. Right shoulder width;
6. Shoulder type;
7. Horizontal alignment; and
8. Vertical alignment.

The three degrees of deficiency are identified by three user-specified levels: DL (deficiency level); SDL (serious deficiency level); and UL (unacceptability level). The roles of these three levels in the HERS improvement-selection procedure are:

1. If the DL for a particular characteristic of a section is violated, HERS will analyze the benefits and costs of potential improvements that would correct this condition. If the resulting benefit/cost ratio of such an improvement is high enough, it may be selected to be implemented.
2. If the SDL for a particular characteristic of a section is violated, then only improvements that correct this condition are evaluated by the HERS benefit-cost analysis procedure.
3. If the user has specified that improvements are mandatory if the UL for a particular characteristic is violated, then an improvement that corrects this condition is normally selected automatically. (See paragraph 3.3.2, "Addressing Unacceptable Conditions: the Optional First Pass.") The B/C ratio for the improvement is considered by HERS only if the limiting constraint (whether funds available or system performance level) is insufficient to correct all such conditions.

The values used by HERS are contained in an external ASCII file (DLTBLS.DAT) for convenient user access and modification.

3.3 Identifying Improvements for Analysis

During each funding period, HERS is designed to make two passes over the entire set of sample sections to identify improvements that might warrant implementation. The first pass is optional and is used to identify improvements to be implemented based upon engineering criteria, regardless of their economic desirability. During the first pass, for paved sections with unacceptable present serviceability ratings for pavement condition and for unpaved sections with unacceptable surface type or lane width, HERS selects an appropriate inexpensive improvement. If sufficient funds are available, all such improvements are implemented without any B/C analysis. Otherwise B/C analysis is used to select the improvements to be implemented. Note: this optional first pass is not used in the analysis for the *C&P Report*.

During the second pass, HERS identifies additional deficiencies as well as appropriate improvements to address these deficiencies. B/C analysis is then used to determine which of these improvements to implement.

The procedures used to identify improvements during each of these passes are presented below. As the procedure used during the second pass is central to the use of B/C analysis by HERS, that procedure is described first.

3.3.1 Addressing Ordinary Deficiencies: the Second Pass

During the second pass, HERS identifies deficiencies on the basis of the user-specified DLs and SDLs. HERS identifies an improvement type only when a pavement or capacity deficiency exists in the current funding period. When such a deficiency exists, HERS generally will identify at least one improvement type that will address it. (The exception to this rule is when the only deficiency is a capacity deficiency, and additional lanes are either not needed or cannot be added, and it is not possible to widen the section to correct any substandard shoulder or lane widths.)

The procedure for identifying improvement types to address ordinary deficiencies consists of two components:

1. Identification of one (or, in some cases, two) “aggressive improvement type(s)” that will correct all identified deficiencies; and
2. Identification of any less aggressive improvement types warranting B/C analysis as possible alternatives to the first, more aggressive, improvement(s). These alternatives would address some but not all of the segment’s deficiencies.

These two components of the procedure are discussed below.

3.3.1.1 Aggressive Improvement Types

The procedures for selecting pavement, width and alignment options are presented in Exhibit 3-2, “Identification of Aggressive Pavement Option,” Exhibit 3-3, “Identification of Aggressive Widening Options,” and Exhibit 3-4, “Identification of Aggressive Alignment Options,” respec-

I. Reconstruct if:
    A. PSR at the beginning of the funding period is less than reconstruction PSR;
    B. surface type is low and deficient, and a widening option is identified; or
    C. surface type is unpaved and:
        1. surface type is deficient; or
        2. a widening option is identified.
II. Otherwise resurface if:
    A. PSR at the end of the funding period is deficient; or
    B. a widening option is identified.

Exhibit 3-2. Identification of Aggressive Pavement Option

I. For <u>unpaved</u> sections:
  A. <u>Widen lanes</u> if a deficiency exists in lane width or (for collectors in the lowest volume category) in sum of lane width and shoulder width.

II. For <u>paved</u> sections:
  A. <u>Add lanes</u> if lanes can be added and
    1. more lanes are needed[1] or
    2. pavement requires reconstruction, and more lanes will be needed in the design year
  B. <u>Widen lanes</u> if lanes can be widened and
    1. more lanes are not needed, or lanes cannot be added and
      a. lane width is deficient, and PSR is deficient; or
      b. design hour V/C is deficient, and capacity would be increased by widening lanes[2], and lane width is less than design standard; or
    2. If PSR is deficient, and design hour V/C is not deficient but will be in the design year, and capacity would be increased by widening lanes[2], and lane width is less than the design standard, and
      a. section is an urban freeway by design type; or
      b. the reconstruction option has been identified solely as a result of a pavement or surface type deficiency.
  C. Otherwise, <u>improve shoulders</u> if:
    1. shoulder width is less than the design standard, widening is feasible, design hour V/C is deficient, and capacity would be increased by improving shoulders[2];
    2. shoulder width is deficient, widening is feasible, and PSR is deficient; or
    3. shoulder type is deficient and PSR is deficient.

Exhibit 3-3. Identification of Aggressive Widening Options

[1] "More lanes are needed" means V/C is deficient both now and in the design year.

[2] On some sections with initial capacity coded in the HPMS data base, widening lanes or shoulders may not result in any increase in capacity (because the calculated capacity after widening is no higher than the coded capacity). For such sections, the "widen lanes" and "improve shoulders" options do not produce any benefits recognized by HERS. For such sections, these improvements are analyzed by HERS only if they address a "serious deficiency".

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tively. These three procedures, taken together, identify a set of options that define a maximum of two improvement types.

When considering pavement options, HERS decides whether resurfacing or reconstruction is appropriate based upon PSR at the beginning of the funding period analyzed. This reconstruction level is set by the user. As shown in Exhibit 3-2, the consideration of reconstruction can also be triggered by the inadequacy of the current surface type.

I. <u>For rural sections</u>:
  A. Improve curves and / or grades if:
    1. curves and / or grades by class are specified,
    2. any pavement or widening option is identified, and
    3. horizontal or vertical alignment is deficient.
II. <u>For urban sections</u>:
  A. Improve curves if:
    1. curves by class are specified,
    2. reconstruction is identified, and
    3. horizontal alignment is deficient.

Exhibit 3-4. Identification of Aggressive Alignment Options

When considering widening options, HERS may select both an "add lanes" option and, if appropriate, the "widen lanes" option as well. This is the only situation in which HERS will identify two aggressive improvement types for further analysis. This can occur only when:

1. Additional lanes can be added;
2. More lanes are needed in the design year, but not now;
3. Widening lanes will increase capacity without correcting the design year capacity deficiency; and
4. Reconstruction is needed.

HERS identifies the widen lanes option whenever the PSR is deficient, widening is feasible, and either lanes are needed but cannot be added or lane width is deficient. The HERS decision to widen lanes does not depend upon factors such as whether reconstruction is required, rural or urban location and whether or not the section is an urban freeway / expressway up to design standards.

When considering alignment options, HERS considers both horizontal and vertical alignment improvement for rural sections and horizontal alignment improvements for urban principal arterials. This analysis is done only for segments for which complete information about curves and / or grades by class is available. (The HPMS Field Manual requires this information for rural principal and minor arterials and urban principal arterials.)

3.3.1.2 Less Aggressive Alternatives

After identifying one (or two) aggressive improvement types that will address all of a section's deficiencies, HERS then identifies less aggressive improvement alternatives, and uses benefit-cost analysis to choose among the alternatives. In general, less aggressive improvements can be derived directly from the most aggressive improvement by:

1. Replace a widening option with no widening;

2. Replace a widening option with a less aggressive widening option; or
3. Replace improved alignment with no change in alignment.

Replacement rules 1 and 3 involve replacing a particular option with the corresponding “zero-level” option (as defined and numbered in Table 3-1, “Improvement Options”). If HERS had selected a single aggressive improvement type including both widening and an alignment improvement, these two replacement rules would identify up to three less aggressive alternative improvements for analysis (zero-option for widening, zero-option for alignment, and zero-option for both). If HERS had selected two aggressive improvement types for further analysis, these rules would identify up to four less aggressive alternatives, so up to six alternatives might be analyzed for some sections.

Although an exhaustive evaluation of all such alternatives may, at times, be of interest, it is likely that HERS users frequently will prefer that some of these evaluations be skipped in order to shorten run times. This is accomplished using the SDLs introduced in paragraph 3.2. When the user-specified SDL for a section characteristic is violated, any improvement option designed to address the deficiency is treated as “required” and HERS will not analyze the zero-level alternative. If the SDL is not violated, any improvement designed to address the deficiency is treated as “non-required” or “optional,” and the zero-level alternative to the option is analyzed. (There is no SDL for pavement condition, since the decision on whether to reconstruct or resurface a section is primarily based on the reconstruction level. HERS does not directly compare reconstruction alternatives with resurfacing alternatives for an individual section.)

Replacement rule 2 is used only in the special case in which a lower-level widening option (e.g., improve shoulders, or widen lanes) is required (because the SDL for shoulder-width or shoulder-type is violated), but a non-required higher-level widening option (e.g., widen lanes or add lanes) is included in the aggressive improvement identified by HERS. In this case, HERS considers the required lower-level widening option as an alternative to the aggressive improvement, rather than evaluating the zero-level alternative.

If the user has elected to enable ULs (unacceptability levels), and if the capacity of a section is expected to violate the user-specified UL during the expected design life for a pavement improvement being considered, a capacity improvement option is treated as a required accompaniment to that pavement improvement, regardless of whether the capacity SDL is currently being violated. In this case, the zero-level alternative widening option would not be evaluated. This requirement enables HERS to avoid a situation in which capacity becomes unacceptable at a time when resurfacing (or reconstruction) is not normally performed.

If all SDLs are set equal to the corresponding DLs, then normally only the “most aggressive” improvements identified by the procedures of Exhibits 3-2 through 3-4 are analyzed. If the SDLs are relaxed completely (that is, the SDL for the V/C ratio is set high and all other SDLs are set to zero), all alternatives generated by replacement rules 1 and 3 are evaluated. The implications of how the user chooses to set the DL, SDL, and UL levels are discussed more fully in paragraph 3.5.

3.3.2 Addressing Unacceptable Conditions: the Optional First Pass

An option is available to enable the user to identify unacceptable conditions that receive greater priority for correction than serious deficiencies. In most instances, the improvements selected to correct the unacceptable conditions will be implemented without being subject to B/C analysis. When the analysis is constrained by available funds, a portion of the available funds may be designated for the correction of unacceptable conditions. In the case of paved sections, whenever a section is found to have an unacceptable PSR, an appropriate inexpensive improvement that addresses all unacceptable conditions on the section is identified. In the case of unpaved sections, whenever a section is found to have unacceptable surface type or lane width, an appropriate inexpensive improvement that addresses all such conditions is identified. The procedure for identifying options defining these improvements is presented in Exhibit 3-5, "Identification of Improvement Options for Addressing Unacceptable Conditions."

Paved sections with unacceptable PSR and unpaved sections with unacceptable surface type or lane width will be referred to as sections with "triggering unacceptabilities". The procedure presented in Exhibit 3-5 is designed to identify all such sections and, except for the case in which the V/C ratio is unacceptable, the procedure is designed to identify the least expensive of the available HERS improvements that will correct all unacceptable conditions on such a section. In the case of an unacceptable V/C ratio, the procedure selects the most aggressive widening option warranted by the section's characteristics.

When a section has unacceptable pavement, the improvement identified by the procedure shown in Exhibit 3-5 will generally be selected to improve the section.[1] However, the implementation of mandatory improvements is handled slightly differently depending on the user's analytical objective, as discussed below.

3.4 Default Deficiency Criteria

Suggested default values for the ULs, SDLs, and DLs for the eight section characteristics are presented in Tables 3-2 through 3-9. (These values were used in processing for the 1999 *C&P Report*.) As indicated in the exhibits, for rural sections HERS allows separate values to be specified for three terrain types and eight combinations of functional system and average daily traffic (AADT). For urban sections, HERS allows separate values for each of five functional systems.

In the case of pavement condition (Table 3-2, "Default Pavement Condition Criteria (PSR)"), SDLs are not shown, but a set of "reconstruction levels" (RLs) are. SDLs for pavement condition are not needed because all improvements involve either resurfacing or reconstruction, and, in HERS, only one of these two improvement options are considered for a section in any funding period. The pavement option considered is resurfacing unless PSR is below the RL or certain surface-type deficiencies (specified in Exhibit 3-2) exist.[2]

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[1] It should be noted that (as currently implemented), for paved sections, only pavement-related conditions trigger the correction of unacceptable conditions; but, when unacceptable pavement conditions are corrected, all other unacceptable conditions are corrected as well. This procedure, in conjunction with the procedure for addressing serious deficiencies, guarantees that any non-pavement-related unacceptable conditions will be corrected whenever the pavement of a section is improved. However, except when warranted by benefit-cost analysis, these conditions will normally not be corrected as long as the section's pavement remains in reasonably good condition.

- I. For paved surfaces:
  - A. If at the end of the funding period the PSR is unacceptable:
    - 1. Reconstruct if surface type is low and unacceptable;
    - 2. Otherwise, reconstruct if at the beginning of the funding period the PSR is below the reconstruction PSR;
    - 3. Otherwise, resurface.
  - B. If resurfacing or reconstruction has been selected, then:
    - 1. For rural sections, improve curves and/or grades if horizontal and/or vertical alignments are unacceptable, and curves and/or grades are specified by class;
    - 2. For urban principal arterial, improve curves if horizontal alignment is unacceptable, and curves are specified by class;
    - 3. If V/C is unacceptable:
      - a. Add lanes if more lanes are needed and can be added;
      - b. Widen lanes if lanes can be widened:
        - i. if lane width is unacceptable; or
        - ii. if lane width is less than the design standard, and widening lanes will increase capacity, and widening shoulders will not make V/C acceptable;
      - c. Otherwise, improve shoulders if shoulder width is less than design standard and shoulders can be widened and widening shoulders will increase capacity.
    - 4. Widen lanes if lane width is unacceptable and lanes can be widened;
    - 5. Improve shoulders if shoulder width is unacceptable and widening is feasible;
    - 6. Improve shoulders if shoulder type is unacceptable.
- II. For unpaved surface types:
  - A. Widen lanes and reconstruct if lane width is unacceptable and lanes can be widened;
  - B. Reconstruct if surface type is unacceptable.

Exhibit 3-5. Identification of Improvement Options for Addressing Unacceptable Conditions

Tables 3-2 through 3-9 also show the HPMS minimum tolerable conditions[1] (MTCs) and, in several of the tables, the design standards (DS) for rural sections used by HERS. The design standards used for median width and for curves and grades are shown in Table 3-10, "Default

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[2] For medium and high-type pavement, PSR is the sole determinant of whether a section should be reconstructed; and for low-type pavement, it is the primary determinant. HERS is unable to take into account other influences on the reconstruction decision (e.g., height of the pavement crown), because they are not currently described in the HPMS database.

[1] HPMS does not provide horizontal alignment MTCs for urban sections. The suggested values shown in Table 3-8, "Default Horizontal Alignment Criteria," are used by HERS for statistical purposes.

Design Standards For Median Width," and Table 3-11, "Default Design Standards For Curves and Grades." The design standards used for urban sections are shown in Table 3-12, "Default Design Standards for Urban Sections."

The MTCs are not used by HERS in selecting improvements; however the shoulder type MTCs are used as design standards when shoulders are improved and the lane width MTCs are used to specify the lane width following reconstruction of an unpaved section. Also, the MTCs for PSR are used in determining the end of the useful pavement life. Finally, the MTCs are used for developing some summary statistics.

Table 3-2. Default Pavement Condition Criteria (PSR)

UL	RL	MTC	DL			
				Rural:		
1.8	2.0	3.0	3.2		Interstate:	Flat
1.8	2.0	3.0	3.2			Rolling
1.8	2.0	3.0	3.2			Mountainous
1.8	2.0	3.0	3.2		OPA AADT>6000:	Flat
1.8	2.0	3.0	3.2			Rolling
1.8	2.0	3.0	3.2			Mountainous
1.5	2.0	2.8	3.0		OPA AADT<=6000:	Flat
1.5	2.0	2.8	3.0			Rolling
1.5	2.0	2.8	3.0			Mountainous
1.2	1.5	2.4	2.6		MA AADT>2000:	Flat
1.2	1.5	2.4	2.6			Rolling
1.2	1.5	2.4	2.6			Mountainous
1.2	1.5	2.4	2.6		MA AADT<=2000:	Flat
1.2	1.5	2.4	2.6			Rolling
1.2	1.5	2.4	2.6			Mountainous
1.0	1.1	2.0	2.4		Coll.'s AADT>1000:	Flat
1.0	1.1	2.0	2.4			Rolling
1.0	1.1	2.0	2.4			Mountainous
0.8	1.1	2.0	2.4		Coll.'s AADT=400-1000:	Flat
0.8	1.1	2.0	2.4			Rolling
0.8	1.1	2.0	2.4			Mountainous
0.6	0.8	1.8	2.2		Coll.'s AADT<400:	Flat
0.6	0.8	1.8	2.2			Rolling
0.6	0.8	1.8	2.2			Mountainous
				Urban:		
2.0	2.2	3.2	3.4		Interstate	
1.8	2.0	3.0	3.2		Other Freeway & Expressway	
1.6	1.8	2.8	3.0		Other Principal Arterial	
1.0	1.1	2.4	2.6		Minor Arterial	
0.8	1.0	2.0	2.4		Collector	

Table 3-3. Default Surface Type Criteria and Standards[1]

UL	SDL	MTC	DL	DS[2]		
					Rural:	
2	2	2	2	2[3]	Interstate:	Flat
2	2	2	2	2[3]		Rolling
2	2	2	2	2[3]		Mountainous
2	2	2	2	2[3]	OPA AADT>6000:	Flat
2	2	2	2	2[3]		Rolling
2	2	2	2	2[3]		Mountainous
3	3	2	2	2[3]	OPA AADT<=6000:	Flat
3	3	2	2	2[3]		Rolling
3	3	2	2	2[3]		Mountainous
3	3	3	3	2[3]	MA AADT>2000:	Flat
3	3	3	3	2[3]		Rolling
3	3	3	3	2[3]		Mountainous
4	4	3	3	3	MA AADT<=2000:	Flat
4	4	3	3	3		Rolling
4	4	3	3	3		Mountainous
4	4	3	3	3	Coll.'s AADT>1000:	Flat
4	4	3	3	3		Rolling
4	4	3	3	3		Mountainous
4	4	4	4	4	Coll.'s AADT=400-1000:	Flat
4	4	4	4	4		Rolling
4	4	4	4	4		Mountainous
5	5	5	5	4	Coll.'s AADT<400:	Flat
5	5	5	5	4		Rolling
5	5	5	5	4		Mountainous
					Urban:	
2	2	2	2		Interstate	
2	2	2	2		Other Freeway & Expressway	
3	3	2	2		Other Principal Arterial	
4	4	3	3		Minor Arterial	
5	5	4	4		Collectors	

[1] Surface Type Codes: 1 = High flexible; 2 = High rigid; 3 = Intermediate; 4 = Low; 5 = Unpaved.

[2] HERS does not allow design standard of 5 (unpaved), substituting 4 if a standard of 5 is specified.

[3] Design standard is high type. HERS actually uses flexible pavement for all resurfacing and for reconstruction of flexible pavements; rigid pavement is used for reconstruction of rigid and composite pavements

Table 3-4. Default Volume/Capacity Ratio Criteria

UL	SDL	MTC	DL			
				Rural:		
0.90	0.85	0.75	0.70		Interstate:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
0.90	0.85	0.75	0.70		OPA AADT>6000:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
0.90	0.85	0.75	0.70		OPA AADT<=6000:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
0.90	0.85	0.75	0.70		MA AADT>2000:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
0.90	0.85	0.75	0.70		MA AADT<=2000:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
0.90	0.85	0.75	0.70		Coll.'s AADT>1000:	Flat
0.95	0.90	0.90	0.80			Rolling
0.98	0.95	0.95	0.90			Mountainous
1.00	1.00	1.00	0.95		Coll.'s AADT=400-1000:	Flat
1.00	1.00	1.00	0.95			Rolling
1.00	1.00	1.00	0.95			Mountainous
1.00	1.00	1.00	1.00		Coll.'s AADT<400:	Flat
1.00	1.00	1.00	1.00			Rolling
1.00	1.00	1.00	1.00			Mountainous
				Urban:		
0.98	0.95	0.95	0.90		Interstate	
0.98	0.95	0.95	0.90		Other Freeway	
0.98	0.95	0.95	0.90		Other Principal Arterial	
0.98	0.95	0.95	0.90		Minor Arterial	
0.98	0.95	0.95	0.90		Collectors	

Table 3-5. Default Lane Width Criteria and Standards (Feet)[1]

UL	SDL	MTC	DL	DS		
					Rural:	
11	11	12	12	12	Interstate:	Flat
11	11	12	12	12		Rolling
11	11	12	12	12		Mountainous
10	11	11	12	12	OPA AADT>6000:	Flat
10	11	11	12	12		Rolling
10	11	11	12	12		Mountainous
10	11	11	12	12	OPA AADT<=6000:	Flat
10	11	11	12	12		Rolling
10	11	11	12	12		Mountainous
8	9	10	12	12	MA AADT>2000:	Flat
8	9	10	12	12		Rolling
8	9	10	12	12		Mountainous
8	9	10	12	12	MA AADT<=2000:	Flat
8	9	10	12	12		Rolling
8	9	10	12	12		Mountainous
8	9	10	12	12	Coll.'s AADT>1000:	Flat
8	9	10	12	12		Rolling
8	9	10	12	12		Mountainous
8	8	8	11	11	Coll.'s AADT=400-1000:	Flat
8	8	8	11	11		Rolling
8	8	8	11	11		Mountainous
8[2]	8[2]	8[2]	10[2]	10	Coll.'s AADT<400:	Flat
8[2]	8[2]	8[2]	10[2]	10		Rolling
8[2]	8[2]	8[2]	10[2]	10		Mountainous
					Urban:	
11	11	12	12		Interstate	
10	11	11	12		Other Freeway	
9	10	10	12		Other Princ. Arterial	
8	8	8	12		Minor Arterial	
8	8	8	12		Collectors	

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[1] For sections for which the database contains roadway width instead of lane width, HERS treats lane width as one-half the roadway width.

[2] For unpaved collectors in this volume category, these criteria are applied to the sum of lane width and shoulder width.

Table 3-6. Default Right-Shoulder Width Criteria and Standards
(Feet)

UL	SDL	MTC	DL	DS			
					Rural:		
6	7	8	10	12		Interstate:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	7	8	9	10		OPA AADT>6000:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	7	8	9	10		OPA AADT<=6000:	Flat
6	7	8	9	10			Rolling
6	6	6	7	8			Mountainous
6	6	6	7	8		MA AADT>2000:	Flat
6	6	6	7	8			Rolling
4	4	4	6	8			Mountainous
4	5	6	7	8		MA AADT<=2000:	Flat
4	5	6	7	8			Rolling
4	4	4	6	6			Mountainous
2	3	4	6	8		Coll.’s AADT>1000:	Flat
2	3	4	6	8			Rolling
2	3	4	6	6			Mountainous
0	0	2	4	4		Coll.’s AADT=400-1000:	Flat
0	0	2	4	4			Rolling
0	0	2	4	4			Mountainous
0	0	0	2	2		Coll.’s AADT<400:	Flat
0	0	0	2	2			Rolling
0	0	0	2	2			Mountainous
					Urban:		
6	7	8	9			Interstate	
6	7	8	9			Other Freeway	
0	5	6	8			Other Principal Arterial	
0	5	6	8			Minor Arterial	
0	3	6	6			Collectors	

Table 3-7. Default Shoulder Type Criteria[1]

UL	SDL	MTC	DL			
				Rural:		
2	2	2	2		Interstate:	Flat
2	2	2	2			Rolling
2	2	2	2			Mountainous
2	2	2	2		OPA AADT>6000:	Flat
2	2	2	2			Rolling
2	2	2	2			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	3	3	3		MA AADT<=2000:	Flat
3	3	3	3			Rolling
3	3	3	3			Mountainous
3	3	3	3		Coll.’s AADT>1000:	Flat
3	3	3	3			Rolling
3	3	3	3			Mountainous
4	3	3	3		Coll.’s AADT=400-1000:	Flat
4	3	3	3			Rolling
4	3	3	3			Mountainous
4	3	3	3		Coll.’s AADT<400:	Flat
4	3	3	3			Rolling
4	3	3	3			Mountainous
				Urban:		
1	1	1	1		Interstate	
1	1	1	1		Other Freeway	
4	2	2	2		Other Principal Arterial	
4	3	3	3		Minor Arterial	
4	3	3	3		Collectors	

[1] Shoulder Type Codes: 1 = Surfaced; 2 - Stabilized; 3 = Earth; 4 = Curbed.

Table 3-8. Default Horizontal Alignment Criteria[1]

UL	SDL	MTC	DL			
				Rural:		
2	2	2	1		Interstate:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
2	2	2	1		OPA AADT>6000:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT<=2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		Coll.'s AADT>1000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
4	3	3	2		Coll.'s AADT=400-1000:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
4	3	3	2		Coll.'s AADT<400:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
				Urban:		
2	2	2	1		Interstate	
2	2	2	1		Other Freeway	
3	2	2	1		Other Principal Arterial	

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[1] Alignment Codes: 1 = All curves meet design standards; 2 = Some curves below design standards; 3 = Curves with reduced speed; 4 = Several curves unsafe.

Table 3-9. Default Vertical Alignment Criteria[1]

UL	SDL	MTC	DL			
				Rural:		
2	2	2	1		Interstate:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
2	2	2	1		OPA AADT>6000:	Flat
2	2	2	1			Rolling
2	2	2	1			Mountainous
3	2	2	2		OPA AADT<=6000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT>2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		MA AADT<=2000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
3	2	2	2		Coll.'s AADT>1000:	Flat
3	2	2	2			Rolling
3	2	2	2			Mountainous
4	3	3	2		Coll.'s AADT=400-1000:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous
4	3	3	2		Coll.'s AADT<400:	Flat
4	3	3	2			Rolling
4	3	3	2			Mountainous

[1] Alignment Codes: 1 = All grades meet design standards; 2 = Some grades below design standards; 3 = Grades with reduced speed; 4 = Significant reduction of speed on grades.

Table 3-10. Default Design Standards For Median Width (Feet)

DS			
	Rural:		
64		Interstate:	Flat
64			Rolling
16			Mountainous
40		OPA AADT>6000:	Flat
40			Rolling
16			Mountainous
40		OPA AADT<=6000:	Flat
40			Rolling
16			Mountainous
40		MA AADT>2000:	Flat
40			Rolling
16			Mountainous
0		MA AADT<=2000:	Flat
0			Rolling
0			Mountainous
0		Coll.’s AADT>1000:	Flat
0			Rolling
0			Mountainous
0		Coll.’s AADT=400-1000:	Flat
0			Rolling
0			Mountainous
0		Coll.’s AADT<400:	Flat
0			Rolling
0			Mountainous
	Urban:		
20		Freeway/Expressway by design	

Table 3-11. Default Design Standards For Curves and Grades

Curve Class	Grade Class			
		Rural:		
4	3		Interstate:	Flat
4	3			Rolling
7	5			Mountainous
4	3		Other Principal Arterial:	Flat
4	3			Rolling
7	5			Mountainous
4	3		Minor Arterial:	Flat
6	3			Rolling
7	5			Mountainous
6	4		Major Collectors:	Flat
7	5			Rolling
10	6			Mountainous
8	4		Minor Collectors:	Flat
10	5			Rolling
12	6			Mountainous
		Urban:		
7			Interstate	
7			Other Freeway	
8			Other Principal Arterial	

Table 3-12. Default Design Standards for Urban Sections

Surface Type[1]	Lane Width (Feet)	Shoulder Width (Feet)	
2	12	10	Freeway by design
2	12	10	Other divided
2	12	9	Undivided arterials
3	12	8	Undivided collectors

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[1] Surface Type Codes: 1 = High flexible; 2 = High rigid; 3 = Intermediate; 4 = Low; 5 = Unpaved.

3.5 Discussion of Criteria Levels

The three paragraphs below provide some general discussion of the default values for the unacceptability levels, deficiency levels, and serious deficiency levels, respectively, and the effects of using values that are more or less stringent.

3.5.1 Unacceptability Levels

A review of Table 3-2, “Default Pavement Condition Criteria (PSR),” indicates that the default UL values for pavement condition are slightly below the reconstruction level, and a review of Tables 3-3 through 3-9 indicates that the other UL values represent conditions that are the same as or (more frequently) somewhat worse than the MTCs. The default values thus suggest an acceptance of conditions on some sections that are somewhat worse than the “minimum tolerable conditions.” (Note that if the user doesn’t want to require that unacceptable conditions be addressed, this can be indicated using a switch in the run specifications, rather than by changing all of the UL values.)

One obvious alternative to the UL values shown in the exhibits is the use of the MTC values as the ULs. Default values that are somewhat worse than the MTCs are provided in the exhibits so that:

- there is a high likelihood that sufficient funds will be available to correct conditions that are truly unacceptable (under the proposed weaker standards of unacceptability); and
- there will be sufficient funds left over to select high B/C ratio improvements for more mildly deficient sections.

A second alternative to the UL values shown is the use of UL values that can never be violated (e.g., PSR = 0.0). When such UL values are specified, HERS will select improvements purely on the basis of B/C ratios. Under these circumstances, conditions on sections with relatively low traffic volumes may be allowed to deteriorate indefinitely.

Within the range of UL values bounded by the alternatives discussed in the two preceding paragraphs lie a large number of alternatives that can reasonably be used as default values. The defaults shown in Tables 3-2 through 3-9 merely represent one possible set of such values.

3.5.2 Deficiency Levels

The DLs are used to identify deficiencies that warrant analysis by HERS. Logically, the DLs may be set at any value between the MTCs and the design standards. Relatively relaxed DLs (i.e., DLs that are close to the MTCs) will limit the number of potential improvements analyzed by HERS and decrease computation time; while more stringent DLs will require HERS to analyze a larger number of potential improvements and may permit HERS to find a more cost-effective set of improvements to be implemented. HERS users should be aware that the optimal set of DLs will actually vary with the particular objective function used (that is, the type of analysis requested) and with the size of the highway-improvement budget. (The optimal DL settings will get more stringent as the budget increases.) The DLs presented in Tables 3-2 through 3-9 are the values used in the 1999 *C&P Report*.

3.5.3 Serious Deficiency Levels

The SDLs are used by HERS to limit the number of alternative improvements analyzed for a given section. Logically, the SDLs may be given values between the UL values and the DL values. If all SDLs are set equal to the corresponding DLs, no more than one improvement will be analyzed for each section in a given funding period, and any improvement analyzed will address all deficiencies identified for the section. If all SDLs are set equal to the corresponding ULs, up to six different improvements may be analyzed for each section. (These consist of a pavement option with or without the improve alignment option and with zero, one or two widening options.) The settings used for the SDLs thus will have a significant effect on the computation time required by HERS.

The SDLs have another potentially significant effect. When an SDL is violated for a particular section for which no UL is violated, any improvement selected for the section must address the specified serious deficiency. This restriction may decrease the attractiveness of improving the section, but it also decreases the likelihood that the section will be improved without correcting all serious deficiencies. (It does not guarantee that all serious deficiencies will be corrected since, if an unacceptable condition develops, HERS is likely to correct the unacceptable condition without correcting other serious deficiencies.)

This second effect of the SDLs suggests that it may be appropriate to set all SDLs to the corresponding MTC values. Many of the suggested SDL default values presented in Tables 3-2 through 3-9 are, in fact, set to the corresponding MTC values. However, to make things interesting, less stringent values are used for some SDLs.

4 Evaluating Improvements

After potential improvements have been identified, HERS evaluates them to gauge their economic attractiveness. HERS makes decisions about improvements on the basis of the ratio of the net present value of each improvement's incremental benefits to the present value of the incremental costs. This ratio is referred to as the incremental benefit-cost ratio, or IBCR. The decisions HERS makes based upon IBCR are:

- Does the section warrant improvement during this funding period?
- If so, which is the economically most attractive improvement for this section?

In a constrained scenario, HERS also asks:

- Among the potential improvements to all sections in the highway system under analysis, which are the economically most attractive?

This chapter first presents the steps HERS uses in determining the benefit-cost ratio (BCR, used interchangeably with IBCR). It then examines how HERS uses the BCR to answer the first question above. The manner in which HERS handles the second and third questions is presented in Chapter 5, ”Selecting Improvements.” A more exhaustive description of the benefit-cost analysis procedure used by HERS can be found in Appendix A, ”Benefit-Cost Analysis.”

The evaluation process consists of determining the benefit-cost ratio of each candidate improvement. This is accomplished in several steps:

1. identifying the base case;
2. determining the length of the analysis period;
3. determining the user, agency, and external costs associated with the base case;
4. determining the user, agency, and external costs associated with the candidate improvement;
5. determining the capital cost of the improvement;
6. determining the residual value of the improvement; and
7. calculating the benefit-cost ratio.

This chapter addresses the *process* of determining the BCR for candidate improvements. The detailed discussions of the calculations involved are discussed in Chapter 6, ”HERS Internal Models” (the forecast of traffic volume and pavement condition) and Chapter 7, ”Cost and Benefit Calculations” (the calculation of user, agency, external, and capital costs).

4.1 The Base Case

In a typical HERS run, when the option to force the model to address unacceptable conditions has not been selected, the initial base case is the unimproved section. That is, the potential benefits of candidate improvements will be compared against the case in which no improvement is made to the section. HERS uses this base case when determining whether a section warrants improvement during the current funding period (see paragraph 4.8, ”Does a Section Warrant Improvement?”). However, if the option to force the model to make mandatory improvements to address unacceptable conditions has been selected, HERS uses the mandatory improvement as the base case.

HERS also uses a previously selected improvement as the base case when considering more aggressive improvements. This situation commonly arises in the selection process for constrained runs, and is also used to discover the economically most attractive improvement for a section during a minimum BCR run. Since the differences between the costs and benefits of the two improvements are used in calculating the benefit-cost ratio, the term ‘incremental benefit-cost ratio’, or IBCR, is often used interchangeably with the term ‘benefit-cost ratio’.

4.2 Determining the Benefit-cost Analysis Period

HERS evaluates the benefits and costs of potential improvements for different lengths of time in order to accommodate section-specific situations and in response to two different questions HERS evaluates: “Should the section be improved now? And if so, what is the best improvement to make?” The benefit-cost analysis period (BCA period) can be a single funding period, or multiple funding periods in length. Analysis over a multi-period time-frame is more complex and requires more computation than analysis over a single period.

Generally, when evaluating whether to improve the section during the current funding period, HERS uses a benefit-cost analysis period equal in length to one funding period. This BCA period would start at the midpoint of the current funding period, and extend to the midpoint of the next funding period (see Exhibit 2-6, “HERS Time Periods”). When determining which of several candidate improvements would be the best improvement for the section, a longer BCA period is used, beginning at the midpoint of the current funding period and extending to the midpoint of some subsequent funding period. It should be noted that when there is more than one candidate improvement, the same BCA period is used for all of the improvements under consideration.

Table 4-1, “Length of BCA Period,” provides a brief summary of how the last funding period of a BCA period is determined. Benefit-cost analysis periods consist of an integral number of funding periods, and extend from the mid-point of the funding period in which the improvement is implemented to the midpoint of some subsequent funding period.

The opening paragraph of this chapter framed the first question asked by HERS:

- Does the section warrant improvement during this funding period?

The phrasing of this question is significant. In highway management, the issue is not whether a section should be improved, but when? In many cases warranting careful analysis, the two most serious alternatives are “improve during the current funding period” and “improve during the next funding period.” For such cases, the HERS procedure usually evaluates improvements that

Table 4-1. Length of BCA Period

Situation Being Analyzed	Funding Period in Which BCA Period Ends
Section for which no improvement has yet been selected during the current funding period:	
If section is in unacceptable condition or unpaved;	Next funding period
Otherwise, if current funding period is the last one in which resurfacing is practical;	Period in which condition first becomes unacceptable[a]
Otherwise, if traffic volume is declining and improvement involves reconstruction;	Period in which condition first becomes unacceptable[a]
Otherwise, if traffic volume is declining;	Last period in which resurfacing is practical
Otherwise.	Next funding period
Section for which an improvement has already been selected during the current funding period.	Next period in which pavement would "normally" be improved or period in which condition becomes unacceptable[a], whichever occurs first.

[a] Unacceptable conditions that cannot be corrected (e.g., those that require more widening than is feasible) are excluded from consideration in this test.

might be implemented during the current funding period by comparing them to a "base case" in which the same improvement is implemented during the next funding period (and no improvement is implemented during the current funding period). Use of such a base case, in conjunction with a procedure for estimating the residual value (see paragraph 4.6 below) of an improvement, permits frequent use of analysis periods that are only one funding period long.

Consider a section for which no improvement has yet been selected during the current funding period. The analysis of potential improvements to such a section addresses the question as to whether any of the improvements should be implemented during the current funding period. If the section does not have any unacceptable conditions, this analysis depends upon whether or not traffic volume on the section is increasing. These two alternatives are discussed below; the special case of a section with unacceptable conditions is discussed in paragraph 5.2, "Selecting Mandatory Improvements."

4.2.1 Traffic Volume on Section is Constant or Increasing

Consider a section in which traffic volume is constant or increasing, and consider a potential improvement that is likely to either warrant funding during this period or at least to come close. If traffic is relatively constant, the annual benefits of such an improvement will also be relatively constant over the life of the improvement; if traffic is increasing, the annual benefits will grow over time. If the improvement is implemented in the next funding period, it will generate at least as many benefits over its life as it would if it were implemented in the current period. Therefore, if it is practical to implement the same improvement in the next funding period and if it fails to be selected during the current period, it will almost certainly be selected for implementation during the following period. Accordingly, the issue is: should the improvement be implemented in this period or in the next one? Therefore, in most instances, HERS analyzes any potential improvement to such a section by estimating the benefits and costs of implementing it in this period relative to a base case in which it is implemented in the next period. With an appropriate definition of the residual value of the improvement (see paragraph 4.6, “Residual Value”) at the end of the BCA period, the BCA period can be limited to a single funding period.

The one exception to the above procedure occurs in the case of improvements that cannot be implemented in the next funding period. Because of the mechanistic way in which HERS handles the resurfacing / reconstruction decision, this situation arises whenever the PSR of a section drops below the “reconstruction level” during the current funding period. In this situation, a relatively inexpensive improvement (involving resurfacing) can be made during the current funding period[1], but only a much more expensive improvement (involving reconstruction) can be made in the next period. If the section is not improved in the current funding period, it is unlikely to warrant a more expensive improvement in the next period. Accordingly, potential improvements to such a section should be analyzed relative to a base case in which no improvement is made for a more extended time period. In HERS, any potential improvement to such a section is analyzed by estimating the benefits and costs of implementing it in this period relative to a base case in which improvement of the section is postponed until the PSR becomes unacceptable.

4.2.2 Traffic Volume on Section is Declining

For a section with declining traffic volume, the annual benefits tend to decline over time. An improvement implemented during the current funding period will generate more benefits over its life than one implemented during the next period. Accordingly, if the benefit-cost analysis procedure indicates that the section does not warrant improvement in the current funding period, then, unless conditions change, the procedure is unlikely to indicate that improvement is warranted in subsequent funding periods on the basis of a benefit-cost ratio.

In this situation, if the section is paved, and the PSR is not already unacceptable, an appropriate base case frequently consists of not improving the section until its PSR becomes unacceptable and improving the section becomes mandatory. However, there are two cases in which a shorter timeframe is used. One case occurs when the section is already in unacceptable condition; in this case, a single-period BCA period is used.

The other case occurs when it is still possible to resurface the section during the next funding period. Because reconstruction is much more expensive than resurfacing, it may not be desirable to postpone improving the section until reconstruction is required. Accordingly, for this situation, potential improvements are analyzed relative to a base case in which no improvement is implemented until the last funding period in which resurfacing is still practical (according to the reconstruction-level criteria).

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[1] Although all improvements are analyzed as if they are implemented in the middle of a funding period, it is recognized that actual implementation of several improvements will be spread over an entire funding period. Accordingly, it is reasonable to presume that sections for which resurfacing is feasible at the beginning of the funding period but not at the end can be resurfaced while resurfacing is still considered to be feasible (according to the artificial resurfacing / reconstruction decision criterion).

In the case of unpaved sections with declining traffic volume, if an improvement is not implemented in the current funding period, it may well never be implemented.[2] For such sections, a very long (or even infinite) BCA period is appropriate. However, the benefits of improvements to such sections will usually be low, and such improvements are likely to have relatively unattractive B/C ratios. For computational efficiency and simplicity, HERS evaluates such improvements relative to a base case in which the improvement is deferred for one funding period resulting in some overestimation of improvement benefits. (The degree of overestimation varies with the extent to which traffic is declining.) It is believed that this computational simplification has no material effect on the selection of improvements for such sections; however, this assertion has not been tested.

4.3 Estimating Variable Costs for the Base Case

After determining the length of the BCA period, HERS calculates the costs associated with the base case for each of the funding periods involved. First (if it has not already been calculated while identifying candidate improvements), HERS predicts the traffic volume (see paragraph 6.3, ”The Travel Forecast Model”) and pavement condition (see paragraph 6.2, ”The Pavement Deterioration Model”) at the end of the funding period. It then calls upon the routines which calculate the operating costs, travel time costs, safety costs, maintenance costs, and emissions costs (see Chapter 7, ”Cost and Benefit Calculations”). The costs are calculated for the end of the funding period. This process of prediction and cost calculation is repeated for each funding period in the BCA period.

4.4 Determining Costs Associated with the Candidate Improvement

The process of calculating the costs associated with the potential improvement is similar to that for the base case. The model first simulates the effect of the improvement on the section (see Chapter 8, ”Effects of HERS Improvements”). This establishes the pavement condition at the time of the improvement, and HERS applies short-run elasticity to determine the new traffic volume (see paragraph 6.3.4, ”The Simultaneous Solution”). Traffic volume and pavement condition are then forecast for the end of the funding period, and the cost calculation routines are called upon to determine the user, agency, and external costs associated with the improved section at that time. The model then repeats the prediction and cost calculation for each funding period in the BCA period.

4.5 Determining the Capital Costs of the Improvements

For most sections being improved, HERS calculates the capital cost by multiplying the cost per lane mile by the number of lanes and by the length of the section. The cost per lane mile depends

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[2] The only situation in which the improvement is implemented in a subsequent funding period occurs when its B/C ratio is greater than one, but there are insufficient funds to implement it in the current funding period. If the user-specified assumptions allow funding of improvements with lower B/C ratios in subsequent periods than in the current period, the improvement may warrant implementation in such a subsequent period.

upon the particular improvement, the section’s functional class, and, for rural sections only, the prevailing terrain (flat, rolling, or mountainous). For sections receiving alignment improvements, HERS employs a more complex approach (including the cost of earthwork, clearing and grubbing, pavement, etc.) to determine the cost over the portion of the section being re-aligned. Portions of the section not being re-aligned are costed in the same manner as sections receiving no alignment improvements.

See paragraph 7.4, ”Capital Cost of Improvements,” for the detailed presentation of how HERS calculates improvement costs.

4.6 Residual Value

This section is divided into two parts. The first part consists of a summary or overview definition of the “residual value” of an improvement. The second part provides a much more detailed description of this value.

4.6.1 A Summary Definition

For purposes of benefit-cost analysis, HERS regards the residual value of a highway improvement as analogous to the “salvage value” of a piece of equipment. At the end of the period being analyzed (the normal life-cycle of a piece of equipment), the equipment has some salvage value that can be recovered by the entity that originally invested in the equipment and can be applied toward the purchase of a replacement. Similarly, in the case of a highway improvement, at the end of the benefit-cost analysis (BCA) period, the improvement has some residual value that reduces the cost of the next improvement.

Residual value differs from salvage value in that, for some improvements, the residual value can be quite high. Consider, for example, an improvement consisting of reconstruction and improved alignment. The new pavement has a finite life, say 15 years, but the improved alignment has an effectively infinite life. Another improvement (e.g., resurfacing) will be required at the end of 15 years, but benefits of the new alignment will continue beyond then. If the benefits and costs of this improvement are analyzed over 15 years (i.e., until the next improvement is required), the benefits of the improved alignment that will accrue beyond the end of this 15-year period must be taken into consideration. To avoid the need to estimate these benefits for many periods into the future, it is assumed that, if alignment were not improved now, it would be improved at the end of the 15-year BCA period. The residual value of the improvement then represents avoided costs of not improving the alignment in 15 years.

In the above example, the residual value is not limited to that of the alignment improvement. Pavement reconstruction itself results in substantial improvement in the roadbed that significantly reduces the cost of the pavement improvements that would be required in 15 years.

4.6.2 Detailed Description of Residual Value

This section presents a formal definition of the residual value of an improvement, I1, at the end of the benefit-cost analysis (BCA) period over which it is analyzed.

Assume that the BCA period starts at time T1 and ends at time T2.

First consider the case in which no improvements are likely between T1 and T2 regardless of whether I1 is implemented. Then, let I3 be the most likely improvement (if any) to be made at T2 if I1 is implemented at T1. Next consider the case in which I1 is not implemented and let I2 be the more extensive improvement required at T2 in order to produce the same conditions that would exist if I1 were implemented at T1 and I3 were implemented at T2. Then the residual value of I1 at time T2 is the cost of I2 minus the cost of I3. Although one would expect the residual value of an improvement to be smaller than its initial cost, this is not always the case. In particular, if I2 involves reconstruction while I1 and I3 do not, the residual value of I1 at time T2 can be appreciably greater than the initial cost of I1.

The present value of the residual value is then obtained by discounting the residual value back to the beginning of the BCA period; i.e., by dividing by $(1+r)^n$, where r is the (user-specified) discount rate and n is the length of the BCA period in years (that is, n=T2-T1). If, for example, a value of seven percent[3] is used for the discount rate, the residual value of an improvement at the end of twenty years is divided by 3.869 (which is equal to 1.07^{20}) to obtain its present value.

A common special case of the above definition occurs when no improvement would normally be made at time T2 if I1 is implemented at time T1. In this case, I2 is the improvement implemented at time T2 to produce the same conditions at T2 that would exist if I1 were implemented at T1.

If one or more improvements are likely between T1 and T2, the definition of the discounted value of residual value becomes more complex. To develop a more general definition, let A1 be the set of improvements, if any, to be made during or at the end of the BCA period if I1 is implemented at T1; and let S2 represent the resulting condition at T2. Let A0 be the set of improvements, if any, that would be made during the BCA period if I1 is not implemented at T1; and let S3 be the resulting condition at T2. Let I2 be the improvement that would bring the section from condition S3 to condition S2. Finally, discount the costs of I2 and of all improvements in A0 and A1 back to time T1 by dividing the cost of each improvement by (1+r)n, where n = Ti - T1, and Ti is the year in which the improvement is implemented. Then the (net) present value of the residual value of I1 is obtained by subtracting the discounted cost of any improvements in A1 from the sum of the discounted cost of I1 and the discounted cost of any improvements in A0. Provided no confusion results, we may, for brevity, refer to the “present value of the residual value” simply as the “residual value.”

The present value of the residual value is treated as an agency benefit and incorporated into the numerator of the benefit-cost ratio. This procedure seeks to optimize the benefits obtained from funds available during a single funding period.

4.7 The Benefit-Cost Ratio

The formal HERS benefit-cost ratio, as shown in Equation 4.1 below, compares a base case to a potential improvement. The base case may be the unimproved section or a previously identified improvement, in which case all potential improvements will be more aggressive than the base case improvement. The HERS procedure includes estimation of the incremental costs and benefits of each potential improvement for each period of the benefit-cost analysis period, as well as

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[3] As recommended by the Office of Management and Budget, a discount rate of seven percent was used in runs supporting the 1999 *Conditions and Performance Report*.

estimation of the improvement's residual value at the end of the analysis period. The residual value of the improvement is discounted back to the initial year of the analysis period and treated as a benefit of the improvement.

$$IBCR = \frac{(UCost_B + ACost_B + ECost_B) - (UCost_I + ACost_I + ECost_I) + RV}{ImpCost_I - ImpCost_B} \qquad Eq.\ 4.1$$

where:

$IBCR$ = incremental benefit-cost ratio;
$UCost$ = user costs (travel time costs, operating costs, and safety costs) for either the base case B or the improved case I;
$ACost$ = agency costs (maintenance costs) for either the base case B or the improved case I;
$ECost$ = external costs (emissions costs) for either the base case B or the improved case I;
RV = residual value of the improvement relative to the base case; and
$ImpCost$ = the capital cost of either the base case B or the improved case I, or zero when the base case is unimproved.

The actual process is slightly more complex. When the benefit-cost analysis period is longer than one funding period in length, benefits must be calculated and accrued for each period. These accruing benefits are then discounted back to the time of implementation. The introduction of demand elasticity results in different traffic volumes for the base and improved case in each subsequent period. This yields a consumer surplus which must be included in the IBCR calculations for benefit components which are dependent upon VMT. (HERS calculates consumer surplus for operating cost benefits, safety benefits, and travel time benefits.)

In Exhibit 4-1, "User Benefits and Consumer Surplus," the base case is represented by the price p_0 and the volume q_0, which intersect on the demand curve. The price to the user after improvement is represented by p_1, and results in movement along the demand curve to yield the increased volume q_1. The rectangle labeled "user benefits" represents lower user costs on trips which would have been made had the improvement not changed the price to the user. The triangle labeled "consumer surplus" represents benefits from the additional trips that resulted from the lower price.

For each funding period, HERS first determines the gross benefit for each of the benefit components: travel time benefits, safety benefits, and operating cost benefits (grouped as user benefits); maintenance cost benefits (agency benefits); and emission cost benefits (external benefits). Maintenance costs are calculated per lane mile; all other components are per vehicle mile traveled. For each of the components, the benefit is:

$$BEN = COST_B - COST_I \qquad Eq.\ 4.2$$

where:

BEN = the benefit for a specific cost component;
$COST_B$ = the base case cost for a specific cost component; and
$COST_I$ = the improvement case cost for a specific cost component.

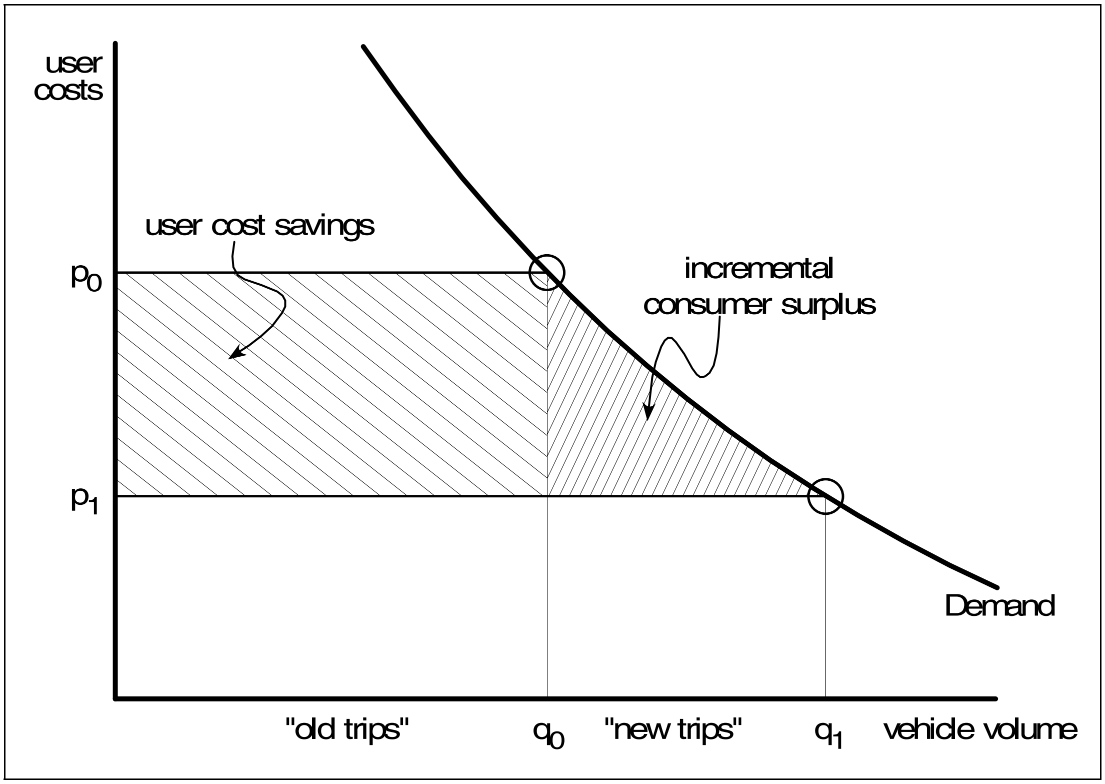

Exhibit 4-1. User Benefits and Consumer Surplus

HERS also computes a discount factor based upon the user-specified discount rate:

$$DFACTR = DRATE^{(LFP \times (FPC - 0.5))} \qquad \textit{Eq. 4.3}$$

where:

DFACTR = discount factor;
DRATE = 1 + the user-specified discount rate divided by 100;
LFP = length of a funding period in years; and
FPC = funding period counter pointing to funding period under analysis.

The discount factor is calculated separately for each funding period in the analysis period. HERS next calculates the "per-vehicle" benefit for user and external benefits:

$$BENPV = LFP \times 365 \times SLEN \times (OPBEN + SAFBEN + TTBEN + EMBEN) / DFACTR \qquad \textit{Eq. 4.4}$$

where:

BENPV = discounted benefit per vehicle trip;
SLEN = the section length in miles;
OPBEN = operating cost benefits per VMT;
SAFBEN = safety benefits per VMT;
TTBEN = travel time benefit per VMT; and
EMBEN = emission cost benefit per VMT.

The interim total in Equation 4.4 includes the discounted benefits for each mile traveled over the section for each day of the funding period for the benefit components expressed by VMT. However, it does not include traffic volume, neither the "old trips", or the "new trips" which result from the change in user price. HERS calculates the total benefit to include the benefits from "old trips", the consumer surplus, and the discounted maintenance cost savings:

$$TOTBEN = BENPV \times AADT_B + BENPV \times \frac{AADT_I - AADT_B}{2} + MNCBEN / DFACTR \qquad \text{Eq. 4.5}$$

where:

$TOTBEN$ = discounted total benefits for the funding period;
$AADT_B$ = AADT for the base case B;
$AADT_I$ = AADT for the improved case I; and
$MNCBEN$ = maintenance cost benefit for the period.

This total, *TOTBEN*, is calculated for each funding period of the benefit-cost analysis period. When benefits have been calculated for all periods of the benefit-cost analysis period, HERS calculates the IBCR for the improvement:

$$IBCR = \frac{TOTBEN_{SUM} + RV}{(IMPCOST_I - IMPCOST_B)} \qquad \text{Eq. 4.6}$$

where:

$IBCR$ = the incremental benefit-cost ratio for the improvement;
$TOTBEN_{SUM}$ = the sum of the discounted total benefits for all funding periods in the benefit cost analysis period;
RV = the discounted residual value of the improvement;
$IMPCOST_I$ = the capital cost of the improvement being analyzed; and
$IMPCOST_B$ = the capital cost of the base case improvement (zero when the base case is "no improvement.")

4.8 Does a Section Warrant Improvement?

When considering one or more candidate improvements for a section, HERS calculates the BCR for each of them relative to the same base case and for the same evaluation period. When the user has not requested mandatory improvements HERS will decide whether or not the section warrants improvement based upon the highest BCR relative to the unimproved base case. Except for the cases discussed in paragraph 4.2 (declining traffic or the current period is the last one in which resurfacing is practical), the benefit-cost analysis period will be one funding period in length. HERS will not improve the section if the highest BCR is less than the qualifying threshold. For constrained runs, the threshold is set at 1.0. For minimum BCR runs, the user specifies the minimum BCR in the specification file. (The term "economic efficiency run" is used for a minimum BCR run with a minimum BCR of 1.0.)

The case of a section where improvement is not warranted by benefit-cost analysis is shown in Exhibit 4-2. Three potential improvements have been identified for the section, numbered 10, 20, and 30. The cost of each improvement is shown on the x-axis (shown as c10, c20, and c30), and the benefits of each improvement during the benefit-cost analysis period are plotted on the y-axis (b10, b20, and b30). For each improvement, a dotted line is drawn from the origin through the intersection of its costs and benefits depicting the improvement's benefit-cost ratio. These are labeled r10, r20, and r30 (the "r" is for ratio). The dashed line drawn at 45° represents a benefit-cost ratio of 1.0. Potential improvement 10 has the highest benefit-cost ratio, as it is closest to 45°; however, as in the other two cases, the potential benefits are less than the capital costs, and the section will not be improved.

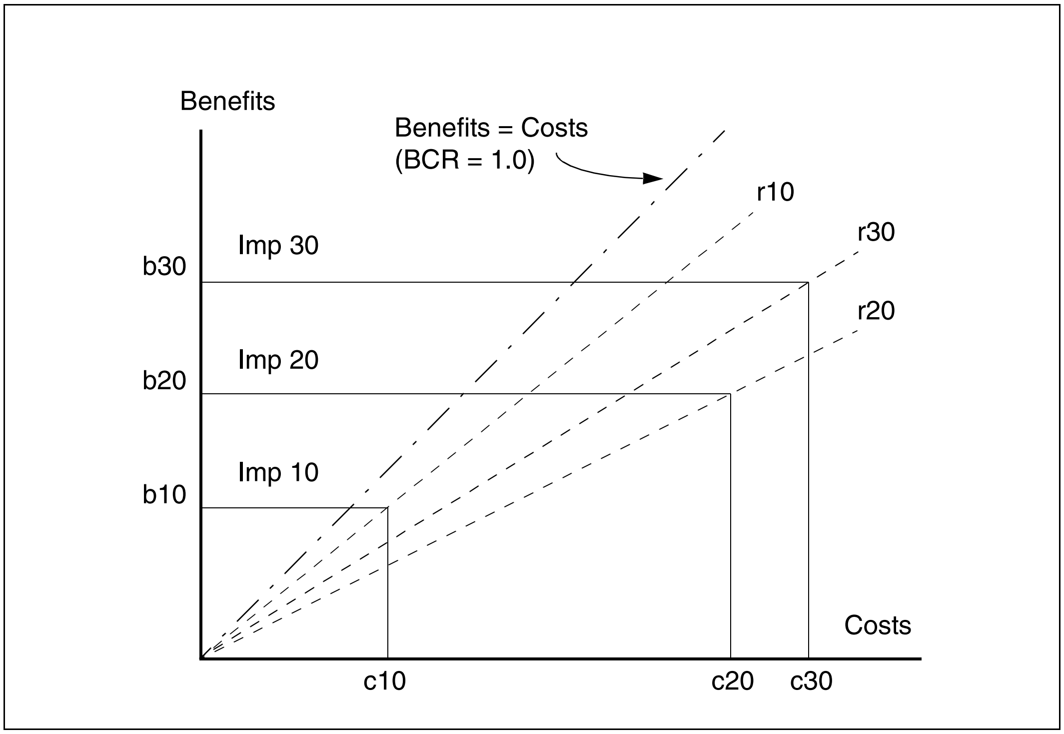

Exhibit 4-2. Improvement Not Warranted

Exhibit 4-3, "Section Warranting Improvement," illustrates the case of a section where two of the potential improvements have initial benefit-cost ratios greater than 1.0. (These initial BCRs are calculated over a single funding period.) In this case, potential improvement 10 has the highest benefit-cost ratio. In a minimum BCR run, either improvement 10 or 20 will be implemented; in a constrained run, improvements 10 and 20 will be eligible for implementation.

When the user has specified mandatory improvements, *all* sections for which mandatory improvements have been identified are deemed to justify improvement and, unless the funding limits are reached in a constrained fund run, will be improved. Thus, if improvement 10 in Exhibit 4-2 were a mandatory improvement, it would be implemented even though its benefit-cost ratio is less than 1.0. A discussion of the selection of more aggressive improvements, including the replacement of mandatory improvements, is contained in Chapter 5, "Selecting Improvements."

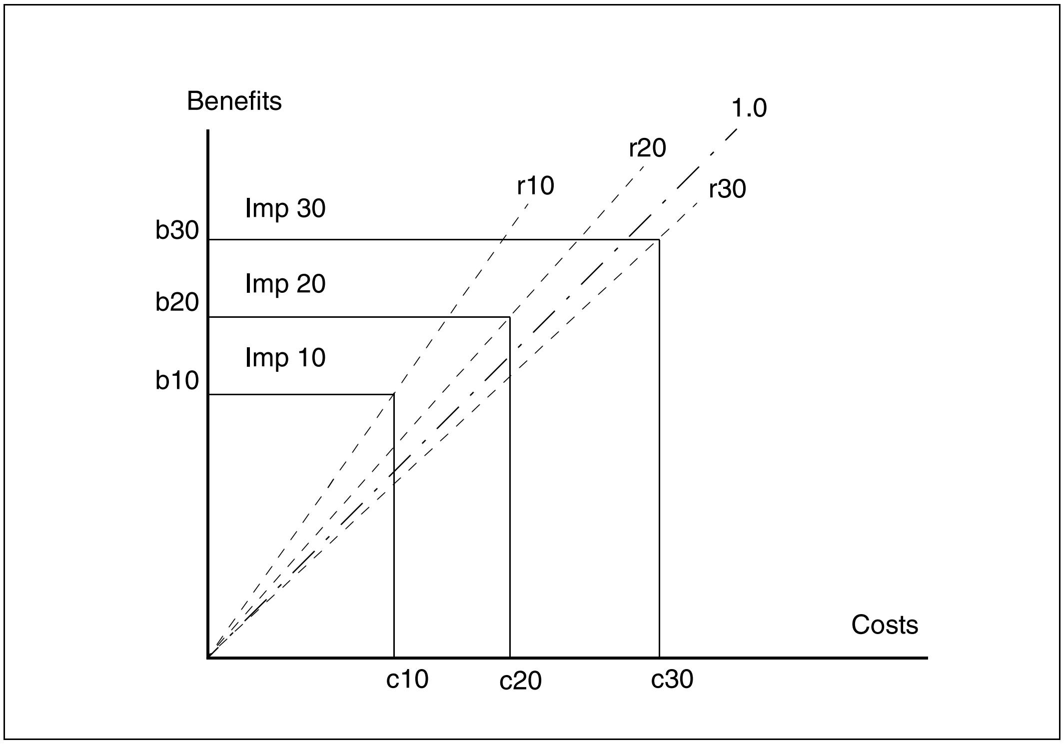

Exhibit 4-3. Section Warranting Improvement

5 Selecting Improvements

As first presented in Chapter 2, ”An Outline of the Model Structure,” the HERS process has several variants depending upon the analytical objective and whether the user has stipulated that mandatory improvements must be made to correct unacceptable conditions. Chapter 4, ”Evaluating Improvements,” presented the steps HERS uses to calculate an improvement’s BCR and to determine whether a section warranted improvement during the current funding period. Chapter 5 examines the HERS methods for deciding which improvement to implement on sections warranting improvement and, during a constrained run, which of the sections warranting improvement will be improved and which will not be improved. The first part of this chapter examines the process when no mandatory improvements have been specified by the user. First examined is the process for minimum BCR runs, followed by the process for constrained runs. The second portion of this chapter contains a discussion of how mandatory improvements are involved in the selection process for each of the three analytical objectives.

5.1 Improvement Selection Without Mandatory Improvements

In most cases, the HERS model is run without the specification of mandatory improvements. (This includes runs used in preparation of the 1995, 1997, and 1999 *C&P Reports*.) As shown in Exhibit 2-1, “HERS Process Flow Without Mandatory Improvements,” HERS uses either of two logic flows when selecting improvements without mandatory improvements. When conducting a minimum BCR analysis, HERS is able to select an improvement for each section immediately after evaluating its potential improvements and determining that it warrants improvement during the current funding period. During a constrained run, HERS “pre-selects” a list of improvements for those sections warranting improvement, and, after processing all sections, selects from that list until the specified constraint has been satisfied. These two processes are presented below in more detail.

5.1.1 Minimum BCR Analysis

When the analytic objective stipulates a minimum BCR run, every section which warrants improvement will be improved. For these sections, then, the question HERS asks is:

- What is the economically most attractive improvement for this section?

When determining that a section warrants improvement during the current funding period, HERS calculates BCRs for all the potential improvements and identifies the improvement with the highest initial BCR. This improvement is designated the base case improvement. This base case improvement might not be the most desirable improvement to implement during this period. It may be that an improvement that costs more and generates more benefits is more desirable.

In Exhibit 5-1, “Initial Improvement for Minimum BCR Run,” improvement 10 has the highest initial benefit-cost ratio relative to the unimproved base case: it’s benefit-cost line (labeled “r10”) lies above those for improvements 20 and 30. Improvement 10 has qualified the section for improvement, as its BCR is greater than the minimum threshold of 1.0. Improvements 20 and 30 would also have justified improvement in this funding period. Because no improvement had yet been selected for the section, and no special conditions prevailed, the length of the benefit-cost analysis period was set to a single funding period. (See paragraph 4.2, ”Determining the Benefit-cost Analysis Period,” for details.) Improvement 10 thus becomes the new base case improvement against which the BCRs of more aggressive improvements will be calculated.

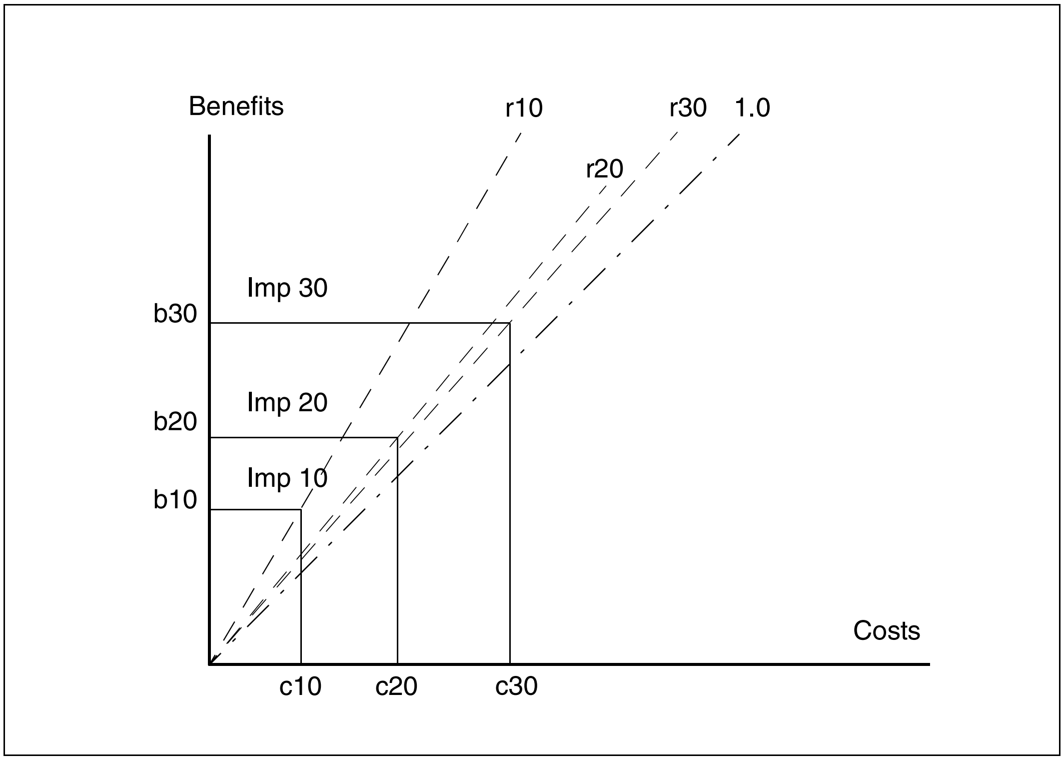

Exhibit 5-1. Initial Improvement for Minimum BCR Run

To determine whether a more desirable improvement exists, HERS next identifies all more aggressive improvements worth analyzing. HERS then estimates the incremental benefits and costs of implementing each more aggressive improvement relative to the new base case improvement.

In general, the more aggressive improvement will incorporate some widening and/or alignment option not included in the base case improvement. If this option is not implemented in the current funding period, normally, it is not likely to be implemented until the section is next resurfaced. Accordingly, the incremental benefits and costs of immediately implementing the more aggressive improvement are analyzed over a time frame that ends when the section would normally next be resurfaced. In HERS, the length of this time frame is limited to sixty years when the funding period length is two years or longer and to forty years, when one-year funding periods are used.[1]

The example continues in Exhibit 5-2, "Selecting a More Aggressive Improvement." Here, incremental benefit-cost ratios have been calculated for improvements 20 and 30 relative to improvement 10. The length of the benefit-cost analysis period has been determined by the "normal life" of improvement 10, which extends for several funding periods. For the more aggressive improvements, the longer benefit-cost analysis period allows for accrual of more total benefits at the same level of initial capital investment. In the exhibit, the increased benefit levels (subscripted "nl" for "normal life") are shown by the dotted lines which extend the figures for improvements 20 and 30 along the benefits axis. Note that the BCR for the base case improvement (improvement 10 in the example) is not re-calculated over the normal life.

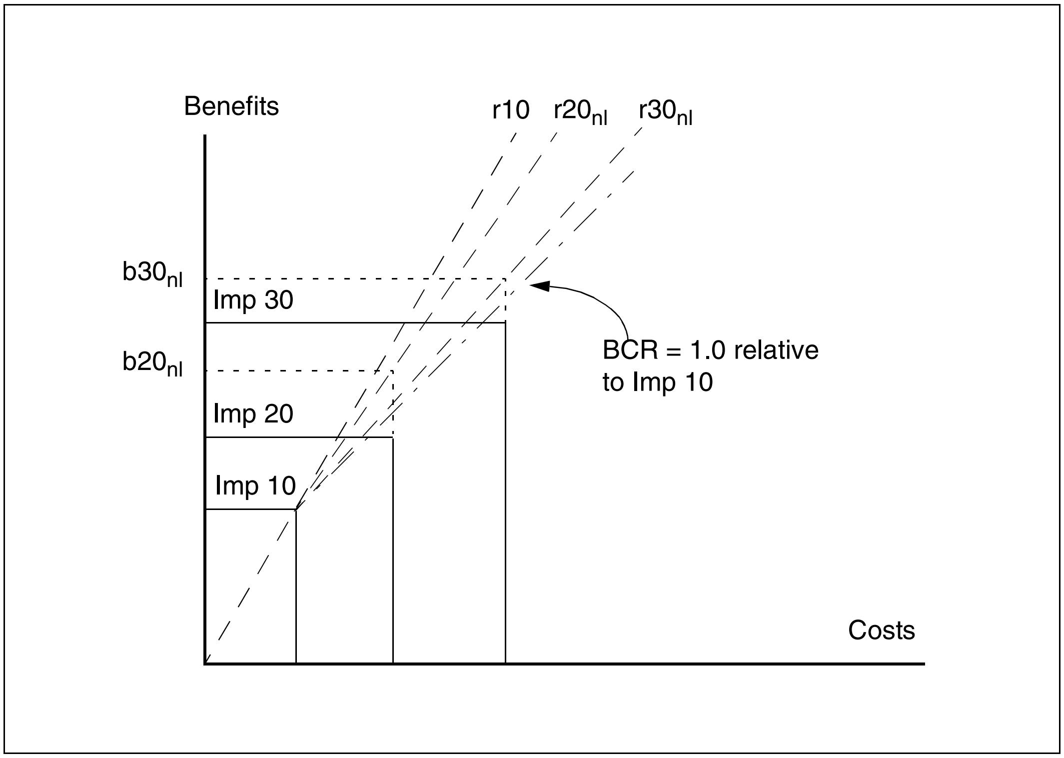

Exhibit 5-2. Selecting a More Aggressive Improvement

Improvement 10's initial benefit-cost ratio is still more attractive than the "normal life" BCRs of the other two potential improvements. This is shown in Exhibit 5-2, as the two new BCRs (subscripted "nl") lie to the right of improvement 10's BCR. Note that the two new BCRs are drawn as originating from the intersection of improvement 10's costs and benefits. This is because the normal life BCRs are calculated relative to the "base case" of improvement 10. The line representing the minimum BCR threshold of 1.0 also originates from this point. The normal life ratios for improvements 20 and 30 lie above (to the left of) this threshold line.

The algorithm examines the candidate improvements in order. Finding that improvement 20's BCR is greater than that of improvement 30 (both relative to improvement 10), it designates improvement 20 as the new base case and re-calculates improvement 30's BCR relative to improvement 20. Once again, the length of the benefit-cost analysis period is determined by the

---

[1] A review of improvements analyzed by HERS indicates that resurfacing is usually expected to occur in less than 40 years after a section is improved, sometimes in 40 years to 55 years, and never in more than 55 years.

normal life of the base case, which in this iteration is improvement 20. In our example, improvements 10 and 20 share the same life span, although this may not always be the case. As shown in Exhibit 5-3, improvement 30's BCR relative to improvement 20 (labeled $r30_{nl}$ and originating from the intersection of improvement 20's costs and benefits) lies below the 1.0 threshold, therefore it is not selected to replace improvement 20 and will not be implemented. Improvement 20 is therefore selected for implementation.

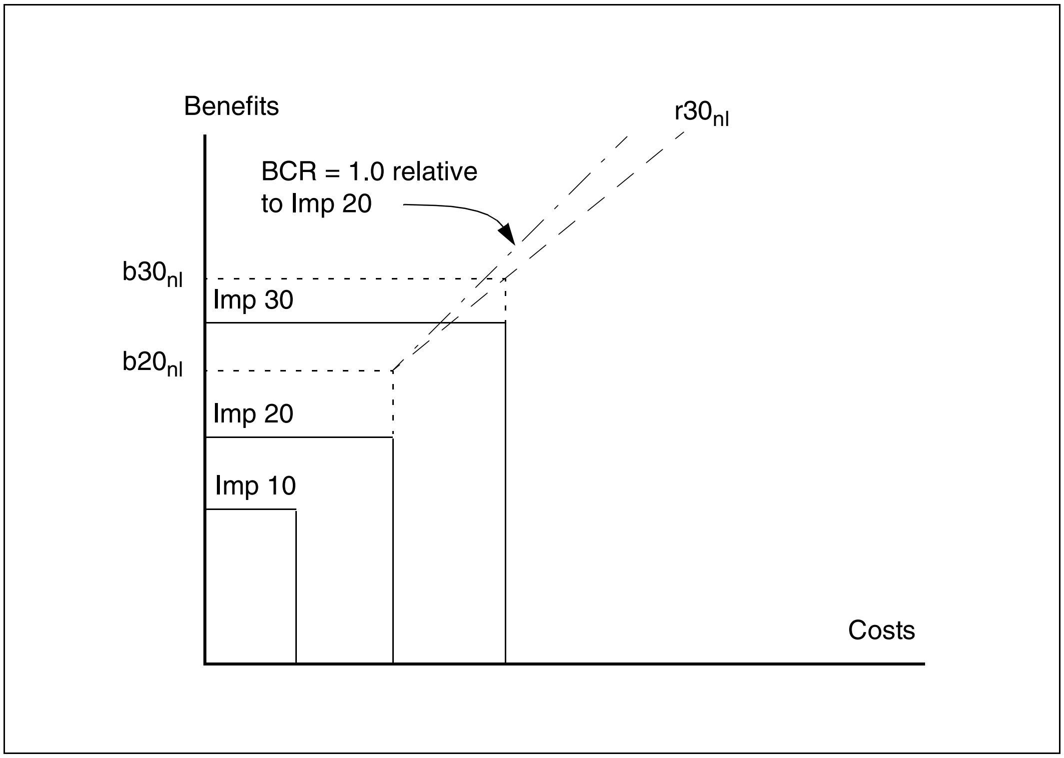

Exhibit 5-3. Rejecting a More Aggressive Improvement

5.1.2 Constrained Analysis

In a constrained run, whether the constraint is a performance goal or a funding limit, it is possible that not all sections warranting improvement will actually be improved. HERS uses benefit-cost analysis to identify the most attractive set of improvements to meet the analytical objective. If the constraint is a funding limit, the model chooses the set of improvements which will return the greatest net benefit for the capital investment. When the constraint is the attainment of a specified level of highway system performance, the model chooses the set of improvements which will meet the goal with the least expenditure of capital.

Conceptually, the method is easily visualized: calculate BCRs for all possible improvements for all sections, order them by BCR, and select them for implementation in order of economic attractiveness until the constraint/goal is reached. The process is the same for the two types of constraints: the difference is in determining that the constraint has been reached, either (a) all the funds have been expended, or (b) enough improvements have been implemented to satisfy the performance goal.

In practice, HERS uses a ‘two-listed’ approach which avoids calculating incremental BCRs for more aggressive improvements until they are actually candidates for selection. As with the minimum BCR option, HERS calculates BCRs for all candidate improvements to determine whether the section warrants improvement during the current funding period. Typically, these are calculated over a benefit-cost analysis period extending for a single funding period. Having identified the candidate improvement with the highest initial BCR, that improvement is placed on a list of improvements for potential selection.

After HERS has processed all the sections in the highway system, it has a list of potential improvements. Each list entry consists of:

- a section number,
- an improvement number,
- and the improvement’s BCR.

Only sections which warrant improvement during the current funding period are placed on the list. The improvement specified for a section is the one with the highest BCR relative to the unimproved base case.

The list of selected improvements is ordered by section number and contains the number of the improvement selected for implementation on the section. If no improvement has been selected, zero is used as the improvement number. Initially, all list entries are set to zero.

HERS begins by sorting the potential improvement list by BCR. The list is processed in order of descending BCR. The number of the improvement from the potential list is placed on the list of selected improvements. The model checks whether implementing this improvement violates the funding constraint or satisfies the performance goal. If not, it examines any more aggressive improvements which may have been identified for the section.

A more aggressive improvement might be the better choice for implementation in the current funding period if the original selection of the less aggressive improvement was due to a bias toward low-cost improvements resulting from restricting the original analysis to a single time period. (This shorter analysis period is employed in order to determine whether improving the section during this funding period is economically justified.) If this is the case, the incremental BCR obtained for the more aggressive improvement (relative to the less aggressive improvement) will be higher than the BCR obtained for the original improvement, and an immediate decision will be made to select the more aggressive improvement.[2] Accordingly, HERS calculates incremental BCRs for all more aggressive improvements using a benefit-cost analysis period which corresponds to the normal life of the base case improvement. The “most recently selected” improvement is used as the base case. If there are even more aggressive improvements, the model repeats the process using the newly selected improvement as the base case, and its ‘normal’ life as the length of the benefit-cost analysis period.

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[2] The decision as to whether or not to postpone the improvement for one period is based on the BCR of the original improvement, which is calculated over a single period. The IBCR of the more aggressive improvement is calculated over a longer time period. In this case, if any improvement is to be implemented, it is the one with the higher IBCR -- i.e., the more aggressive one. In order to guarantee this result, some special code is required when full implementation of either improvement results in exceeding a funding constraint or a benefits goal. In this situation, the more aggressive improvement is implemented on some of the mileage represented by the sample section, and no improvement is implemented on the remaining mileage; the number of miles to be improved is determined so that the specified objective is just reached.

This is illustrated in Exhibit 5-4, "Selecting Improvements in a Constrained Run." Improvement 10 was placed on the potential improvement list for the section during the initial evaluation procedure. The selection procedure uses improvement 10 as the base case when calculating incremental BCRs for the more aggressive improvements 20 and 30, and uses the normal life of improvement 10 as the length of the benefit-cost analysis period. The increases in benefits due to the longer analysis period are labeled $b20_{nl}$ and $b30_{nl}$ for improvements 20 and 30, respectively.

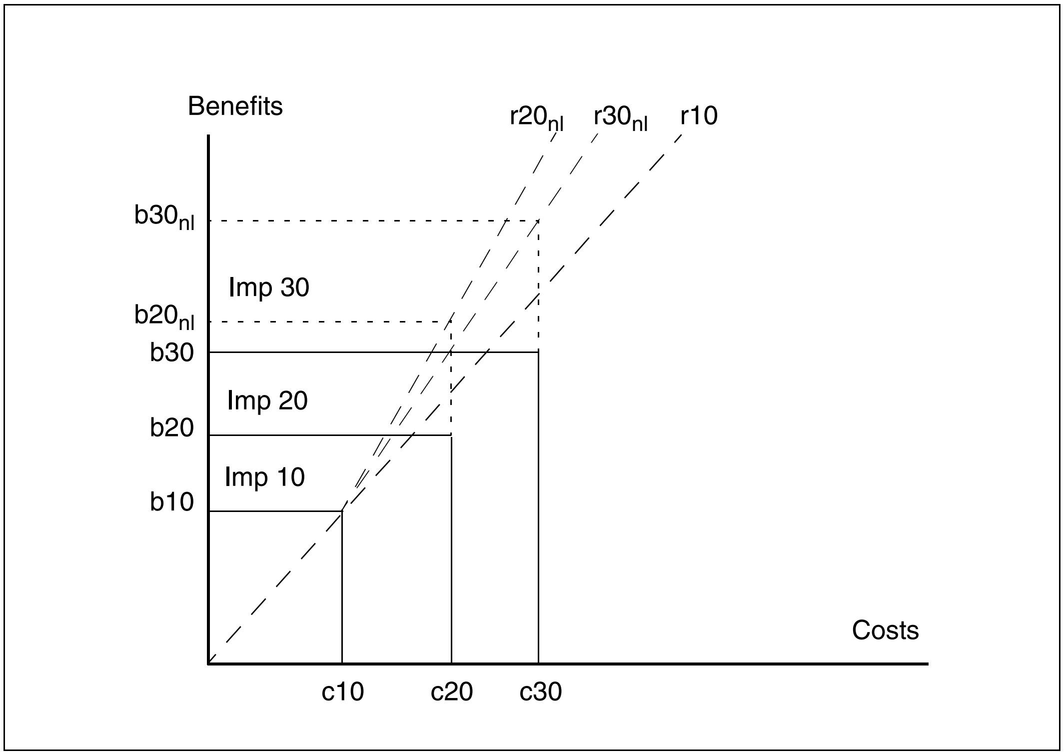

Exhibit 5-4. Selecting Improvements in a Constrained Run

The incremental BCRs for improvements 20 and 30 are greater than the BCR for improvement 10. Of the two, improvement 20 is the most attractive: its BCR, $r20_{nl}$, lies above improvement 30's $r30_{nl}$. HERS removes improvement 10 from the list of selected improvements and replaces it with improvement 20.

HERS then repeats the process, calculating the BCR of improvement 30 relative to improvement 20, and using the normal life of improvement 20 for the length of the analysis period. As shown in Exhibit 5-5, "Detecting Potential Improvements in a Constrained Run," the BCR of improvement 30 is less attractive than the BCR of improvement 20, as $r30_{nl}$ lies to the right of $r20_{nl}$. However, improvement 30 is still attractive, as its incremental BCR is greater than 1.0 relative to improvement 20.[3] It is possible that other potential improvements for other sections will be more attractive than improvement 30, so improvement 30 is placed on the list of potential improvements. The potential list is then re-ordered. Improvement 30 may yet be selected for implementation when all more attractive alternatives on other sections have been selected.

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[3] Had this been a minimum BCR run, improvement 30 would be selected for implementation at this point.

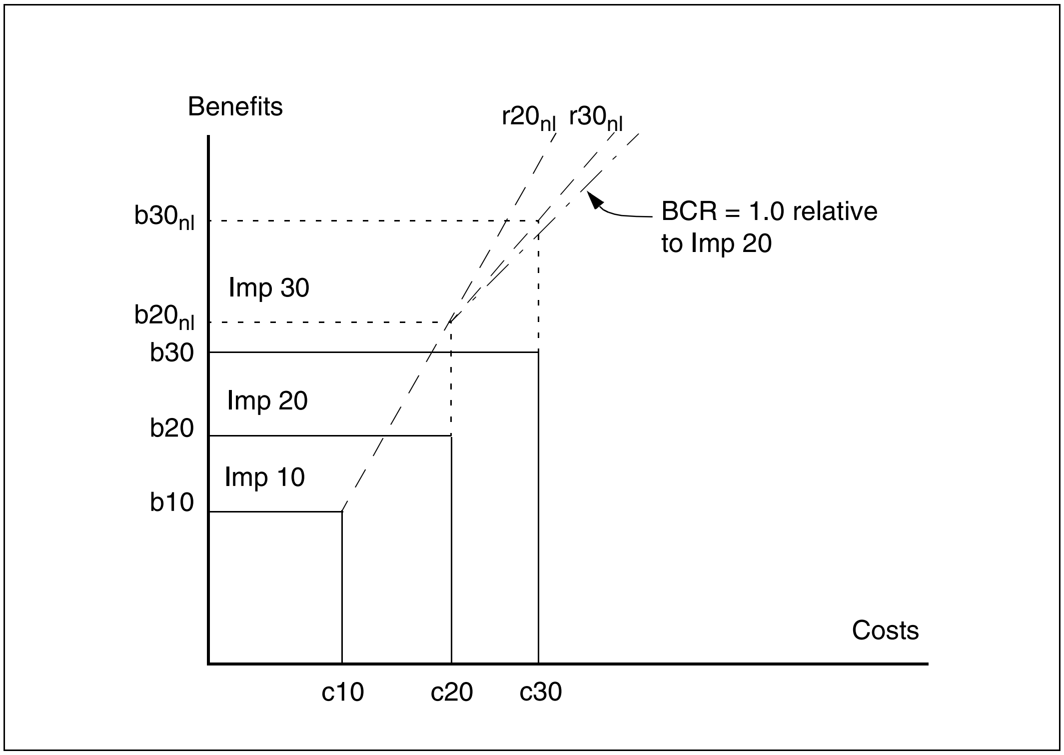

Exhibit 5-5. Detecting Potential Improvements in a Constrained Run

5.2 Selecting Mandatory Improvements

The HERS process for identifying mandatory improvements is presented in paragraph 3.3.2, ”Addressing Unacceptable Conditions: the Optional First Pass.” Normally, all mandatory improvements will be selected for implementation. The two exceptions are when there are insufficient funds to implement all mandatory improvements (this applies to fund-constrained runs only), and when a selected mandatory improvement is replaced by a more aggressive improvement.

When a mandatory improvement has been identified for a section during the first processing pass, it is subsequently identified as the base case improvement during analysis of more aggressive improvements. (When mandatory improvements are not being considered, the unimproved case is used as the base case.) This may result in the implementation of an improvement with a BCR below the usual threshold of 1.0. While this may seem anomalous in an economic model, the mandatory improvement feature is provided to allow the user to ensure that highways in unacceptably poor condition are improved regardless of whether the improvements can be justified economically.

Exhibit 5-6, “Replacement of a Mandatory Improvement,” presents an example. During the initial pass, improvement 10 was selected as a mandatory improvement for the section. As a mandatory improvement, its BCR (designated r10) does not have to meet a minimum threshold. Improvement 20 was identified during the second pass, and its incremental BCR (shown as $r20_{nl}$) was calculated using improvement 10 as the base case with the length of the analysis period set to the normal life of improvement 10.

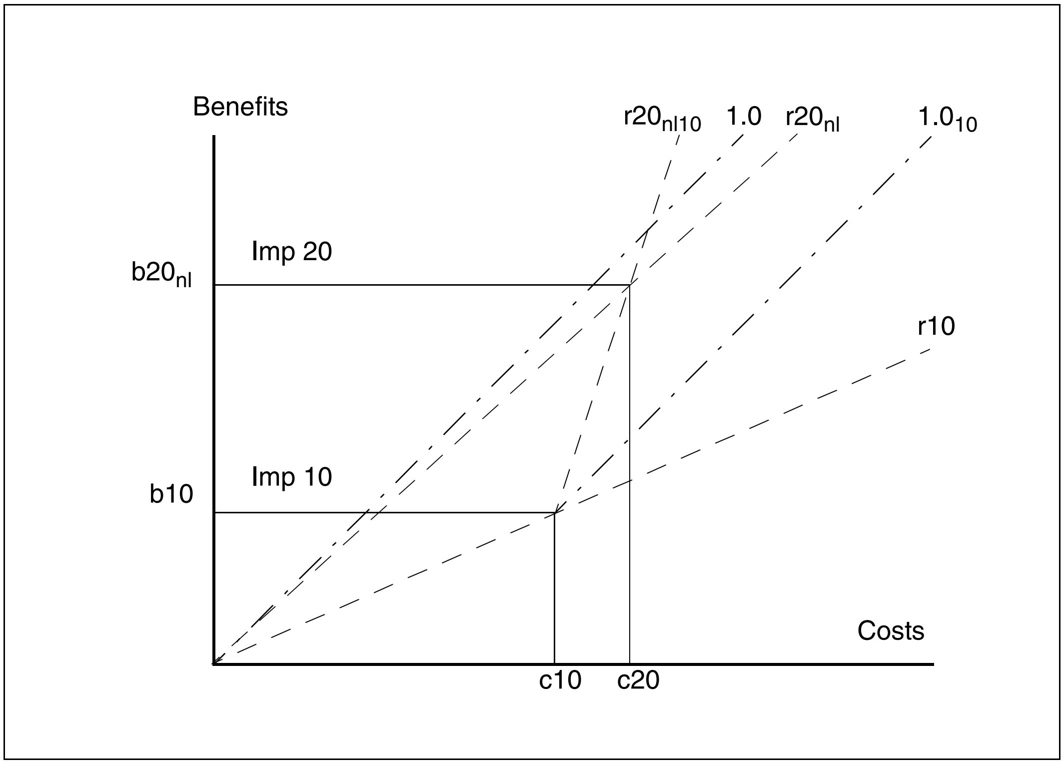

Exhibit 5-6. Replacement of a Mandatory Improvement

While improvement 20 is certainly more attractive than the mandatory improvement 10 ($r20_{nl}$ lies above r10), neither would have been selected had the user not specified the correction of unacceptable conditions, as both of their BCRs are less than 1.0 relative to an unimproved base case. (Both r10 and $r20_{nl}$ lie below the threshold designated 1.0.) However, as the mandatory improvement 10 was used as the base case, the model calculates improvement 20's BCR relative to improvement 10, shown in Exhibit 5-6 as $r20_{nl10}$. (The designation indicates that the BCR is computed over the natural life of the base case improvement, and that it is relative to improvement 10.) This BCR lies above the threshold 1.0_{10}, which is relative to improvement 10. The model therefore replaces improvement 10 with improvement 20.

The case illustrated represents a possibility which can occur in both constrained and minimum BCR runs when mandatory improvements are specified, and results from the use of the mandatory improvement as the base case. Note that the objective of the mandatory improvement of unacceptable conditions is still achieved: unacceptable conditions are corrected. And while the replacement improvement (improvement 20 in the example) is not in itself attractive, it is an economically more attractive improvement than the one it replaces.

5.2.1 Unacceptable Conditions and the Constrained Fund Run

During a constrained fund run, HERS uses benefit-cost analysis to select among potential improvements until the available funds are expended. The user electing to have unacceptable conditions identified and corrected during a constrained fund run will designate a portion of the total funds for this purpose. If the designated funds are sufficient to implement all mandatory improvements identified in the first pass, the remaining funds are available for the correction of other deficiencies during the second pass.

If the designated funds are insufficient, then benefit-cost analysis is used to select the most economically attractive of the mandatory improvements for implementation. The procedure used is the same as presented above for constrained runs (see paragraph 5.1.2), except that the universe of potential improvements consists only of the mandatory improvements identified during the first pass through the sections. Those mandatory improvements not selected at this point are placed on the list of potential improvements and will be evaluated for implementation during the second pass, competing (on the basis of their relative BCR values) with non-mandatory improvements for the non-reserved funds.

During the second pass, improvements selected as mandatory may be replaced by a more aggressive improvement on that section if it presents a more economically attractive alternative.

It is important to consider carefully the designation of funds for the correction of unacceptable conditions. Consider the case where, during the initial funding period of a run, a large number of unacceptable conditions may be identified, and funds remaining for use during the second pass may be very limited. In the case of a section with two deficiencies, including one that is unacceptable, only the unacceptable deficiency would be corrected during the initial funding period. The other deficiency would frequently be corrected with a separate improvement selected during a subsequent funding period - an inefficient means of correcting the two deficiencies. For this reason, when the option of correcting unacceptable conditions is exercised, it is desirable that at least some funds be reserved in each period for implementing more aggressive improvements. HERS allows the user to specify either (a) specific funding levels for the correction of unacceptable conditions, or (b) a maximum percentage of available funds that can be allocated for mandatory improvements for each combination of functional classes during any funding period. (See paragraph 2.5.2 for the combinations of functional classes recognized by HERS.)

5.2.2 Unacceptable Conditions and the Performance Constrained Run

During a performance constrained run, HERS uses benefit-cost analysis to select among potential improvements until designated system performance levels are met. The user may either specify explicit levels of performance or require that the program maintain the current level of system performance. If the user selects to have unacceptable conditions identified and corrected during such a run, the program executes the first loop to identify sections with unacceptable conditions and improvements for their correction. If implementing all such improvements would improve the system beyond the specified level, all the mandatory improvements are implemented, and no more aggressive improvements are identified. In this case, unlike the constrained fund run, HERS does not use benefit-cost analysis to select the smallest (and most economically attractive) set of mandatory improvements which meet the specified goal.

Should the implementation of all identified improvements not bring the system performance level to the desired goal, the second pass procedures are exercised to identify deficiencies and improvements. As in the case of the Constrained Fund run, a more aggressive improvement may be selected to replace an improvement originally selected to correct an unacceptable condition.

5.2.3 Unacceptable Conditions and the Minimum BCR Run

During a minimum BCR run, HERS evaluates potential improvements for all deficient sections and selects the most aggressive improvement with an incremental BCR above the user specified minimum. If the user opts to have unacceptable conditions identified and corrected during such a run, the program executes the first loop to identify sections with unacceptable conditions and improvements for their correction. The model then executes the second loop to identify improvements to correct “normal” deficiencies and to identify more aggressive improvements.

Each section found to be in unacceptable condition by the first processing loop will be improved, either with the improvement which corrects the unacceptable condition or by a more aggressive improvement. In this case, as with constrained runs, improvements originally selected to correct unacceptable conditions are implemented regardless of their BCR unless superseded by a more aggressive improvement. As depicted in Exhibit 5-6, the more aggressive improvement which replaces a mandatory improvement may not in itself have qualified for implementation had its incremental BCR not been calculated against the mandatory improvement.

As in a minimum BCR run in which the option to correct unacceptable conditions was not exercised, economically attractive improvements from the second processing loop will be implemented if their incremental BCRs are above the specified threshold.

6 HERS Internal Models

This section discusses the way HERS models discrete processes: speed calculation, pavement wear, traffic forecasts, capacity calculations, and user, agency, and external costs.

6.1 The HERS Speed Model

HERS uses computed vehicle speed for three purposes: calculation of travel time costs; calculation of external costs due to vehicular emissions; and calculation of vehicle operating costs[1]. Average effective speed (AES) across the section is used in the first two calculations above and for most of the operating cost calculations. To calculate excess operating costs due to speed change cycles induced by traffic signals and / or stop signs, HERS uses distance travelled between traffic control devices and the average travel speed over the portions of the section which contain signals and stop signs.

The HERS speed model has been changed from the method previously employed in HERS. The earlier HERS version was based on the Texas Research and Development Foundation (TRDF) adaptation[2] of the "Aggregate Probabilistic Limiting Velocity Model" (APLVM), one of four related procedures originally developed by the World Bank.[3] HERS 3.26 uses a simplified version of the APLVM procedures to calculate "free-flow" speed (FFS). It then applies algorithms developed by Science Applications International Corporation[4] (SAIC) and Cambridge Systematics, Inc.[5] (CSI) for use in the HPMS Analytical Process to incorporate the effects of grades (free-flow speed uphill, or FFSUP), traffic-control devices, and congestion on vehicle speed.

For each section, HERS models speed for each of the seven vehicle types (except for autos and pickup trucks) in each direction of travel. Overall average speed per section is aggregated from the speeds of the individual vehicle types. HERS uses vehicle speed data in calculating operating costs and travel time costs.

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[1] See Exhibit 2-5, "Prediction and Calculation Model Linkages.".

[2] G.C. Elkins, *et al.*, *Estimating Vehicle Performance Measures*, Texas Research and Development Foundation, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., July 1987, pp. 128-177.

[3] Thawat Watanatada, Ashok M. Dhareshwar and Paulo Roberto S. Rezende Lima, *Vehicle Speeds and Operating Costs*, The World Bank, Johns Hopkins University Press, Baltimore, 1987.

[4] Science Applications International Corporation and Cambridge Systematics, Inc., *Roadway Usage Patterns: Urban Case Studies*, prepared for Volpe National Transportations Systems Center and the Federal Highway Administration, June 1994, Appendix A; Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, October 31, 1993.

[5] Cambridge Systematics, Inc., *Revisions to the HERS Speed and Operating-Cost Procedures*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, January 25, 1996, Section 2.

6.1.1 Free-Flow Speed and the APLVM

The HERS version of APLVM involves a four-step procedure; the first three of which involve the computation of three "limiting velocities." These limiting velocities represent the approximate speeds that would be obtained should a single factor (e.g., pavement condition) limit speed to a value much lower than would otherwise be the case. The three limiting velocities[6] are:

VCURVE = maximum allowable speed on a curve;
VROUGH = maximum allowable ride-severity speed; and
VSPLIM = maximum speed resulting from speed limits.

The fourth step is to combine the three limiting velocities, using the APLVM, to determine the free-flow speed.

In APLVM, the dominant role in the determination of free-flow speed[7] is played by the smallest of the limiting velocities.[8] Each of the other limiting velocities are assumed to play some probabilistic role in influencing the speed of some drivers, but, except when they have values close to that of the lowest velocity, their influence on average free-flow speed tends to be negligible.

The following subsections describe the four steps of the HERS version of APLVM.

6.1.1.1 Calculating the Effect of Curves

In the World Bank procedure, the effect on speed attributed to the presence of curves is represented by *VCURVE.* The World Bank estimates *VCURVE,* in meters per second:

$$VCURVE = \sqrt{(FRATIO + SP) \times g \times RC} \qquad \textit{Eq. 6.1}$$

where:

RC = radius of curvature (meters);
SP = superelevation; and
g = the force of gravity = 9.81 m/sec^2.

The remaining variable in Equation 6.1, *FRATIO*, known as the maximum perceived friction ratio, is the ratio of the lateral force on a horizontal curve to the normal force. TRDF derived values for *FRATIO* of 0.103 for combination trucks and 0.155 for automobiles; and they suggest the use of the 0.155 figure for single-unit trucks as well. HERS uses these values.

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[6] HERS 2.0 used four limiting velocities: VCURVE, VROUGH, VDRIVE, and VMISC. VDRIVE was a function of vehicle characteristics and average grade, which are handled in HERS 3.26 through calculation of uphill free-flow speed. The fourth limiting velocity, VMISC, was a replacement for a factor called "desired speed" (VDESIR) by the World Bank and TRDF, and reflected the effects of speed limits, safety concerns, and congestion. In HERS 3.26, these factors are represented by VSPLIM and the congestion delay algorithms applied to free-flow speed.

[7] The World Bank and TRDF use the term "steady-state speed," or Vss, to refer to free-flow speed.

[8] The original version of APLVM also uses a fifth limiting velocity, maximum allowable braking speed on downhill sections (VBRAKE). This limitation affects only heavy trucks and only on long, steep downhill sections (e.g., a five percent grade more than 10.5 miles long, or an eight percent grade more than three miles long). Since most HPMS sections are less than five miles long, there are likely to be only a handful of sections for which one would find braking speed to be a limiting factor (though, undoubtedly, some additional HPMS sections are part of longer descents for which braking speed is indeed a factor). Accordingly, TRDF's recommendation to exclude VBRAKE from the procedure has been adopted.

Replacing radius of curvature in Equation 6.1 by degrees of curvature (DC) and converting the equation to estimate *VCURVE* in miles per hour produces:

$$VCURVE = 292.5 \times \sqrt{(FRATIO + SP)/(DC)} \qquad \textit{Eq. 6.2}$$

For all arterial sections except urban minor arterials, a weighted average value of degrees of curvature can be obtained from detailed data on curves by class contained in the HPMS database. For all collectors and for urban minor arterials, typical values of degrees of curvature are produced by existing HPMS software from horizontal alignment adequacy and type of terrain. (The HPMS submittal software is used in preparation of the HPMS database prior to HERS' processing the data.)

Although data on superelevation are not contained in the HPMS database, typical superelevation can be estimated from degrees of curvature using the equation:

$$SP = \begin{cases} 0.0 & \text{for} DC \le 1 \\ 0.1 & \text{for} DC \ge 10\text{, otherwise:} \\ 0.0318 + 0.0972 \times \ln(DC) - 0.0317 \times DC + 0.007 \times DC \times \ln(DC) \end{cases} \qquad \textit{Eq. 6.3}$$

This equation was derived by regression from a table presented by Zaniewski[9], but fits so well ($R^2 = 0.9999$) as to suggest that it may be the equation that was used to generate the values in the table.

6.1.1.2 Estimating Velocity Limited by Pavement Roughness

The effect of pavement roughness on speed is represented by *VROUGH*. HERS uses PSR to measure pavement roughness. Descriptions of pavement characteristics corresponding to the various PSRs are presented in Exhibit 6-1, "Pavement Condition Ratings."

A review of these descriptions indicates that pavement condition begins to become a limiting factor on high speed roads at approximately the boundary between the Good (3.0 to 4.0) and Fair (2.0 to 3.0) ratings, suggesting that *VROUGH* should play a minimal role in limiting speed when PSR greater than or equal to 3.0. Similarly, the descriptions suggest 52.5 mph as an appropriate value for *VROUGH* when PSR equals 2.0.

In order to avoid a speed of zero when PSR drops to zero (which can occur in HERS when funds are short), and to allow additional user control over the function used for *VROUGH*, HERS allows the user to specify *VROUGH* as a pair of line segments with different slopes meeting at a user-specified breakpoint, *PSRB*. These parameters are specified in the parameter file PARAMS.DAT.

Specifically, HERS uses the function:

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[9] J.P. Zaniewski, *et al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Washington, D.C., March 1982, p. E-7.

PSR and Verbal Rating	Description
5.0	
Very Good	Only new (or nearly new) pavements are likely to be smooth enough and sufficiently free of cracks and patches to qualify for this category. All pavements constructed or resurfaced during the data year would normally be rated very good.
4.0	--
Good	Pavements in this category; although not quite as smooth as those described above, give a first class ride and exhibit few, if any visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.
3.0	--
Fair	The riding qualities of pavements in this category are noticeably inferior to those of new pavements and may be barely tolerable for high speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and cracking, and some pumping.
2.0	--
Poor	Pavements that have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes ravelling, cracking, rutting, and occurs over 50 percent or more of the surface. Rigid pavement distress includes joint spalling, faulting, patching, cracking, scaling, and may include pumping and faulting.
1.0	--
Very Poor	Pavements that are in an extremely deteriorated condition. The facility is passable only at reduced speeds and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.
0.0	

Exhibit 6-1. Pavement Condition Ratings[a]

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[a] Source: U.S. Department of Transportation, Federal Highway Administration, *Highway Performance Monitoring System Field Manual*, Washington, D.C., December 1987, p.IV-28. The version in the April 1994 edition excludes the verbal ratings.

$$VROUGH = \begin{cases} VR1 + (VR2 - VR1) \times \dfrac{PSR}{PSRB} & \text{if } PSR \le PSRB \\ VR2 + VRSLOP \times (PSR - PSRB) & \text{if } PSR > PSRB \end{cases} \qquad \text{Eq. 6.4}$$

where:

*VR*1 = value of *VROUGH* when *PSR* is zero;
*VR*2 = value of *VROUGH* when *PSR* = *PSRB* (the breakpoint); and
VRSLOP = slope of the function when *PSR* > *PSRB*

The default values of the above parameters are:

$PSRB$ = 1.0
$VR1$ = 5 mph
$VR2$ = 20 mph
$VRSLOP$ = 32.5[10]

For PSR below 2.5, the default values produce intentionally lower estimates of speed than either the current AP procedure or that proposed by TRDF. For PSR = 1.5, they produce *VROUGH* = 36 mph, while TRDF's formula would produce values of 48 mph for automobiles and 44 mph for large trucks,[11] and the AP procedure would permit speeds of 49 mph. On the basis of the preceding discussion, 36 mph appears to be a more appropriate speed; however, users can choose different values for the four parameters if higher values of *VROUGH* are desired.

For purposes of deriving *VROUGH* for unpaved sections, HERS treats these sections as having a PSR of 1.0 (i.e., when *VR1*, *VR2* and *VRSLO*P are set to their default values, *VROUGH* for unpaved sections is 20 mph); the user may change this PSR value if desired.

For HERS, the same formula for *VROUGH* is used for all vehicle classes. Using Brazilian data, the World Bank study[12] obtained results that imply a very significant difference (about 30 mph) between the effects of roughness on automobiles and on combination trucks; and TRDF has proposed formulas that produce a much more modest difference (two to four mph). However, TRDF did not provide any recommended formulas for use with single-unit trucks.

6.1.1.3 Estimating Velocity Limited by Speed Limits

HERS represents the effect of speed limits on speed with *VSPLIM*. *VSPLIM* is assumed to be 10 or 15 kilometers per hour greater than the speed limit. Fifteen kmph is used for urban freeways by design and rural multilane roads with partial or full access control and a median which is either a positive barrier or has a width of at least 4 feet. Ten kmph is used for all other sections. These values correspond to 6.215 and 9.323 mph.

6.1.1.4 Determining Free-Flow Speed

The general formula for estimating free-flow speed, *FFS*, is:

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[10] This represents a change from HERS v2, where the default value for VRSLOP was set at 20. The previous value produced a limiting velocity of 60 mph for a pavement of PSR 3.0 -- This change produces a limiting velocity of 85 mph when PSR is 3.0.

[11] The TRDF formulas are:

$$VROUGH = \frac{1}{0.025 - 0.00275PSR} \qquad \text{for automobiles}$$

$$VROUGH = \frac{0.9}{0.0255 - 0.00333PSR} \qquad \text{for large trucks}$$

[12] Elkins, *et al.*, *op. cit.*, pp. 144-149.

$$FFS = \frac{\exp(\sigma^2/2)}{\left((1/VCURVE)^{\frac{1}{\beta}} + (1/VROUGH)^{\frac{1}{\beta}} + (1/VSPLIM)^{\frac{1}{\beta}}\right)^{\beta}} \qquad \text{Eq. 6.5}$$

where σ^2 and β are parameters discussed below.

In the above equation, β is a parameter that may vary with vehicle class and reflects the standard deviation of the sensitivity of drivers of vehicles in that class to the different conditions reflected in the equation. For the moment, ignore the effect of σ^2 (i.e., assume $\sigma^2 = 0$). In this case, when two factors produce very similar limiting velocities, the variation in sensitivities results in some vehicles being limited more by one factor while some vehicles are limited more by the other, with an overall average speed somewhat lower than either of the limiting velocities. The smaller the value chosen for β, the more this average speed approaches the lower of the two limiting velocities.

The World Bank[13] used Brazilian data to estimate β for six vehicle classes, deriving values of 0.24 to 0.31. After comparing the effects of values of 0.01, 0.1 and 0.3 on the behavior of the FFS equation, TRDF recommended a value of 0.1 for all vehicle classes.[14]

In Equation 6.5, σ^2 is described by the World Bank as the variance of the logarithm of section-specific errors of observed speed. The World Bank's estimates[15] for σ^2 are between 0.007 and 0.036; and TRDF[16] suggests using 0.01. The effect of these values for σ^2 is a small upward adjustment in FFS (of about 0.5 percent using $\sigma^2 = 0.01$, and about 1.8 percent using $\sigma^2 = 0.036$). For simplicity, the effect of σ^2 has been omitted from the HERS equation.

Setting $\beta = 0.1$ and $\sigma^2 = 0$, Equation 6.5 becomes:

$$FFS = ((1/\mathrm{VCURVE})^{10} + (1/\mathrm{VROUGH})^{10} + (1/\mathrm{VSPLIM})^{10})^{-0.1} \qquad \text{Eq. 6.6}$$

where VCURVE is given by Equation 6.2, VROUGH by Equation 6.4, and VSPLIM is derived from the section's speed limit as described above.

Equation 6.6 produces estimates of free-flow speed that are always below the lowest of the limiting velocities in the equation, but are exceedingly close to that velocity whenever that velocity is appreciably smaller than the other limiting velocities.

6.1.2 The Effects of Grades on Free-Flow Speed

Using an SAIC algorithm[17], HERS next calculates free-flow speed in the uphill direction (FFSUP) for trucks[18]. (For "personal vehicles" - automobiles and pickup trucks - HERS assumes that

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[13] Watanatada *et al., op. cit.*, Table 4.3(a), p. 85.

[14] Elkins, *et al., op. cit.*, p. 156.

[15] Watanatada *et al.*, Table 4.3(c), p. 86. The reference uses σ_e^2 to represent our σ^2.

[16] Elkins, *et al., op. cit.*, p. 156.

[17] Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, pp 78-79.

[18] Since the HPMS database does not contain any information on the direction of grades, one-way facilities are treated in the same way as two-way facilities; i.e., as if traffic may be moving either uphill or downhill.

grades have no effect on free-flow speed.) First, crawl speed for the section is estimated as follows:

$$CRAWLS = 1/(j + k \times GRADE) \qquad \text{Eq. 6.7}$$

where:

CRAWLS = Crawl speed in miles per hour;
j, k = constants which depend upon vehicle characteristics; and
GRADE = the average grade of the section (expressed as a fraction).

The values used for constants *j* and *k* are shown in Table 6-1[19].

Table 6-1. Values of Crawl Speed Constants by Truck Type

Vehicle Type	*j*	*k*
6-Tire Truck	0.0090	0.0815
3-4 Axle Truck	0.0090	0.2755
4-Axle Combination	0.0090	0.2755
5-Axle Combination	0.0090	0.2755

HERS then calculates the delay due to grades:

$$DGRADE = \begin{cases} a(1 - \exp(b/a)) + b & \text{if } CRAWLS < FFS \\ 0 & \text{otherwise} \end{cases} \qquad \text{Eq. 6.8}$$

where:

$$b = SLEN(1/CRAWLS - 1/FFS) \qquad \text{Eq. 6.9}$$

$$a = -0.05(1/CRAWLS - 1/FFS)^{0.6} \qquad \text{Eq. 6.10}$$

DGRADE = delay in hours; and
SLEN = length of the section

The delay due to grades is then combined with free-flow speed to yield free-flow speed uphill, FFSUP:

$$FFSUP = 1/(1/FFS + DGRADE/(SLEN)) \qquad \text{Eq. 6.11}$$

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[19] Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, Table 3-3, and Herbert Weinblatt, "The Effects of Grades on Truck Speed," memorandum, Cambridge Systematics, Inc., Feb. 25, 1998.

6.1.3 Delay Due to Congestion and Traffic Control Devices

The SAIC algorithms address four types of highway conditions based upon number of lanes and the presence of traffic control devices. HERS identifies two additional conditions, defining a total of six highway classifications for use within the speed model. Table 6-2 lists the salient characteristics of each of the six classifications, and indicates which of the SAIC equations are used for each classification. Note that the number of lanes is not a factor when either signals or stop signs are present on the section.

Table 6-2. HERS Highway Classifications and the SAIC Algorithms

Total Lanes in Both Directions	Stop Signs	Traffic Signals	HERS Classification	SAIC Algorithms Used
N/A	Yes	No	Sections with Stop Signs	Urban Arterials with Unsignalized Intersections
N/A	No	Yes	Sections with Traffic Signals	Urban Arterials with Signalized Intersections
N/A	Yes	Yes	Sections with Stop Signs and Traffic Signals	Both: Urban Arterials with Unsignalized Intersections and Urban Arterials with Signalized Intersections
2	No	No	Free-Flow Sections, One Lane per Direction	Two-Lane Rural Sections
3	No	No	Free-Flow Sections, Three-Lane Two-way	Two-lane Rural Sections and modified Freeways and Multilane Rural Highways
4 or more	No	No	Free-Flow Sections, Two or More Lanes per Direction	Freeways and Multilane Rural Highways

Each of the implemented algorithms consists of two or more equations. Selection of the appropriate equation hinges upon the ratio of the section's Average Annual Daily Traffic (AADT) to the section's two-way peak hour capacity[20]. This AADT/Capacity ratio is referred to as the *ACR*. Each of the routines below yields delay in hours per 1000 vehicle miles. HERS converts this to average effective speed using the equation:

$$AES = 1/(1/FFS + D/1000) \qquad \text{Eq. 6.12}$$

where:

AES = Average Effective Speed;

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[20] Other than in the calculation of the AADT/Capacity ratio (used in the speed calculations and the elasticity calculations), capacity generally means one-way capacity (except for two-lane rural roads) as reported in the HPMS data records.

FFS = Free Flow Speed (or FFS Uphill), as calculated above; and
D = average delay in hours per 1000 vehicle miles, with delay due to congestion and/or traffic control devices.

6.1.3.1 Sections with Stop Signs

For roads with stop signs, HERS selects an equation based upon both the AADT/Capacity ratio and the number of stop signs per mile. The equations are presented in Table 6-3.

Table 6-3. Delay Equations for Sections with Stop Signs

AADT/C Range	**Stop Signs/ mile**	
<6		$D_{ss} = N_{sspm} \times (1.9 + 0.067 \times FFS + 0.103 \times ACR + 0.0145 \times ACR^2)$
>6 and <15	<10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS - 0.029 \times (ACR - 6)^2)$ $+ 0.354 \times (ACR - 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.064 \times (ACR - 6)^2$
>15	<10	$D_{ss} = N_{sspm} \times (0.691 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2$
	>10	$D_{ss} = N_{sspm} \times (3.04 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2 - 23.49$

where:

D_{ss} = Delay due to congestion and stop signs in hours per 1000 vehicle miles;
N_{sspm} = Number of stop signs per mile (average);
FFS = Free flow speed (or free flow speed uphill); and
ACR = the AADT/Capacity ratio for the section.

6.1.3.2 Sections with Traffic Signals

HERS uses modified versions of the SAIC equations to calculate delay on sections with traffic signals. As presented in Table 6-4, the equation selected is dependent upon the AADT/Capacity ratio.

where:

D_{ts} = average delay due to congestion and traffic signals in hours per 1000 vehicle miles;
ACR = the AADT/Capacity ratio for the section; and
N = the number of traffic signals per mile.

Table 6-4. Delay Equations for Sections with Traffic Signals

AADT/C Range	
<7	$D_{ts} = (1 - \exp(-N/24.4))(68.7 + 17.7 \times ACR)$
>7 and <13.2	$D_{ts} = (1 - \exp(-N/24.4)) \times (192.6 + 14.4 \times (ACR - 7) - 1.16 \times (ACR - 7)^2) + 0.16 \times (ACR - 7)^2$
>13.2	$D_{ts} = 237.3 \times (1 - \exp(-N/24.4)) + 0.16 \times (ACR - 7)^2$

6.1.3.3 Sections With Stop Signs and Traffic Signals.

To calculate the average effective speed for section with both types of traffic control devices, HERS calculates two speeds over the section: one, as if all the devices were stop signs, and two, as if all the devices were signals. HERS then averages these speeds together, weighted by the ratio of traffic signals to stop signs.

6.1.3.4 Free-Flow Sections, One Lane per Direction

The equation selection for two-lane roads depends only upon AADT/Capacity ratio. The equations are presented in Table 6-5.

Table 6-5. Delay Equations for 2-lane, 2-way Roads

AADT/C Range	
< 10	$D_{cong1} = 0.432 \times ACR$
> 10	$D_{cong1} = 9.953 - 1.66 \times ACR + 0.109 \times ACR^2$

where:

D_{cong1} = average congestion delay in hours per 1000 vehicle miles; and
ACR = the AADT/Capacity ratio for the section.

6.1.3.5 Free-Flow Sections, Three-Lane Two-Way

For three-lane, two-way roads without traffic control devices, HERS assumes that the volume is split evenly between the two directions, and that capacity is split 7:5 in favor of the two-lane direction. This is implemented by multiplying the section's AADT/Capacity ratio by 0.857 to derive the AADT/Capacity ratio in the two-lane direction, and 1.2 to derive the AADT/Capacity ratio in the one-lane direction. These modified AADT/Capacity ratios are then used in the respective delay calculations. HERS calculates the delay in the single-lane direction using the equations for two-lane rural roads, and in the two-lane direction using the multilane equations. HERS then figures total delay as the average of the two.

6.1.3.6 Free-Flow Sections, Two or More Lanes per Direction

Following the SAIC equations presented in Table 6-6, HERS calculates delay due to congestion for sections with at least two lanes in each direction and no traffic signals or stop signs. The equation employed depends upon the section's AADT/Capacity ratio.

Table 6-6. Delay Equations for Freeways and Multilane Rural Highways

AADT/C Range	
<8	$D_{cong} = 0.0797 \times ACR + 0.00385 \times ACR^2$
>8 and <12	$D_{cong} = 12.1 - 2.95 \times ACR + 0.193 \times ACR^2$
>12	$D_{cong} = 19.6 - 5.36 \times ACR + 0.342 \times ACR^2$

where:

D_{cong} = average congestion delay in hours per 1000 vehicle miles;
ACR = the AADT/Capacity ratio for the section.

6.1.4 Distance Traveled Between Traffic Control Devices

HERS uses the distance travelled between stops when traversing a section as an input to the operating cost model. HERS assumes that drivers stop at all stop signs, and at traffic signals when they are red. For sections with stop signs, this distance is simply the length of the section divided by the number of traffic control devices. For sections with traffic signals, HERS allows for signals which might be green and not require a stop.

6.2 The Pavement Deterioration Model

HERS models pavement wear as a function of traffic and environment. First, HERS calculates the effects of vehicular traffic on a section's PSR. Then, HERS figures both a minimum and a maximum rate of deterioration. The minimum rate is designed to reflect the effects of weather. The maximum rate of deterioration is designed to limit deterioration on sections with low structural numbers[21]. HERS applies these limits to the PSR value (which reflects pavement wear due to traffic) to arrive at a forecast pavement condition. HERS does not deteriorate unpaved sections, and roads without reported truck traffic are deteriorated at the minimum rate.

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[21] Structural numbers (SN), which range from 1.0 to 6.0, indicate the strength of pavement. Sections whose SN is in the range from 1.0 through 3.0 are considered “light”.

6.2.1 Equivalent Single-Axle Loads

Except for roads with relatively light traffic volumes, the rate of pavement deterioration is dependent primarily on the number of 18,000 pound (18 kip) equivalent single-axle loads (ESALs). For any time period, ESALs on the most heavily traveled lane of each sample section are estimated using

- total traffic for the time period;
- percentages of single unit trucks and combination trucks on the sample section;
- an 18-kip equivalent load factor; and
- a lane-load adjustment factor.

The 18-kip equivalent load factor is a function of pavement type, functional class, and truck type; values for this factor are given in Table 6-7, "Equivalent 18-KIP Load Applications per Truck." The lane load adjustment factor provides an estimate of the percentage of trucks that travel in the lane most heavily used by trucks as a function of the number of lanes in one direction; these values follow the AASHTO Pavement Design Guide[22] and are given in Table 6-8, "Lane Load Distribution Factors."

Table 6-7. Equivalent 18-KIP Load Applications per Truck

	Single Unit Trucks		Combination Trucks	
	Flexible Pavement	Rigid Pavement	Flexible Pavement	Rigid Pavement
Rural:				
Interstate	0.2898	0.4056	1.0504	1.6278
Other Principal Arterials	0.3141	0.4230	1.1034	1.7651
Minor Arterials	0.2291	0.3139	1.0205	1.0819
Collectors	0.2535	0.3485	0.7922	1.3265
Urban:				
Interstate and Other Freeways and Expressways	0.6047	0.8543	2.3517	3.7146
Other Principal Arterials	0.5726	0.8123	0.8584	1.3047
Minor Arterials	0.3344	0.4109	1.0433	1.5276
Collectors	0.8126	1.1595	0.6417	0.9968

HERS estimates pavement deterioration using Percent Average Daily Single Unit Commercial Vehicles and Percent Average Daily Combination Commercial Vehicles. HERS allows the user

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[22] American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, Washington, D.C., 1986.

Table 6-8. Lane Load Distribution Factors

Number of Lanes (One Direction)	Lane Factor
1	1.0
2	0.9
3	0.7
4 or more	0.6

to specify a set of annual growth factors to be applied to each section's percent truck values. (See 6.4, "The Fleet Composition Model.")

For any time period beginning at t_0 and ending at t_f, HERS first calculates the total traffic:

$$TOTRAF = \frac{(AADT_{t_0} + AADT_{t_f})}{2} \times 365 \times (t_f - t_0) \qquad \text{Eq. 6.13}$$

where $(t_f - t_0)$ represents the length of the period in years.

HERS then calculates ESALs for the time period:

$$\begin{aligned} ESALS = {} & (TOTRAF \times PCAVSU \times ELF_{SU} \times LF) \\ & + (TOTRAF \times PCAVCM \times ELF_{CM} \times LF) \end{aligned} \qquad \text{Eq. 6.14}$$

where:

$ESALS$ = ESALs accumulated during the time period;
$PCAVSU$ = average percentage of single-unit trucks during the time period;
ELF_{SU} = equivalent load factor for single unit trucks for this pavement type and functional class (from Table 6-7);
$PCAVCM$ = average percentage of combination trucks during the time period;
ELF_{CM} = equivalent load factor for combination trucks for this pavement type and functional class (from Table 6-7); and
LF = lane load distribution factor (from Table 6-8).

HERS uses one-half the length of a funding period as the time period for calculating total traffic and incremental ESALs in order to capture changes in both AADT and average percentages of trucks. Therefore, when estimating the number of ESALs which will accumulate during a funding period, it utilizes Equations 6.13 through Equations 6.13 and 6.14 twice, once for the first half and once for the second half of the funding period.

6.2.2 Pavement Condition

HERS determines present and future pavement condition using AASHTO Road Test equations that have been modified to accommodate PSR values from 0.1 to 5.0. The first step is to obtain the number of ESALs that would have resulted in causing PSR to decline from 5.0 to its base-year value. The number of ESALs applied during any subsequent period is then estimated and added to the previous ESAL value. This result is then used to estimate PSR at the end of this period.

For flexible pavement, the HPMS database contains either the structural number (SN) or pavement weight (light, medium or heavy); for rigid pavement it contains either thickness (D) or pavement weight. If any of the optional information is not provided for a section, HERS uses the default values shown in Table 6-9, “Pavement Section Default Values,” to obtain values describing the initial pavement. When the pavement is improved, procedures described in Chapter 8, ”Effects of HERS Improvements,” are used to obtain the thickness of the overlays or of the new pavement and, for flexible pavements, a new value of SN.

Table 6-9. Pavement Section Default Values

	Pavement Section		
	Heavy	Medium	Light
SN (Flexible Pavement)	5.3	3.8	2.3
D (Rigid Pavement)	10.0	8.0	6.5

6.2.2.1 Flexible Pavement

For flexible pavements, the number of ESALs that would cause PSR to decline from 5.0 to its base-year value is obtained using the equation:

$$ESAL = 10^{LOGELA} \qquad \textit{Eq. 6.15}$$

where:

$$LOGELA = XA + XG/XB \qquad \textit{Eq. 6.16}$$

$$XA = 9.36 \times \log(SNA) - 0.2 \qquad \textit{Eq. 6.17}$$

$$XB = 0.4 + 1094/SNA^{5.19} \qquad \textit{Eq. 6.18}$$

$$XG = \log((5 - PSRI)/3.5) \qquad \textit{Eq. 6.19}$$

$$SNA = SN + \sqrt{(6/SN)} \qquad \textit{Eq. 6.20}$$

and

PSRI = PSR at the beginning of the base year;

and all logarithms are taken to the base ten.

The PSR at the end of any subsequent time period, *PSRF*, is then obtained by adding the number of ESALs incurred during that time period to the initial value of ESALs, substituting *PSRF* for *PSRI* in Equation 6.19, solving the above system of equations for *PSRF*, and performing the indicated computations. Solving Equation 6.19 for *PSRF* produces:

$$PSRF = 5 - 3.5 \times PDRAF_{pt} \times 10^{XG} \qquad \textit{Eq. 6.21}$$

where:

$PDRAF_{pt}$ = A user-specified pavement deterioration rate adjustment factor for pavement type *pt*, normally set to one[23];

and solving Equations 6.15 and 6.16 for XG produces:

$$XG = XB \times (\log(ESAL) - XA) \qquad \textit{Eq. 6.22}$$

6.2.2.2 Rigid Pavement

The procedure for obtaining the pavement condition of rigid pavements differs from that used for flexible pavements only in the equations used for XA and XB. For rigid pavements, these equations are:

$$XA = 7.35 \times \log(D + 1) - 0.06 \qquad \textit{Eq. 6.23}$$

$$XB = 1 + 16.24 \times 10^{6} / (D + 1)^{8.46} \qquad \textit{Eq. 6.24}$$

where *D* is pavement thickness.

6.2.2.3 Minimum Deterioration Rate

For both flexible and rigid pavements, minimum deterioration rates are used to reflect pavement deterioration due to environmental conditions. HERS uses the following equation to calculate an appropriate minimum deterioration rate:

$$PSRMAX_t = PSR_{t_0} \times 0.3^{((t - t_0)/ML)} \qquad \textit{Eq. 6.25}$$

where:

t = any time of interest;
$PSRMAX_t$ = upper limit on the PSR of a given section at time *t*;
t_0 = time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
ML = maximum life of the section in years.

The use of Equation 6.25 requires knowing the time that each section was last improved (t_0) and the PSR immediately after the improvement (PSR_{t0}). For all improvements analyzed or selected by HERS, this information is readily available. For improvements that occurred prior to the start of a HERS run, the preprocessor uses the time of last improvement specified in the HPMS dataset, if available, or the middle of the year preceding the start of the HERS run. In the former case, the preprocessor assumes that the PSR immediately following the improvement (PSR_{t0}) is the maximum possible for the improvement. In the latter case, the PSR immediately following

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[23] If HERS is being used to analyze data for a single state, PDRAF$_{pt}$ can be used to reflect the effects of the state's environment and materials used in that state. Separate values of PDRAF$_{pt}$ can be specified for flexible and rigid pavement types.

the last improvement is estimated from the PSR at the start of the run and the traffic data for the six-month period between the assumed time of the last improvement and the start of the run.

The maximum pavement life values for rigid and flexible pavements for three types of pavement section (light, medium and heavy) are shown in Table 6-10, “Maximum Pavement Life Values (Years).”

Table 6-10. Maximum Pavement Life Values (Years)

Surface Type	**Pavement Section**		
	Heavy	Medium	Light
Flexible	35	30	25
Rigid	40	35	30

The HERS model then enforces the minimum deterioration rate:

$$PSRMX_t = \text{the lesser of } \begin{cases} PSRMAX_t \\ PSR_{t_{ESALS}} \end{cases} \qquad \textit{Eq. 6.26}$$

where:

$PSRMAX_t$ = upper limit on PSR at time t from Equation 6.25;
PSR_{tESALS} = PSR at time t as a function of ESALs (PSRF from Equation 6.21); and
$PSRMX_t$ = PSR at time t after enforcement of the minimum deterioration rate.

6.2.2.4 Maximum Deterioration Rate

A user-specified maximum PSR deterioration rate is used to limit pavement deterioration on sections with low values of SN. The default value for this maximum rate of deterioration is 0.3 per year. This maximum rate is applied after the enforcement of the minimum deterioration rate:

$$PSR_t = \text{the larger of } \begin{cases} PSR_{t_0} - MAXPDR \times (t - t_0) \\ PSRMX_t \end{cases} \qquad \textit{Eq. 6.27}$$

where:

t = any time of interest;
PSR_t = PSR at the time t after enforcement of both the maximum and minimum deterioration rates;
t_0 = time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
$PSRMX_t$ = PSR at time t after enforcement of the minimum deterioration rate from Equation 6.26; and
$MAXPDR$ = maximum PSR deterioration rate per year.

6.3 The Travel Forecast Model

HERS v3.10 introduced travel demand elasticity to the travel forecast model. See Appendix B, ”Induced Traffic and Induced Demand,” for a discussion of the concepts guiding these modifications to HERS. See Appendix C, ”Demand Elasticities for Highway Travel,” for a discussion of appropriate elasticity values for use in HERS. Appendix D, ”Basic Theory of Highway Project Evaluation,” presents the principles that apply generally to evaluating highway improvements. HERS v3.26 implements a subset of these general principles.

This paragraph first addresses the tasks performed by HERS during initialization:

- estimating the baseline price;
- setting the baseline V/C; and
- determining the adjusted initial volume.

It then discusses the specific steps utilized by the model in:

- forecasting baseline travel;
- adjusting the baseline forecast for long run elasticity; and
- applying the short run elasticity to yield a traffic volume forecast.

6.3.1 Initialization: Assuming the Baseline Price

The section input data includes AADT for the data year and also for a future data year, typically 20 years beyond the data year. HERS generally assumes that the future volume forecast is based upon a continuation of the initial level of service, as defined by volume-to-capacity (V/C) ratio and PSR. The exception is congested sections, in which case HERS assumes the forecast includes an improvement to increase capacity. HERS calculates the initial user price as the sum of the operating, travel time, and safety costs at the beginning of the analysis period and saves the initial V/C ratio as the baseline V/C level. The baseline price is set equal to the initial price. However, if the section’s initial V/C ratio is equal to or greater than one, then HERS sets the baseline V/C level to one, and calculates the baseline price at a volume consistent with a V/C of one and a minimum PSR of two.

HERS next calculates an initial adjusted volume for the section at the beginning of the analysis period. The adjusted volume is used as the “departure point” for the calculation of future baseline traffic volumes. During initialization, HERS calculates adjusted volume:

$$VADJ = (AADT/(INPRI^{SRE})) \times BASPRI^{SRE} \qquad \text{Eq. 6.28}$$

where:

$VADJ$ = adjusted volume at beginning of analysis period;
$AADT$ = reported volume -- AADT at beginning of analysis period;
$INPRI$ = initial price to user at beginning of analysis period;
$BASPRI$ = baseline price; and
SRE = short run elasticity.

Note that, for sections with initial V/C less than one, the adjusted volume will equal the reported volume because the initial price is equal to the baseline price. For sections with initial V/C greater than one, the re-calculated baseline price is likely to be lower than the initial price (the lower level of congestion should lower travel time costs). As a result, the adjusted volume should be higher than the initial volume, and reflects backing out the effects of short run elasticity.

6.3.2 Forecasting Baseline Traffic Volume

HERS provides the user with the flexibility to project baseline traffic using one of several options, each reflecting different travel growth characteristics. Parameters for each option are initialized by the PreProcessor, and are determined so that, were no elasticity applied, traffic volume on the section would reach the specified Future AADT value at the Future AADT Year. Option One is for concave geometric growth, Option Two is for linear growth, and Option Three provides for convex geometric growth, as shown in Exhibit 6-2.

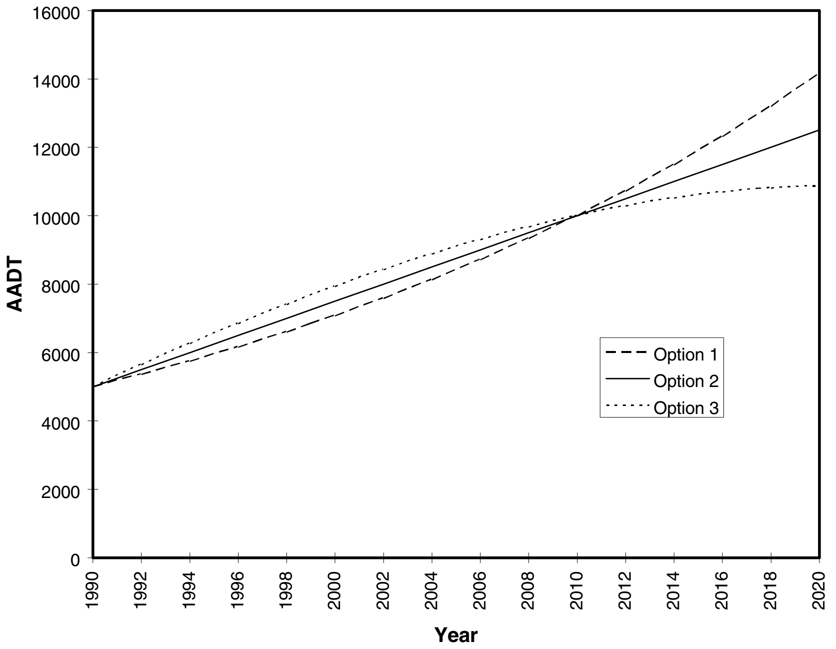

Exhibit 6-2. Travel Growth Options

The example in Exhibit 6-2 is of a section with an initial AADT of 5000 in data year 1990. The future AADT year is 2010, at which time the AADT will have grown to 10,000. The growth rate is calculated for each section based upon the data in its HPMS record. The trend lines show baseline traffic volume without the application of demand elasticity. The linear growth method (option Two) was used for the 1997 and 1999 editions of the *C&P Report*.

6.3.2.1 Option One - Concave Geometric Growth

The geometric option projects baseline traffic by applying a constant rate of growth throughout the analysis period. Because the volume of additional traffic each year is based upon the previous year's volume, more vehicles are added each year. The PreProcessor calculates the growth factor, AADTGR:

$$AADTGR = \left(\frac{FAADT}{AADT}\right)^{1/(FAADTYR - AADTYR)} \qquad \textit{Eq. 6.29}$$

where:

AADTGR	=	constant growth rate;
FAADT	=	Future AADT from HPMS section record;
AADT	=	current AADT from HPMS section record;
FAADTYR	=	year of Future AADT from HPMS section record; and
AADTYR	=	year of current AADT from HPMS section record.

AADT for any time t_1 may be projected along a concave curve:

$$AADT_{t_1} = AADT_{t_0} \times AADTGR^{(t_1 - t_0)} \qquad \textit{Eq. 6.30}$$

where:

$AADT_{t0}$ = known AADT at time t_0.

6.3.2.2 Option Two - Linear Growth

The second option applies a linear, or constant, growth function throughout the period, so that the same number of vehicles are added each year. The growth factor (*AAGRSL*) is calculated by the PreProcessor:

$$AAGRSL = \frac{FAADT - AADT}{FAADTYR - AADTYR} \qquad \textit{Eq. 6.31}$$

where:

AAGRSL = straight line growth rate.

Using the linear growth function, AADT is projected:

$$AADT_{t_1} = AADT_{t_0} + AAGRSL \times (t_1 - t_0) \qquad \textit{Eq. 6.32}$$

This is the growth option used for the 1997 and 1999 versions of the *C&P Report*.

6.3.2.3 Option Three - Convex Geometric Growth

In the third option, the geometric and linear models are combined to project growth along a convex curve. This curve is the mirror image of the concave geometric curve relative to the linear growth function, and provides for rapid initial growth followed by less aggressive growth. Future AADT at time of interest *t*1 is calculated:

$$AADT_{t_1} = 2 \times (AADT_{t_0} + AAGRSL \times (t_1 - t_0)) \\ - AADT_{t_0} \times AADTGR^{(t_1 - t_0)} \qquad \text{Eq. 6.33}$$

6.3.3 Applying Elasticity to Travel Volume Forecasts

To calculate future traffic volume, HERS performs the following steps:

- project future baseline traffic volume by applying the section-specific growth factor to the adjusted present volume;
- determine the future adjusted volume by applying long run elasticity to the baseline projection;
- apply short run elasticity to the adjusted volume to produce an initial, estimated volume;
- using the initial estimate as a departure point, perform a simultaneous solution to determine the equilibrium point between the demand and delay functions to arrive at a final traffic volume.

The model applies elasticity separately to each funding period. When the traffic prediction model calculates the volume after a time span of more than one funding period, it calculates the volume for each funding period successively. The calculation period for volume prediction is from the midpoint of one funding period to the midpoint of the following funding period, a schedule which coincides with the implementation of improvements (at the middle of the funding period) and the benefit-cost analysis period.

The baseline projection begins with the adjusted volume from the “current” funding period (that is, the last period for which volume data is known). The adjusted volume represents the volume on the section before the application of within period short run elasticity. As shown in Equation 6.34, any of the baseline forecast options discussed in paragraph 6.3.2, ”Forecasting Baseline Traffic Volume,” may be used in the calculation of baseline traffic volume at time t_1 from previous long run adjusted volume (at time t_0):

$$VBASE_{t_1} = \begin{cases} VADJ_{t_0} + (AAGRSL \times LFP) \\ VADJ_{t_0} \times AADTGR^{LFP} \\ 2 \times (VADJ_{t_0} + (AAGRSL \times LFP)) - VADJ_{t_0} \times AADTGR^{LFP} \end{cases} \qquad \text{Eq. 6.34}$$

where:

$VBASE_{t1}$ = baseline traffic volume at the midpoint of funding period t_1;
$VADJ_{t0}$ = adjusted traffic volume at the midpoint of the previous funding period t_0;
$AAGRSL$ = linear growth rate (see paragraph 6.3.2);
$AADTGR$ = constant growth rate (see paragraph 6.3.2); and

LFP = the length of a funding period.

HERS next applies the long run share of elasticity to get adjusted volume at time t_1:

$$VADJ_{t_1} = VBASE_{t_1} \times (1 + LRS \times (FINPRI_{t_0} - BASPRI) / (BASPRI)) \qquad Eq.\ 6.35$$

where:

$VADJ_{t1}$ = the adjusted volume at time t_1;
$VBASE_{t1}$ = the baseline volume at time t_1 (from Equation 6.34);
LRS = the long run share;
$FINPRI_{t0}$ = the final user price at time t_0, based upon the AADT at time t_0; and
$BASPRI$ = the baseline price.

Short run elasticity is applied to the adjusted volume to estimate an initial volume:

$$VINIT_{t_1} = ALPHA \times FINPRI_{t_0}^{SRE} \qquad Eq.\ 6.36$$

where:

$VINIT_{t1}$ = the initial volume at time t_1;
$ALPHA$ = $VADJ_{t_1} / BASPRI^{SRE}$; and
SRE = short run elasticity.

6.3.4 The Simultaneous Solution

To locate a point on the demand curve, knowing the price is sufficient to determine volume. If the price were constant with respect to volume, there would be a simple functional relationship with a single argument. However, as both demand and price vary with volume, HERS must find a simultaneous resolution of the supply and demand functions. The equilibrium is the intersection of the supply and demand.

For most of the components of price to the highway user, price does not vary with volume (that is, the rate of flow). Pavement condition is related to cumulative usage (not immediate volume), and the effects of volume-to-capacity (V/C) on accident costs is not well understood, so these are treated as unit costs invariant with flow volume. The exception is congestion, which is clearly related to V/C, although the relationship is not precisely known.

Starting with a price (p_0) that includes all components other than delay, and a demand curve, the volume (v_0) is determined from the price, as shown in Exhibit 6-3, "Adjustment of Calculated Delay for Congestion Reduction." To this price, adding the additional cost for delay, measured off the curve marked "price of delay," generates the upper curve "price with delay." At the price with delay corresponding to the initial volume, p_d, demand would be reduced to some point to the left of the vertical axis (this axis is not at zero volume); delay, however, would be largely eliminated, so the price would no longer apply at this volume. The correct solution is the circled point "equilibrium," which balances the increase in price with the reduction in congestion.

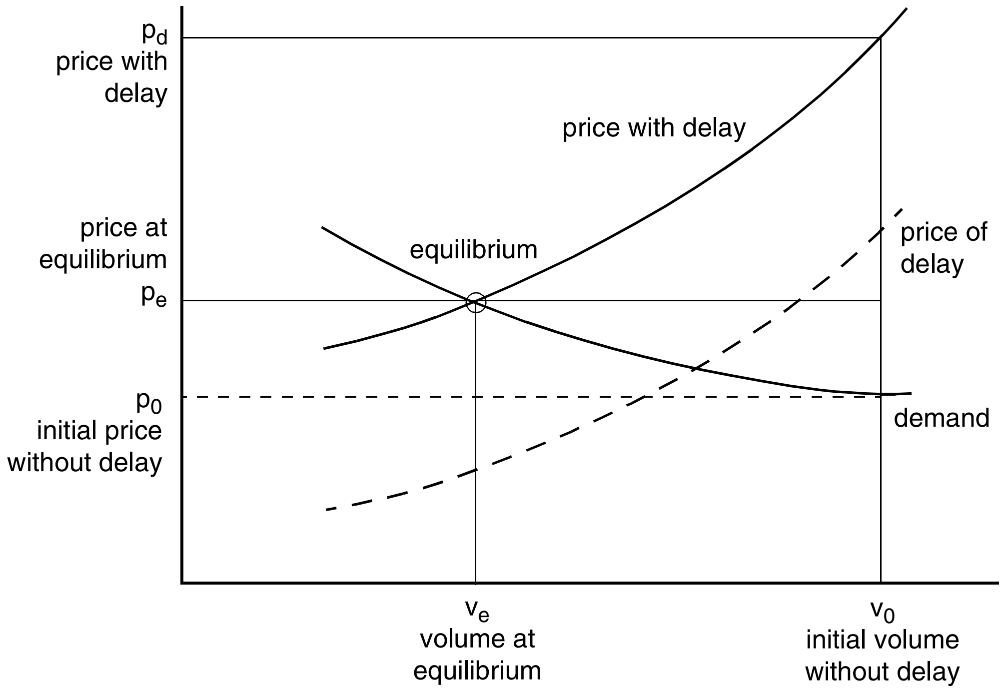

Exhibit 6-3. Adjustment of Calculated Delay for Congestion Reduction

Ideally, this equilibrium point could be found by solving for the intersection of the two functions. While the demand curve is either a straight line or a constant elasticity curve, either of which is a simple single-valued function with two parameters, the delay curve is more complex. The delay curve differs with each of the six road types, and for three of these has different equations for different volume levels. Because of the variety and complexity of these equations, closed-form solutions to the supply-demand intersection are not feasible. Numerical solutions could be obtained to any precision desired, but convergence under all possible conditions would be difficult to ensure, and computational effort might be excessive.

HERS instead uses the alternative approach of a numerical approximation, whose properties are:

1. Rapid convergence because of the smooth shapes of the demand and delay functions; and
2. A fixed number of iterations (two) which necessarily limits computational effort.

This strategy is acceptable because a high degree of numerical precision is not required; the only purpose is to adjust the volume of traffic to a reasonable level given congestion and other generalized price factors.

The approximation strategy uses the slopes of the two curves to estimate the intersection as the apex of a triangle (as if the curves were straight lines), and uses the resulting volume adjustment to re-estimate the slopes as the average of two slopes. In Exhibit 6-4, the first iteration is shown in heavy solid lines, and the second iteration in heavy dashed lines. The first iteration uses the

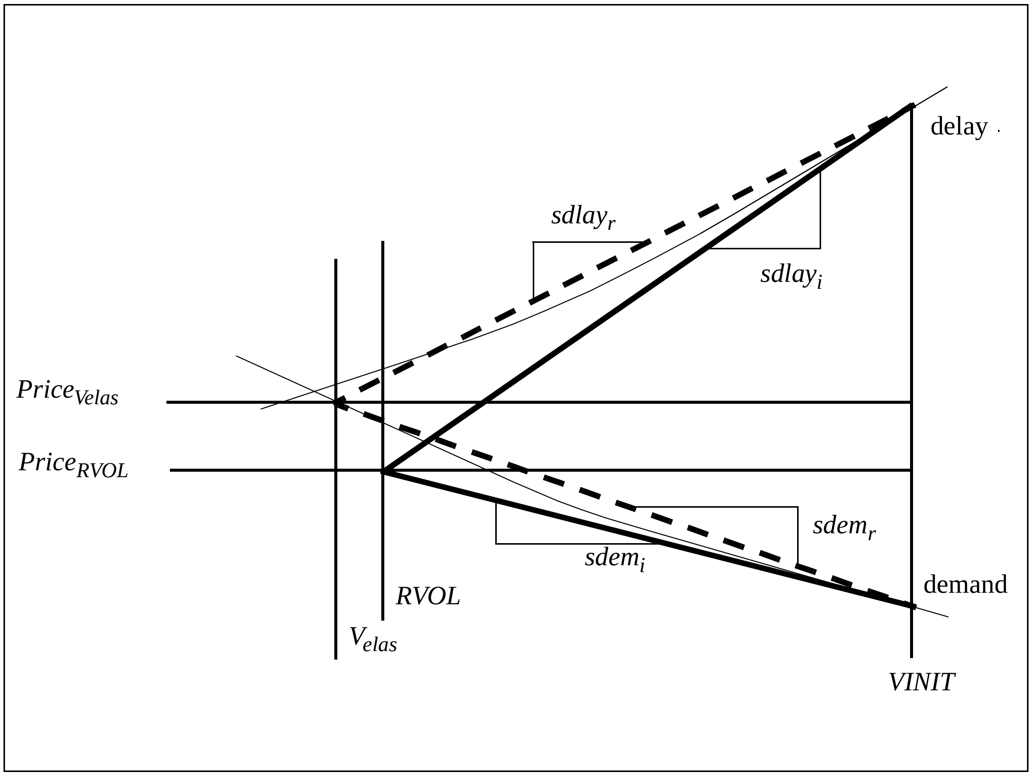

Exhibit 6-4. Details of Successive Approximation

tangents at the initial volume, *VINIT*, shown as $sdlay_i$ and $sdem_i$ (for delay and demand, respectively), to yield the volume *RVOL* and the price $Price_{RVOL}$. Averaging the demand slope at *RVOL* with that for *VINIT* ($sdem_i$) gives the arc slope of the demand curve (shown as $sdem_r$) between those two points, which is a much closer approximation of the slope between the equilibrium and the initial volumes than is the tangent at *VINIT*. Doing the same for the delay function gives the revised delay slope $sdlay_r$, and applying the two revised slopes to *VINIT* produces the second-iteration result of volume V_{elas} and price $Price_{Velas}$. This is still not the true equilibrium point, but it is close enough.

The lower the AADT/Capacity ratio, the more accurate this procedure becomes. The situation displayed in Exhibit 6-4 is an extreme scenario, in that *VINIT* represents an AADT/Capacity ratio of 19.5, which means the facility is operating at capacity for 15-19 hours per day. For AADT/C under 12, the second iteration is almost indistinguishable from the first, and for AADT/C under 8 the first iteration is indistinguishable from the equilibrium.

6.3.5 Computational Algorithms

HERS performs a sequence of steps preparatory to the simultaneous solution of the demand and supply functions. HERS first calls upon the pavement model to determine the condition of the pavement at time t_1 based upon the initial volume estimate. Using this provisional PSR and the initial volume, HERS:

- determines free flow speed and free flow speed uphill for each vehicle type;

- using the free flow speeds, determines the travel time cost without delay;
- calculates the operating costs at the baseline level of service (that is, with the volume to the same level relative to capacity as per the baseline price);
- calculates the safety costs at the initial volume at time t_1; and
- sums the travel time, operating, and safety costs to yield “price without delay” (*PWOD*).

HERS first calculates the slope of the initial demand curve:

$$SDEM_i = \frac{PWOD^{(1-SRE)}}{ALPHA \times SRE} \qquad \text{Eq. 6.37}$$

where:

$SDEM_i$ = initial slope of demand curve; and
PWOD = price without delay.

HERS then calculates an initial estimate of the amount of delay at the volume *VINIT* at time t_1, ($EDLAY_i$) and calculates the slope of the delay function ($SDLAY_i$) at that volume. The specific algorithms are based upon the SAIC/CS equations used in the speed model, and like them are dependent upon the road type, the AADT/Capacity ratio, and the number of traffic signals and stop signs per mile, if any. The equations for specific road types are in Tables 6-11 through 6-12 in paragraph 6.3.6, ”Delay Equations by Road Type.” The examples below (in Equations 6.38 and 6.39) are for two-lane, two-way roads without traffic control devices where the AADT/Capacity ratio (figured using the initial volume as AADT) is less than 10. The initial estimate of delay is determined:

$$EDLAY_i = 0.432 \times \frac{VINIT}{Capacity} \times VOT/1000 \qquad \text{Eq. 6.38}$$

where:

$EDLAY_i$ = estimate of delay at the initial volume;
VINIT = initial volume estimate (from Equation 6.36); and
VOT = value of an hour of travel time.

The slope of the delay equation at the initial volume is:

$$SDLAY_i = 0.432 \times VOT/(Capacity \times 1000) \qquad \text{Eq. 6.39}$$

where:

$SDLAY_i$ = slope of the delay curve at the initial volume.

The first approximation for a revised volume is the height of a triangle (laying on its side) whose base is the initial estimate of delay and whose sides slope at $SDEM_i$ and $SDLAY_i$ (as shown in Exhibit 6-4):

$$RVOL = VINIT + \frac{EDLAY_i}{SDEM_i - SDLAY_i} \qquad \textit{Eq. 6.40}$$

where:

$RVOL$ = revised volume estimate
$EDLAY_i$ = initial estimate of delay (from road type specific equation)
$SDLAY_i$ = initial slope of delay function (from road type specific equation)

This revised volume is then substituted for the initial volume in Equation 6.38 to yield a revised estimate of delay ($EDLAY_r$). (Note that the revised volume is also substituted for the initial volume in determining the AADT/Capacity ratio used to select the specific form of the equation.) HERS next calculates the price associated with the initial volume:

$$Price_{VINIT} = (VINIT/ALPHA)^{(1/(SRE))} \qquad \textit{Eq. 6.41}$$

and the price associated with the revised volume:

$$Price_{RVOL} = (RVOL/ALPHA)^{(1/(SRE))} \qquad \textit{Eq. 6.42}$$

The next step is the calculation of revised slopes for the demand and delay functions. The demand slope is taken as the difference between the initial and revised prices over the difference between their associated volumes:

$$SDEM_r = \frac{(Price_{RVOL} - Price_{VINIT})}{(RVOL - VINIT)} \qquad \textit{Eq. 6.43}$$

where:

$SDEM_r$ = revised demand slope

The delay slope is taken as the difference between the revised and initial delay estimates divided by the difference in the associated volumes:

$$SDLAY_r = \frac{(EDLAY_r - EDLAY_i)}{(RVOL - VINIT)} \qquad \textit{Eq. 6.44}$$

where:

$SDLAY_r$ = revised delay slope

HERS calculates the price of delay at the intersection of the revised slopes:

$$Price_{Delay} = EDLAY_i \times \frac{SDEM_r}{(SDEM_r - SDLAY_r)} \qquad \textit{Eq. 6.45}$$

and uses it to estimate the final, elasticized volume, V_{elas}:

$$V_{elas} = ALPHA \times (PWOD + Price_{Delay})^{SRE} \qquad \textit{Eq. 6.46}$$

6.3.6 Delay Equations by Road Type

These paragraphs contain the delay equations used for each of the four road types. Within each road type, equations are selected based upon the AADT/Capacity ratio and the number of stop signs per mile. The equations are based upon the SAIC[24] and CSI[25] equations implemented in the speed model. The equations yielding *EDLAY* (the estimated delay) would replace Equation 6.38 in the computations detailed above. The equations yielding *SDLAY* (the slope of the delay function) would replace Equation 6.39 as used above.

The "wheres" below apply to the equations in Tables 6-11 through 6-14 which contain the demand equations for the four basic road types:

$EDLAY$ = estimate of delay (equation substitutes for Equation 6.38)
$SDLAY$ = delay slope (equation substitutes for Equation 6.39)
ACR = AADT/Capacity Ratio
VOT = value of an hour of travel time for the section
NSS = the average number of stop signs per mile
NTS = the average number of traffic signals per mile
FFS = free flow speed for the section
$COMPF$ = is the computation factor $1 - \exp(-NTS/24.4)$

The two hybrid road types are treated in the same manner as in the speed model. On sections with both stop signs and traffic signals, the final elasticized volume is the average of the volumes on the two portions of the section, weighted by the relative numbers of stop signs and signals. On three-lane sections in two directions, volume is split equally between the two directions, and capacity is split 7:5 in favor of the two-lane direction. Elasticity is applied using the equations for rural multilane roads (in the two-lane direction) and two-lane roads (in the one-lane direction). The sum of the elasticized volumes is taken as the final elasticized volume for the section.

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[24] Science Applications International Corporation and Cambridge Systematics, Inc., *Roadway Usage Patterns: Urban Case Studies*, prepared for Volpe National Transportations Systems Center and the Federal Highway Administration, June 1994, Appendix A; Science Applications International Corporation, *et al.*, *Speed Determination Models for the Highway Performance Monitoring System*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, October 31, 1993.

[25] Cambridge Systematics, Inc., *Revisions to the HERS Speed and Operating-Cost Procedures*, prepared for the U. S. Department of Transportation, Federal Highway Administration, Washington, D.C, January 25, 1996, Section 2.

Table 6-11. Demand Equations for Freeways and Multilane Rural Highways

AADT/C Range	
<8	$EDLAY = (0.0797 \times ACR + 0.00385 \times ACR^2) \times VOT/1000$
	$SDLAY = (0.0797 + 0.00385 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$
>8 and <12	$EDLAY = (12.1 - 2.95 \times ACR + 0.193 \times ACR^2) \times VOT/1000$
	$SDLAY = (-2.95 + 0.193 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$
>12	$EDLAY = (19.6 - 5.36 \times ACR + 0.342 \times ACR^2) \times VOT/1000$
	$SDLAY = (-5.36 + 0.342 \times 2 \times ACR) \times VOT/(Capacity \times 1000)$

Table 6-12. Demand Equations for 2-lane, 2-way Roads

AADT/C Range	
< 10	$EDLAY = 0.432 \times ACR \times VOT/1000$
	$SDLAY = 0.432 \times VOT/1000$
> 10	$EDLAY = (9.953 - 1.66 \times ACR + 0.109 \times ACR^2) \times VOT/1000$
	$SDLAY = (-1.66 + 0.218 \times ACR) \times VOT/(Capacity \times 1000)$

Table 6-13. Demand Equations for Sections with Stop Signs

AADT/C Range	Stop Signs/ mile	
<6		$EDLAY = (NSS \times (1.9 + 0.067 \times FFS + 0.103 \times ACR + 0.0145 \times ACR^2)) \times VOT/1000$
		$SDLAY = NSS \times (0.103 + 0.029 \times ACR) \times VOT/(Capacity/1000)$
>6 and <15	<10	$EDLAY = (NSS \times (3.04 + 0.067 \times FFS - 0.029 \times (ACR - 6)^2) + 0.354 \times (ACR - 6)^2) \times VOT/1000$
		$SDLAY = (NSS \times (0.348 - 0.058 \times ACR) + 0.708 \times ACR - 4.248) \times VOT/(Capacity \times 1000)$
	>10	$EDLAY = (NSS \times (3.04 + 0.067 \times FFS) + 0.064 \times (ACR - 6)^2) \times VOT/1000$
		$SDLAY = (0.128 \times ACR - 0.768) \times VOT/(Capacity \times 1000)$
>15		$SDLAY = (0.708 \times ACR - 4.248) \times VOT/(Capacity \times 1000)$
	<10	$EDLAY = (NSS \times (0.691 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2) \times VOT/1000$
	>10	$EDLAY = (NSS \times (3.04 + 0.067 \times FFS) + 0.354 \times (ACR - 6)^2 - 23.49) \times VOT/1000$

Table 6-14. Demand Equations for Sections with Traffic Signals

AADT/C Range	
<7	$EDLAY = (COMPF \times (68.7 + 17.7 \times ACR)) \times VOT/1000$
	$SDLAY = 17.7 \times COMPF \times VOT/(Capacity \times 1000)$
>7 and <13.2	$EDLAY = (COMPF \times (192.6 + 14.4 \times (ACR - 7) - 1.16 \times (ACR - 7)^2) + 0.16 \times (ACR - 7)^2) \times VOT/1000$
	$SDLAY = (COMPF \times (14.4 - 2.32 \times (ACR - 7)) + 0.32 \times (ACR - 7)) \times VOT/(Capacity \times 1000)$
>13.2	$EDLAY = (237.3 \times COMPF + 0.16 \times (ACR - 7)^2) \times VOT/1000$
	$SDLAY = 0.32 \times (ACR - 7) \times VOT/(Capacity \times 1000)$

6.4 The Fleet Composition Model

HERS decomposes the vehicle fleet into three vehicle categories which include a total of seven vehicle types. This data on fleet composition is used by HERS when estimating speed, operating costs, travel-time costs, section capacity, and pavement deterioration. The progression from the entire fleet to the seven vehicle types is shown (proceeding from left to right) in Table 6-15, "Fleet Composition."

Table 6-15. Fleet Composition

Fleet	Weighting Factor	Vehicle Category	Weighting Factor	Vehicle Type
All Vehicles	Section data item: Percent Combination Trucks	Combination Trucks	Prorated from HPMS Vehicle Classification Study	Five or More Axle Combination Trucks
				Three/Four Axle Combination Trucks
	Section data item: Percent Single Unit Trucks	Single Unit Trucks	Prorated from HPMS Vehicle Classification Study	Three or More Axle Single Unit Trucks
				Six-Tire Trucks
	100% less percent of Single Unit and Combination Trucks	Four Tire Vehicles	Prorated from HPMS Vehicle Classification Study	Pickups & Vans
				Medium/Large Automobiles
				Small Automobiles

The fleet is divided into vehicle categories based upon section-specific percentages of the two truck classifications. These are reported in the HPMS input data record for each section. The four wheel category consists of the percentage of total traffic which is not part of either truck category. For the disaggregation of vehicle categories to vehicle types, HERS uses factors derived from the 1982 HPMS Vehicle Classification Case Study[26]. As shown in Table 6-16, "Fleet Disaggregation Factors," these functional class dependent factors have been prorated to total 100 percent for each of the three categories.

The HERS parameter file has entries for specifying the annual growth rate of the percentage of truck traffic for each functional class. This is applied to the section-specific percentages for the two truck categories to derive the new percentages for each category. For the 1997 Conditions and Performance Report the truck growth factors were set to 1.0 (i.e., no growth).

As an example of the weighted summation process used by HERS, let $VCAT_A$, $VCAT_{SU}$, and $VCAT_{CM}$ designate the three vehicle categories (four-tire vehicles, single unit trucks, and combination trucks), VT_1 through VT_7 correspond to the seven vehicle types, and FAF_1 through FAF_7 to the fleet disaggregation factors for each of the respective vehicle types (as shown in Table 6-16). After determining the quantity for each vehicle type (for example, travel time cost per

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[26] U. S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Analytical Process *Technical Manual*, Version 2.1, December 1987, Table IV-20.

Table 6-16. Fleet Disaggregation Factors

Functional Classes	Four Tire Vehicles			Single Unit Trucks		Combination Trucks	
	Small Autos	Med/Lg Autos	Pickups & Vans	Six-Tire Trucks	3+Axle SUTs	3-4 Axle Combos	5+ Axle Combos
Rural Interstate	.2365	.5367	.2268	.7372	.2628	.1023	.8977
Rural OPA	.1795	.5335	.2871	.7301	.2699	.1826	.8174
Rural Minor Arterial	.2081	.4762	.3156	.6404	.3596	.1675	.8325
Rural Major Collector	.1536	.4882	.3582	.6180	.3820	.2518	.7482
Urban Interstate	.2521	.5583	.1896	.7000	.3000	.1253	.8747
Urban Other Fwy/Exwy	.2521	.5583	.1896	.7000	.3000	.1253	.8747
Urban OPA	.2081	.5875	.2045	.7490	.2510	.1964	.8036
Urban Minor Arterial	.1976	.5998	.2027	.6590	.3410	.1765	.8235
Urban Collector	.2057	.5551	.2392	.6955	.3045	.3396	.6604

1000 vehicle miles), HERS calculates the quantity for each vehicle category weighted by vehicle type:

$$\begin{aligned} VCAT_A &= VT_1 \times FAF_{1_{fc}} + VT_2 \times FAF_{2_{fc}} + VT_3 \times FAF_{3_{fc}} \\ VCAT_{SU} &= VT_4 \times FAF_{4_{fc}} + VT_5 \times FAF_{5_{fc}} \\ VCAT_{CM} &= VT_6 \times FAF_{6_{fc}} + VT_7 \times FAF_{7_{fc}} \end{aligned} \qquad \text{Eq. 6.47}$$

Note that the fleet disaggregation factors are indexed by functional class. HERS next determines the percentages of single unit and combination trucks at the time of interest (t, in years) by applying the user specified truck growth factor (*TRKFAC*) for the section's functional class to the percentages of average single unit (*PCAVSU*) and combination trucks (*PCAVCM*) reported in the section's HPMS data record:

$$\begin{aligned} PCSU &= PCAVSU \times TRKFAC_{fc}{}^{t} \\ PCCM &= PCAVCM \times TRKFAC_{fc}{}^{t} \end{aligned} \qquad \text{Eq. 6.48}$$

where *PCSU* and *PCCM* are the percentages at the time of interest. Finally, HERS produces a total weighted sum (*TWS*) combining the weighted values of the three vehicle categories:

$$\begin{aligned} TWS = {} & VCAT_A \times (1 - PCSU - PCCM) + VCAT_{SU} \times PCSU \\ & + VCAT_{CM} \times PCCM \end{aligned} \qquad \text{Eq. 6.49}$$

6.5 The Widening Feasibility Model

Six of the seven major HERS improvement options involve increasing the width of the roadway: adding lanes, widening lanes, and improving shoulders[27]. Additionally, widening the median and increasing access control are two upgrades which may be performed on rural sections (when lanes are added) and substandard urban freeways (when they undergo reconstruction) and which also increase the roadway width. “Widening feasibility” refers to the potential for increasing the total width of a particular section. HERS tracks the feasibility of widening each section, and updates the information whenever the section is improved. HERS uses the interaction of system and section-specific constraints to determine first, whether widening improvements can be implemented, and second, whether additional lanes will be added at “normal” or “high” cost. (For information about improvements which widen the roadway, see Chapter 8, and especially Table 8-1, “Effects of Improvements on Section Data Items -- All Sections.”)

There are four factors in HERS which limit the potential width of any section. First, the user specifies the maximum number of lanes (MAXLNS) allowed for each of the functional classes. The number may be as large as 99. It is applied only when determining the number of lanes to be added to a section; it is not used in determining the feasibility of widening existing lanes, widening shoulders or medians, or in improving access control. HERS does not remove lanes from existing highways in order to meet this limit.

Second, HERS will always build to an even number of lanes. Sections with an even number of existing lanes will receive additional lanes in even-numbered increments. Sections with an odd number of existing lanes will receive an odd number of lanes the first time HERS adds lanes to the section, and an even number of lanes should more lanes be added in a subsequent funding period.

Third, each section in the HPMS database includes a Widening Feasibility (WDFEAS) code indicating the extent to which the existing road may be widened. This state-supplied code reflects physical features along the section such as severe terrain, cemeteries and park land, and non-expendable buildings (large office buildings, shopping centers, etc.). It does not reflect restrictions due to current right-of-way, State widening practices, politics, or expendable buildings (single-family residences, barns, private garages, etc.). The widening feasibility codes are described in Table 6-17.

Table 6-17. Widening Feasibility Codes

Code	Description
1	No widening is feasible
2	Partial lane may be added
3	One lane may be added
4	Two lanes may be added
5	Three or more lanes may be added

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[27] Improving shoulders does not always increase width.

Fourth, the user specifies a system-wide Widening Feasibility Override (WDFOVR) code which corresponds to the widening feasibility codes in Table 6-17. When the WDFOVR code is higher than a section's WDFEAS code, HERS may consider additional widening options which would ordinarily be precluded by the WDFEAS value. Lanes that are added up to the level specified by WDFEAS are treated as "normal cost" lanes. Additional lanes added based on the WDFOVR code are treated as "high cost" lanes, and are priced separately in the improvement cost file. High cost lanes are intended to represent extraordinary measures that could be taken to provide additional capacity such as double-decking a freeway, or constructing a new facility on a parallel route. Normal and high cost lanes are reported separately in HERS output.

The interplay of WDFEAS and WDFOVR is shown in Table 6-18, "The Role of WDFOVR in Widening." Each table entry lists the widening improvements HERS will consider for a section of the given widening feasibility code (WDFEAS, by column) for a specific value of the system variable WDFOVR (by row).

Table 6-18. The Role of WDFOVR in Widening

WDFOVR	**Widening Feasibility Code (WDFEAS)**				
	1	**2**	**3**	**4**	**5**
1		SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
2	SH, WL	SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
3	+1 HCL, SH, WL	+1 HCL, SH, WL	+1 NCL[a], SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
4	+1 or 2 HCLs[b], SH, WL	+1 or 2 HCLs[b], SH, WL	+1 NCL[a] or +2 HCLs, SH, WL, Urb, Rur	+1 or 2 NCLs[a], SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur
5	+ HCLs, SH, WL	+ HCLs, SH, WL	+1 NCL[a] and HCLs, SH, WL, Urb, Rur	+1 or 2 NCLs[a] and HCLs, SH, WL, Urb	+ NCLs, SH, WL, Urb, Rur

where: SH = widen shoulders; WL = widen lanes; NCL = add normal cost lane(s); HCL = add high cost lane(s); Urb = on Urban freeways by design: improve access control to full and widen median to design standard; Rur = on Rural sections with added lanes: widen median and upgrade access control to partial.

[a] When the existing facility has an odd number of lanes, add one normal cost lane.

[b] When the existing facility has an odd number of lanes, add one high cost lane.

Setting the WDFOVR code to 1 is the equivalent of disabling the override feature, so that each section's WDFEAS code alone determines the widening options which HERS will consider. This case is illustrated in the first row of Table 6-18. In this situation, if WDFEAS for a section is coded as 1, no widening is considered, while if WDFEAS equals 2, HERS will consider widening the shoulders and/or lanes. If WDFEAS is coded as 3, 4, or 5, HERS may also consider adding normal cost lanes, improving access control, and widening medians. When WDFEAS is coded as 3, HERS will only consider adding a lane when the existing facility has an odd number of lanes. When WDFEAS is coded as 4, HERS will consider adding one lane to a facility with an odd number of lanes, or adding two lanes to a facility with an even number of lanes.

Setting the WDFOVR code higher than 1 causes HERS to consider additional improvement options, including high cost lanes in some cases. Note that the “Rur” and “Urb” values in Table 6-18 are the same in each column. This occurs because WDFOVR is not used in assessing whether the median width and access control upgrades can be made to rural sections receiving additional lanes and substandard urban freeways undergoing reconstruction. Note also that HERS will not add lanes in excess of the MAXLNS value, regardless of how the WDFEAS or WDFOVR variables are coded.

When evaluating improvements, HERS typically uses the initial WDFEAS value at the beginning of the funding period to determine widening feasibility. However, when considering supplemental improvements, the WDFEAS value may first be adjusted downward. On rural sections receiving additional lanes and substandard urban freeways being reconstructed, the main improvement may consume all of the space available, and could preclude any additional upgrades to medians or access control that HERS might otherwise have considered. To address these situations, HERS evaluates supplemental upgrades based on a reduced WDFEAS value that factors in the effect of the main improvement on the initial WDFEAS value. The WDFEAS values shown in Table 6-18 represent the adjusted codes.

For example, a three-lane rural section with an initial WDFEAS of 3 might be resurfaced and have one lane added. Adding a lane would result in reducing WDFEAS to 1, so supplemental rural upgrades would not be considered. This reduction in WDFEAS values is why the “Rur” value doesn’t appear in Table 6-18 in the column where WDFEAS equals 4. HERS only considers median width and access control upgrades to rural sections when lanes are added. If the WDFEAS value at the beginning of the funding period was 4, adding one or two lanes would reduce the WDFEAS code to 3 or 1, respectively. Therefore, for any case in which HERS would be considering median width and access control upgrades to rural sections, WDFEAS could not equal 4. (If the initial WDFEAS value was 5, it would remain 5 after adding lanes.)

HERS updates WDFEAS in response to improvements on the section. See Table 8-5, “Widening Feasibility Code Adjustments,” for the effects of improvements on WDFEAS.

For the 1999 *C&P Report*, the maximum number of lanes was set to 99 for all functional classes. The effect of setting MAXLNS to such a high number was to effectively eliminate it as a factor in regulating roadway width, leaving each section’s WDFEAS value and the WDFOVR override value to determine widening limits. WDFOVR was set to 1, which precluded HERS from adding high cost lanes to any section.[28]

6.6 The Capacity Model

The HERS capacity model has two functions. The first is the calculation of section capacity after improvement; the second is the calculation of the number of lanes needed to accommodate the projected traffic volume in the design year (that is, how many additional lanes are needed).

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[28] This applies to the baseline run for the economic efficiency scenario and most of the over 400 runs executed for the *C&P Report*. Some of the runs were executed with WDFOVR set to 5.

The procedures for estimating capacity for a specific section were developed for the 1994 edition of the *Highway Capacity Manual*[29]. These were modified by FHWA[30] for use in the HPMS submittal software and HERS. Subsequent to the release of the 1998 update to the *Highway Capacity Manual*[31], HERS procedures were modified as needed to maintain conformance with the *Manual*. The reader is referred to the *Highway Capacity Manual*; Chapter 3 of *1999 Revisions to HERS*[32], which documents the changes to the capacity calculations; and Appendix I of the *HPMS Field Manual*. The HPMS submittal software determines the initial capacity for each section, and HERS re-calculates capacity after each improvement to the section.

6.6.1 Design Year Lane Requirements: the General Case

When estimating the future traffic volume for the purpose of determining lane requirements, HERS does not apply demand elasticity[33]. Instead it projects the geometric rate of growth AADTGR (see Equation 6.29) as in Equation 6.34, using the “fully elasticized” AADT of the current funding period for VADJ, and the number of years from the time of that AADT to the “design year” as the “length of the funding period” (LFP).[34] The design year is the length of the design period (specified by the user in the parameter file; the default value is 20 years) from the point of implementing the improvement, which is at the middle of the current funding period.

HERS uses the following formula for determining the number of design year lanes for rural multilane highways, urban freeways by design, and rural freeways by design:

$$DN = DHV \div \left(\frac{UC \times RDMLF}{(1 + PCTRFP \times (ET - 1))}\right) \qquad \textit{Eq. 6.50}$$

where:

DN = design number of lanes;
DHV = design hour volume (30th highest hour in the design year);
UC = unadjusted capacity per lane (from Table 6-19, “Design Year Lane Parameters”);
$RDMLF$ = rural dense multilane factor (set to 0.9 for rural multilane highways in densely developed areas; otherwise set to 1);
$PCTRFP$ = peak percent trucks (in the design year); and
ET = passenger car equivalent for trucks (from Table 6-19).

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[29] Transportation Research Board, *Highway Capacity Manual*, Special Report 209. Third Edition. Washington, D.C., 1994.

[30] U. S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System *Field Manual*, “Appendix I: Highway Capacity Submittal Software,” revised November, 1996.

[31] Transportation Research Board, *Highway Capacity Manual*, Special Report 209. Third Edition. Washington, D.C., 1998. The edition number is unchanged, but updated chapters (Chapters 3, 9, 10, and 11 were extensively revised) have December 1997 dates. Note that the TRB refers to this as “the 1997 update of the third edition.”

[32] Cambridge Systematics, Inc., 1999 Revisions to HERS, prepared for the Department of Transportation, Federal Highway Administration, Washington, D.C., January 2000.

[33] In one sense, this mimics the non-elastic calculations of highway engineers. Practically, it avoids the computationally intense attempt to solve for elasticity when the future capacity is unknown

[34] .The default value for the design period is 20 years, which is presumed to begin at the time the improvement is implemented. Thus, for the initial 5-year funding period, the improvement is implemented at year 2.5, the design year is year 22.5, and the exponent used is 22.5

The number of lanes needed in the design year is rounded up to the next whole number. The actual number of lanes to be added is constrained by widening feasibility and the maximum number of lanes allowed. This number is user-specified for each functional class and is limited to 99 (the value used for the 1999 *C&P Report*). The derivations of unadjusted capacity and passenger car equivalents are shown below in Table 6-19.

Table 6-19. Design Year Lane Parameters

Highway Type	Terrain	ET	Unadjusted Capacity Formula
Rural Multilane	Flat	1.5	$UC = 20 \times DS$
	Rolling	3.0	
	Mountain	6.0	
Rural Freeway by Design	Flat	1.5	$UC = -438.4 - (0.00128 \times DS^3) + (36.6 \times DS)$
	Rolling	3.0	
	Mountain	6.0	
Urban Freeway by Design		1.5	$UC = -835.3 + (0.9188\times10^{-5} \times DS^4) - (0.002212 \times DS^3) - (0.2631 \times DS^2) + 66.82 \times DS$
Where DS is Design Speed; HERS uses the section's weighted design speed from the HPMS input data, with an upper limit of 80 mph, and, for rural and urban freeways by design, a lower limit of 35 mph.			

6.6.2 Design Year Lane Requirements: Urban Surface Streets

For urban surface streets, HERS uses the following formula:

$$DN = \frac{CN \times FW \times DHV}{(0.9 \times Capacity)} \qquad \textit{Eq. 6.51}$$

where:

CN = current number of lanes;
FW = adjustment factor for lane width; and
Capacity = current capacity.

The value 0.9 used in the denominator represents the V/C ratio at level of service D. The adjustment factors for lane width shown in Table 6-20 are from *Highway Capacity Manual* Table 9-5.

Table 6-20. Lane Width Adjustment Factors for Urban Surface Streets

Lane Width (feet)	Adjustment Factor
<9	0.867
9	0.9
10	0.933
11	0.967
12	1.0
13	1.033
14	1.067
15	1.1
>15	1.133

7 Cost and Benefit Calculations

HERS recognizes four broad classes of costs:

- user costs, which are borne by the highway user;
- agency costs, such as maintenance, which are borne by the administrative agency responsible for the section;
- external costs, which are borne by non-users of the highway system (society at large); and
- capital improvement costs.

When performing benefit-cost analysis, HERS places the first three classes in the numerator, with capital improvement costs being the denominator.

Benefits are reductions in costs as the result of an improvement, and are measured as the difference in costs between the base case and the improved case. (The base case can be either the unimproved section or a less aggressive improvement.) Disbenefits are increases in cost as the result of an improvement. It is possible for an improvement to produce both benefits and disbenefits, as when an improvement which increases average speed brings benefits resulting from the reduction in travel time, and disbenefits from an increase in vehicle operating costs.

7.1 User Costs

HERS distinguishes the following components of user costs: travel time costs, vehicle operating costs, and safety costs, which includes both property damage and personal injury. Within the context of the demand elasticity model, these costs make up the user price. User benefits are simply the difference in costs between two predicted future states of the section under consideration: typically, an improvement will lower user costs, producing a benefit. User costs are calculated by vehicle miles traveled; total user costs are a product of user costs per vehicle mile times section length times AADT.

7.1.1 Travel Time Costs

HERS v3.26 incorporates U.S. Department of Transportation values of time per person for personal travel and for business travel.[1] Table 7-1, “Value of One Hour of Travel Time (1995 Dollars),” presents a summary of the major components of the revised HERS estimates of the 1995 value of travel time, by vehicle type. The values used for each of the components are documented below.

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[1] U. S. Department of Transportation, “The Value of Saving Travel Time: Departmental Guidance for Conducting Economic Evaluations,” April 1997, Table 4.

Table 7-1. Value of One Hour of Travel Time (1995 Dollars)

	Small Auto	Med. Auto	4-Tire Truck	6-Tire Truck	3-4 Axle Truck	4-Axle Comb.	5-Axle Comb.
Business Travel							
Value per Person	$ 18.80	$ 18.80	$ 18.80	$ 16.50	$ 16.50	$ 16.50	$ 16.50
Avg. Occupancy	1.43	1.43	1.43	1.05	1.0	1.12	1.12
Vehicle	$ 1.09	$ 1.45	$ 1.90	$ 2.65	$ 7.16	$ 6.41	$ 6.16
Inventory	-	-	-	-	-	$ 0.60	$ 0.60
Personal Travel							
Value per Person	$ 8.50	$ 8.50	$ 8.50	-	-	-	-
Avg. Occupancy	1.67	1.67	1.67	-	-	-	-
Percent Personal	89%	89%	75%	-	-	-	-
Avg Value per Vehicle	**$ 15.71**	**$ 15.75**	**$ 17.84**	**$ 19.98**	**$ 23.66**	**$ 25.49**	**$ 25.24**

For the purpose of indexing the value of time from 1995 dollars to dollars of a subsequent year, HERS allows separate indexing of the value of time per person, the vehicle cost, and inventory-cost components. The indexes currently used for the three components are, respectively: The U.S. Bureau of Labor Statistics (BLS) Employment Cost Index for total compensation of all civilian workers; U.S. Department of Commerce Bureau of Economic Analysis (BEA) data on average expenditures per car; and the implicit gross domestic product (GDP) price deflator, also obtained from BEA. The index values used to convert these components to 1997 dollars (for the 1999 *C&P Report*) are, respectively: 1.059, 1.110, and 1.038.

7.1.1.1 Vehicle Occupants

HERS obtains the value of time to vehicle occupants from the U.S. Department of Transportation (USDOT) Departmental Guidance.[2] The values used are the values (in 1995 dollars) for travel via surface modes. For on-the-clock travel for all occupants of four-tire vehicles, HERS uses the recommended value for "business travel" ($18.80 per person-hour), while the value used for all occupants of larger vehicles is the slightly lower recommended value for truck drivers ($16.50 per person-hour). For personal travel, HERS uses the recommended value for personal local travel ($8.50 per person hour).[3]

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[2] *Ibid.*

[3] The Departmental Guidance recommends using a higher value ($11.90 per person-hour) for personal intercity travel, implying that, at least in rural areas, an average value for personal travel that is slightly higher than $8.50 might be appropriate. (HERS 3.26 does not accept separate values of personal travel time and vehicle occupancy for business and personal travel. The input values of personal travel time and vehicle occupancy used by HERS 3.2 for four-tire vehicles are set so that, when combined with weighted averages of the average vehicle occupancy values in Table 7-1, they will produce the overall average values of time shown at the bottom of the table.)

7.1.1.2 Average Vehicle Occupancy

HERS derives values for average vehicle occupancy (AVO) of four-tire vehicles from 1995 National Personal Travel Survey (NPTS)[4] estimates of VMT and person-miles of travel by trip type. The NPTS data indicates that AVO for "work-related business" (exclusive of commuting) is 1.43, while AVO for all other purposes is 1.67.

For combination trucks, AVO was set to 1.12 on the basis of Hertz' analysis of the frequency of the use of two-driver teams in crash-involved trucks.[5] Six-tire vehicles, which include pick-up-and-delivery vehicles that sometimes carry a helper, were assumed to have an average occupancy of 1.05, while heavier single-unit trucks were assumed to have only one occupant.

7.1.1.3 Personal-Use Percentage of VMT

Approximately 4.7 percent of automobiles are estimated to be in commercial fleets of four or more vehicles, excluding fleet vehicles that are individually leased or used for daily rental;[6] and 6.7 percent of the VMT of the remaining automobiles is for work-related business.[7] These figures indicate that just under 89 percent of automobile VMT represents personal travel (including commuting), while the remainder represents business travel.

For four-tire trucks, the percentage of VMT that was not for personal use was 31 percent in 1992;[8] however, this percentage has undoubtedly dropped in the last several years as small truck-based vehicles have become increasingly popular as personal vehicles. Accordingly, HERS assumes that personal use accounts for 75 percent of the VMT of four-tire trucks and business use accounts for 25 percent of this VMT.

7.1.1.4 Vehicle Costs

Vehicles depreciate as a result of their use and as a result of aging that is independent of vehicle use. The former type of depreciation is estimated by HERS' vehicle operating-cost procedure, while the latter type is a time-related cost incurred by all vehicle owners and included as a component of travel-time cost of commercial vehicle operators. For HERS 3.2, time-related depreciation was estimated by:

1. Estimating total annual depreciation by vehicle type, and converting these estimates to costs per hour of vehicle operation;
2. Using a modified version of HERS to obtain estimates of usage-related depreciation (by vehicle type) per vehicle-mile; and
3. Converting the latter estimates to costs per hour of vehicle operation, and subtracting from the Step 1 results.[9]

The estimation process is described below.

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[4] Oak Ridge National Laboratories, *1995 National Personal Travel Survey*, Table NPTS-1, October 1997 (www-cta.ornl.gov/npts/1995/doc/table1.pdf).

[5] Robin P. Hertz, "Sleeper Berth Use as a Risk Factor for Tractor Trailer Driver Fatality," *31st Annual Proceedings, American Association for Automotive Medicine,* September 1987, pp. 215-227.

[6] American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1995*, Detroit, 1995, pp. 39 and 43.

[7] Oak Ridge National Laboratories, *op. cit*.

[8] U. S. Bureau of the Census, *1992 Truck Inventory and Use Survey*, May 1995.

For autos in commercial motor pools and four-tire trucks, total depreciation per hour was computed as the average vehicle cost per year (assuming a five-year life, with a 15 percent salvage value at the end, with initial cost from the American Automobile Manufacturers Association[10]) divided by 2,000 hours per year of sign-out time (essentially the day shift or other shift when maximal vehicle use occurs). For heavier trucks, total depreciation per hour was computed as the average vehicle cost per year[11] divided by the number of hours in service per year. Six-tire trucks and four-axle combination trucks were assumed to be in service 2,000 hours per year; and five-axle combinations were assumed to be in service 2,200 hours per year. Because three- and four-axle single-unit trucks include many dump trucks that have down time between jobs, especially during cold periods of the winter, they were assumed to be used only 1,600 hours per year.

The resulting estimates of total depreciation per hour of operation are shown in the first column of Table 7-2. The relatively high value shown for three- and four-axle single-unit trucks is the result of the low number of hours per year that they are used and relatively small differences between the initial costs of these vehicles and those of tractor-trailer combinations.

Table 7-2. Estimation of Vehicle Costs (1995 Dollars)

Vehicle Type	Total Depreciation ($/hr.)	Miles per Year[a]	Mileage-Related Depreciation		Time-Related Depreciation ($/hr.)
			($/mile)	($/hr.)	
Small Autos	$ 1.72	11,575	$ 0.109	$ 0.63	$ 1.09
Medium/Large Autos	2.02	11,575	0.098	0.57	1.45
Four-Tire Trucks	2.18	12,371	0.045	0.28	1.90
Six-Tire Trucks	3.08	10,952	0.079	0.43	2.65
3+ Axle Trucks	8.80	15,025	0.175	1.64	7.16
3-4 Axle Combinations	7.42	35,274	0.057	1.01	6.41
5+ Axle Combinations	7.98	66,710	0.060	1.82	6.16

[a] For automobiles, from Federal Highway Administration, *Highway Statistics 1997*, November 1999, Table VM-1; for trucks, from U. S. Bureau of the Census, *1992 Truck Inventory and Use Survey*, May 1995, Table 2a.

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[9] In earlier versions of HERS, Steps 2 and 3 were not performed. Thus, usage-related depreciation was included in HERS estimates of travel-time costs as well as HERS estimates of operating costs. The new procedure is designed to eliminate this double counting.

[10] American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, p. 60.

[11] Estimates of average vehicle cost per year are those used in the *1997 Federal Highway Cost Allocation Study* (U.S. Department of Transportation, July 1997). Sources used in developing thoses estimates were: Jack Faucett Associates, “The Effect of Size and Weight Limits on Truck Costs,” prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1990; Maclean Hunter Market Reports, *The Truck Blue Book*, January 1995, Chicago (sales prices for tractors and chassis); U.S. Bureau of the Census, *Current Industrial Reports, Truck Trailers*, summaries for various years (price adjustments for trailers); and a survey of truck dealers (prices for single-unit trucks).

The second column of Table 7-2 shows estimates of average annual mileage for the seven vehicle types distinguished by HERS. Annual mileage for automobiles is from *Highway Statistics*;[12] and annual mileage for the five categories of trucks is from the *1992 Truck Inventory and Use Survey*.[13]

The third column of Table 7-2 shows the estimates of mileage-related depreciation, in cents per mile. The estimates of annual hours of operation presented above and those of annual miles per year shown in the second column of the table were then used to convert the estimates of mileage-related depreciation to dollars per hour (as shown in the fourth column); and this result was subtracted from total depreciation to produce the estimates of time-related depreciation that are shown in the last column of Table 7-2, and also in Row 3 of Table 7-1.

The estimates of time-related depreciation and mileage-related depreciation shown in the fourth and fifth columns of Table 7-2 are internally consistent in that, for each vehicle type, the two values add up to the estimate of total depreciation (in the first column). These two sets of estimates are thus appropriate for use by HERS (or by any similar system making joint use of both sets of estimates). However, some of the individual values in the last three columns do raise questions. In particular, the values for mileage-related depreciation for trucks appear to be low relative to the corresponding values for automobiles.[14] A brief investigation into the causes of this result suggests that it probably is due to differences between the procedures used for automobiles and those used for trucks in the original estimation of mileage-related depreciation.[15]

7.1.1.5 Inventory Costs

To compute the inventory costs for five-axle combination trucks, an hourly discount rate was computed and multiplied by the value of a composite average shipment. The discount rate selected was 9.8 percent, equal to the average prime bank lending rate in 1995 plus one percent. Dividing this rate by the number of hours in a year produces an hourly discount rate is 0.0033 percent. The average payload of a five-axle combination is about 35,000 pounds. In 1993, the average value of commodities shipped by truck was $1.35 per pound (on a ton-mile weighted basis).17 Inflating to 1995 dollars using the GDP deflator and multiplying by the average payload produces an average payload value of roughly $50,000. The resulting time value of the average payload is approximately $0.60 per hour (ignoring any costs for spoilage and depreciation over time).

Payload for four-axle combination trucks is lower than for five-axle combination trucks, but the value of the cargo probably is higher. Consequently, the value per shipment was assumed to be the same for both types of trucks.

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[12] Federal Highway Administration, *Highway Statistics 1997*, November 1999, Table VM-1.

[13] *Op. cit.*, Table 2a.

[14] A comparison of Columns 4 and 1 indicates that mileage-related depreciation accounts for 28 percent of total depreciation of medium / large automobiles and 37 percent of depreciation for small automobiles. The corresponding figures for the three types of single-unit trucks are only about half as large (13 to 19 percent). Even for five-axle combinations, which have average annual mileages that are five times those of automobiles, mileage-related depreciation represents only 23 percent of total depreciation. Observing that styling obsolescence is a significant contributor to time-related depreciation for automobiles but not for trucks, this suggests that, for vehicles with comparable annual mileages, mileage-related depreciation probably should be smaller for automobiles than for trucks.

[15] J. P. Zaniewski, *et. al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for FHWA, June 1982, pp. 60-67.

7.1.1.6 Estimating Travel Time Costs

For each vehicle type, these values are used by HERS to develop estimates of travel time costs on each section from the equation:

$$TTCST_{vt} = \frac{1000}{AES_{vt}} \times TTVAL_{vt} \qquad \textit{Eq. 7.1}$$

where:

$TTCST_{vt}$ = average travel-time cost (in 1995 dollars per thousand vehicle-miles) for vehicles of type *vt*;
AES_{vt} = average effective speed of vehicles of type *vt* on the highway section being analyzed; and
$TTVAL_{vt}$ = average value of time (in 1995 dollars) for occupants and cargo of vehicles of type *vt* (as shown on the bottom line of Table 7-1).

For each section, the average travel-time cost (per thousand vehicle-miles) is obtained by taking a weighted average of the corresponding costs for each vehicle type. In HERS the weights are obtained by using section-specific HPMS data on the percentages of four-tire vehicles, single-unit trucks, and combination trucks, and then allocating these percentages to the seven vehicle types using distributions (by functional system) obtained from the HPMS Vehicle Classification Study.[16] (See paragraph 6.4, ”The Fleet Composition Model.”)

7.1.2 Estimating Operating Costs

The cost of operating a vehicle on a given section is a function of costs for fuel, oil, tires, maintenance and repair, and mileage-related depreciation. This section discusses the method by which HERS estimates operating costs. These estimates exclude the effect of taxes.[17]

HERS treats operating costs as having three sources, and derives its estimates using a three-step procedure:

1. Constant-speed operating costs are estimated as a function of average effective speed, average grade, and PSR;
2. Excess operating costs due to speed-change cycles are estimated; and
3. Excess operating costs due to curves are estimated.

Exhibit 7-1 provides an overview of the operating cost calculations.

The operating cost calculation process, as outlined above and detailed in the paragraphs below, is performed for each of the seven vehicle types. For the two truck categories the process is performed once for each direction unless free-flow speed and uphill free-flow speed are the same (see paragraph 6.1.1, “Free-Flow Speed and the APLVM”). The process is performed only once

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[16] U. S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Analytical Process *Technical Manual*, Version 2.1, December 1987, Table IV-20.

[17] From the standpoint of the user, taxes are part of user costs. However, from the standpoint of the overall economy, taxes are transfer payments that entail no resource costs.

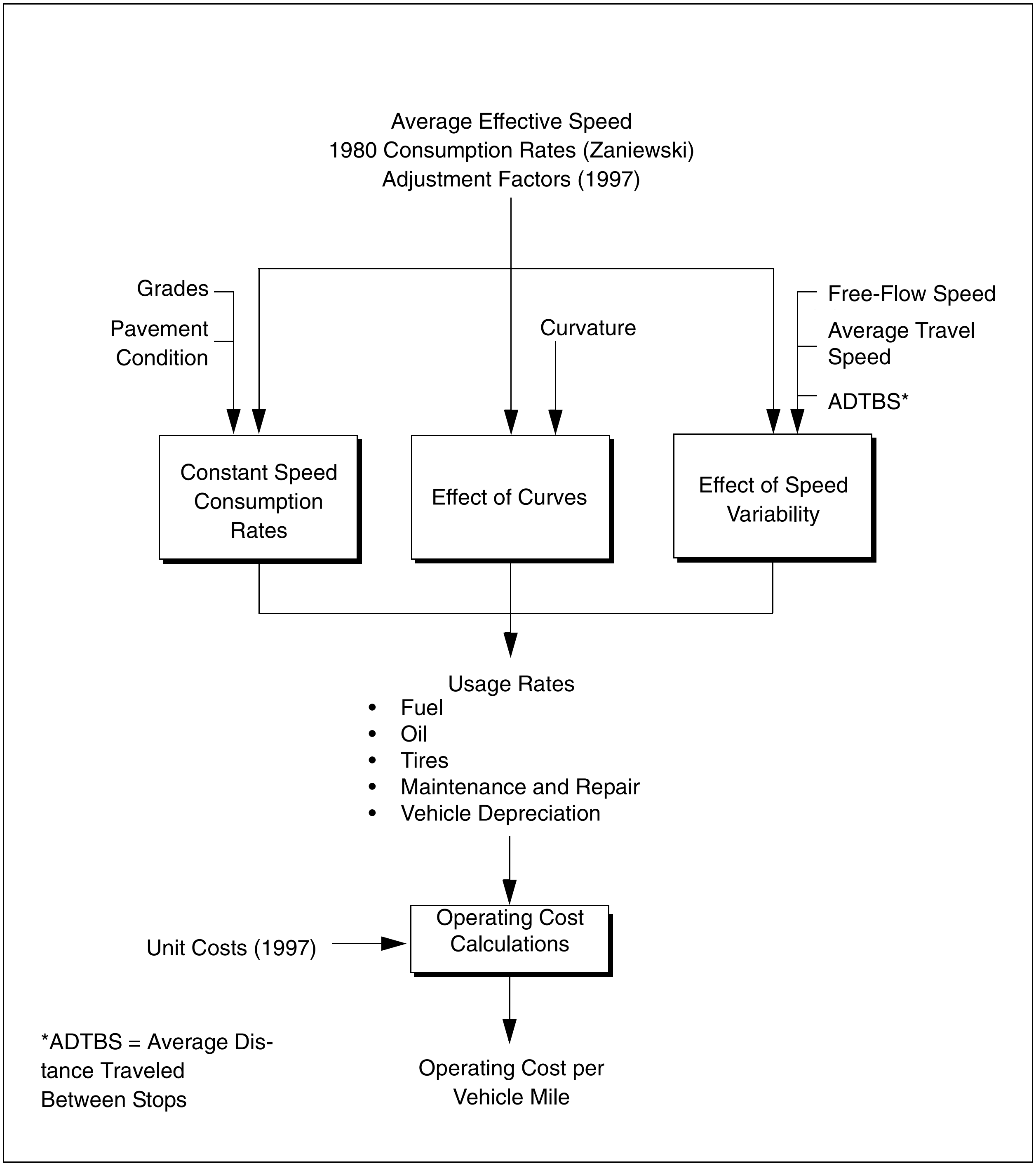

Exhibit 7-1. Operating Cost Calculation Flow

for four-wheel vehicles, as HERS assumes that grades do not affect free-flow speed for these vehicles.

7.1.2.1 Operating Cost Components

HERS v3.26 recognizes five components of operating costs:

- fuel consumption
- oil consumption
- tire wear
- maintenance and repair
- depreciable value.

All five components are included in the calculation of constant-speed costs and excess costs due to speed change cycles: for excess costs due to curves, only fuel, tire wear, and maintenance and repair are included.

7.1.2.1.1 Component Prices

Table 7-3 shows estimates of component prices in 1997 dollars for use in estimating operating costs. The sources of these estimates are described below.

Table 7-3. Component Prices

(1997 dollars)

Vehicle Type	Fuel ($/gallon)	Oil ($/quart)[a]	Tires ($/tire)	Maintenance and Repair ($/ 1,000 miles)	Depreciable Value ($/vehicle)
Automobiles					
Small	$0.871	$3.573	$45.2	$84.1	$18,117
Medium/Large	0.871	3.573	71.5	102.1	21,369
Trucks					
Single Units					
4 Tires	0.871	3.573	78.8	129.8	23,028
6 Tires	0.871	1.429	190.1	242.9	34,410
3+ Axles	0.762	1.429	470.7	343.5	75,702
Combination					
3-4 Axles	0.762	1.429	470.7	355.8	87,690
5+ Axles	0.762	1.429	470.7	355.8	95,349

[a] The unit cost for oil includes the labor charge for changing the oil.

Fuel prices for two-axle vehicles were derived by subtracting federal and state gasoline taxes[18] from the 1997 retail price of gasoline, and fuel prices for larger vehicles were derived by subtracting taxes on diesel fuel from the average 1997 retail price of highway diesel fuel.[19]

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[18] U. S. Department of Transportation, Federal HIghway Administration, *Highway Statistics, 1997*, Washington, D.C., 1998, Table MF-121T.

Values for the cost of oil and tires were obtained by applying appropriate price indexes to the 1995 estimates previously developed[20] from the original Zaniewski estimates[21]. The price index used for oil is the consumer price index (CPI)[22] for motor oil, coolant, and fluids (SS47021). Tire costs were indexed using the CPI for tires (SETC01). The tire-cost index reflects the effects of improvements in quality (as downward adjustments in the index) - improvements that generally decrease the rate of tire wear. Maintenance and repair costs were indexed using the CPI for motor vehicle maintenance and repair (SETD).

For medium and heavy trucks, following Zaniewski, depreciable value was obtained by subtracting tire costs from the vehicle's retail price and then subtracting ten percent salvage value. For the three heaviest vehicles, the vehicle prices were those used by the recent Federal Highway Cost Allocation Study[23] (for three-axle dump trucks and for combinations with a tandem-axle van semi-trailer). The retail price of a 1995 28,000 pound gross vehicle weight six-tire truck was obtained from the Truck Blue Book[24] and adjusted to include a van body.

For the two classes of automobiles, 1995 depreciable value was obtained by adjusting the 1993 values[25] for changes in the average price paid for a new car.[26] For four-tire trucks, 1995 depreciable value was obtained judgementally from the 1995 value for medium/large automobiles by comparing the range of list prices of minivans and sport-utility vehicles to the range for medium and large automobiles.[27] For all vehicle classes, 1997 depreciable value was then obtained by applying the change in the average price of a new car between 1995 and 1997.

7.1.2.1.2 Adjustment Factors for Consumption Rates

The parameters used by the operating cost equations have been indexed to reflect reductions in fuel and oil consumption rates and depreciation rates that occurred between 1980 and 1997. Increases in tire durability are reflected in the consumer and producer price indexes (which have increased by only a few percent since 1980); and reductions in requirements for routine maintenance are similarly reflected in the Runzheimer data for maintenance costs used for adjusting

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[19] U.S. Department of Energy, Energy Information Administration, "On-Highway Diesel Fuel Price Survey," Form EIA-888, 1995.

[20] Cambridge Systematics, Inc., *Revisions to HERS*, prepared for the Federal Highway Administration, December 1997, Chapter 7.

[21] J.P. Zaniewski, *et.al., Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors,* Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1982, Table 2, p. 7.

[22] U.S. Department of Labor, Bureau of Labor Statistics, Consumer Price Index Database.

[23] U. S. Department of Transportation, FHWA, *1997 Federal Highway Cost Allocation Study*, August 1997.

[24] Maclean Hunter Market Reports, *Truck Blue Book*, Chicago, January 1995.

[25] Cambridge Systematics, Inc., *op. cit.* The 1993 values were derived from the original Zaniewski values using the same procedure.

[26] U.S. Department of Commerce, Bureau of Economic Analysis, "Average Transaction Price of a New Car," quoted in American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996,* Detroit, 1996, page 60. This source provides a better indication of changes in vehicle prices than the appropriate components of the CPI and PPI, because the latter indexes are adjusted (downward) to exclude the effect on prices of improvements in the quality of new vehicles. On the other hand, none of the adjustments reflect the effects that some of these improvements have had on servicing requirements or depreciation rates (which, ideally, should be handled by modifying the operating cost equations for maintenance and repair).

[27] The alternative approach of adjusting the original Zaniewski values using data on changes in the price of a new car was rejected because it does not adequately reflect the increase in the quality of appointments of four-tire trucks that has occurred during the last several years. The rejected procedure produces a 1995 value of only $17,002 (instead of the $20,742 value actually used).

maintenance costs per mile through 1995. Hence, separate adjustments are not needed for changes in the rate of tire wear and in the amount of maintenance required. The adjustments for changes in fuel efficiency, oil consumption, and vehicle depreciation are discussed below.

7.1.2.1.2.1 Fuel Efficiency Adjustment Factor

The fuel efficiency adjustment factors for automobiles and four-tire trucks were obtained by dividing on-road fuel efficiency for the 1997 fleet of automobiles and light trucks by corresponding 1980 values. The 1980 values were obtained from Energy and Environmental Analysis.[28] The 1997 values were developed using the following data from the *Transportation Energy Data Book* published annually by Oak Ridge National Laboratory (ORNL):[29]

- 1976-1997 sales of automobiles and 1970-1997 sales of light trucks
- 1976-1997 EPA fuel efficiencies by vehicle class
- estimated survival rates.

The surviving fleets of pre-1970 light trucks and pre-1976 automobiles were assumed to be three times the number of surviving 1970 light trucks and 1976 automobiles, respectively. Fuel efficiencies of pre-1976 automobiles were estimated by extrapolation, while fuel efficiencies of pre-1976 light trucks were assumed to be the same as those of 1976 light trucks (which are 11 percent below those of 1977 light trucks). All averaging was performed using fuel consumption rates (gallons per mile); and in-use fuel efficiency was assumed to be 15 percent below the EPA value.

A single fuel efficiency adjustment factor for the three classes of heavy trucks was developed by comparing fuel efficiency estimates for Class 8 trucks developed by ORNL[30] using data from the 1977 and 1992 Truck Inventory and Use Survey (TIUS) and raising the ratio to the 17/15 power. The relatively small increase in fuel efficiency (16.7 percent over 17 years) is due, in part, to increases in vehicle weights.

The fuel efficiency adjustment factor for six-tire trucks was similarly developed from TIUS data using a weighted average of fuel efficiency estimates for Class 6 trucks (19,500 to 26,000 pound gross vehicle weight). Class 6 is the largest of the five truck classes (Classes 3-7) that consist primarily of six-tire trucks. Use of data for a single truck class minimizes the effect of changes in the mix of six-tire vehicles occurring over the period.

The resulting fuel efficiency adjustment factors are shown in Table 7-4.

7.1.2.1.2.2 Oil Consumption Adjustment Factor

The most common recommended oil change interval for new automobiles was 7,500 miles in both 1980 and 1998. However, for various reasons, some slight reduction in oil consumption between these two years was likely. (These reasons include a reduction in the number of older cars with shorter oil change intervals and reduced burning of oil.) Accordingly, an oil consumption reduction factor of 1.05 was assumed for all vehicle classes.

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[28] Energy and Environmental Analysis, Inc., *The Motor Fuel Consumption Model: Thirteenth Periodical Report*, prepared for the U.S. Department of Energy, Washington, D.C., January 1988, page B-1.

[29] Oak Ridge National Laboratory, *Transportation Energy Data Book*, various editions.

[30] *Ibid.*, Edition 18, September 1998, Table 7.5.

Table 7-4. Fuel Efficiency Adjustment Factors

(1997 Factors)

Vehicle Type	Factor
Small Automobiles	1.536
Medium/Large Automobiles	1.536
4-Tire Trucks	1.596
6-Tire Trucks	1.207
3+ Axle Trucks	1.167
3-4 Axle Combinations	1.167
5+ Axle Combinations	1.167

7.1.2.1.2.3 Depreciation Rate Adjustment Factor

The average age of the automobile fleet increased from 6.6 years in 1980 to 8.6 years in 1996[31], suggesting a 30 percent increase in longevity (or a decline in the average rate of depreciation of about 23 percent). The same increase in average longevity was assumed for trucks. Hence the adjustment factor for depreciation was set to 1.30 for all vehicle types.

7.1.2.2 Constant-Speed Operating Costs

For each vehicle type (vt), constant-speed operating cost per thousand vehicle-miles (*CSOPCST*) is estimated as the sum of five cost components representing costs for fuel, oil, tires, maintenance and repair, and vehicle depreciation. The overall equation for combining these components is:

$$\begin{aligned} CSOPCST_{vt} = {} & CSFC \times PCAFFC \times COSTF_{vt} / FEAF_{vt} \\ & + CSOC \times PCAFOC \times COSTO_{vt} / OCAF_{vt} \\ & + 0.01 \times CSTW \times PCAFTW \times COSTT_{vt} / TWAF_{vt} \\ & + 0.01 \times CSMR \times PCAFMR \times COSTMR_{vt} / MRAF_{vt} \\ & + 0.01 \times CSVD \times PCAFVD \times COSTV_{vt} / VDAF_{vt} \end{aligned} \qquad \text{Eq. 7.2}$$

where:

$CSOPCST_{vt}$ = constant speed operating cost for vehicle type *vt;*
$CSFC$ = constant speed fuel consumption rate (gallons/1000 miles);
$CSOC$ = constant speed oil consumption rate (quarts/1000 miles);
$CSTW$ = constant speed tire wear rate (% worn/1000 miles);
$CSMR$ = constant speed maintenance and repair rate (% of average cost/1000 miles);
$CSVD$ = constant speed depreciation rate (% of new price/1000 miles);
$PCAFFC$ = pavement condition adjustment factor for fuel consumption;

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[31] R. L. Polk and Company, as quoted in American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, p. 39.

$PCAFOC$ = pavement condition adjustment factor for oil consumption;
$PCAFTW$ = pavement condition adjustment factor for tire wear;
$PCAFMR$ = pavement condition adjustment factor for maintenance and repair;
$PCAFVD$ = pavement condition adjustment factor for depreciation expenses;
$COSTF_{vt}$ = unit cost of fuel for vehicle type vt;
$COSTO_{vt}$ = unit cost of oil for vehicle type vt;
$COSTT_{vt}$ = unit cost of tires for vehicle type vt;
$COSTMR_{vt}$ = unit cost of maintenance and repair for vehicle type vt;
$COSTV_{vt}$ = depreciable value for vehicle type vt;
$FEAF_{vt}$ = fuel efficiency adjustment factor for vehicle type vt;
$OCAF_{vt}$ = oil consumption adjustment factor for vehicle type vt;
$TWAF_{vt}$ = tire wear adjustment factor for vehicle type vt;
$MRAF_{vt}$ = maintenance and repair adjustment factor for vehicle type vt; and
$VDAF_{vt}$ = depreciation adjustment factor for vehicle type vt.

Equations for estimating constant-speed consumption rates for fuel, oil, tires, maintenance and repair, and vehicle depreciation are shown in Exhibits E-1 through E-7 in Appendix E, ”Operating Cost Equations.” In these equations, *AES* is average effective speed in miles per hour (an output of the speed model), and *GR* is grade (in percent). The equations were estimated by applying ordinary least squares regression to the consumption tables presented in Zaniewski,[32] and have been modified to handle the higher speeds that HERS will encounter as a result of the recent increase in speed limits.

The Zaniewski tables represent estimated consumption rates for equipment in use in 1980 on roads with PSR = 3.5. Exhibit E-8, “Constant-Speed Operating Costs – Pavement Condition Adjustment Factors,” presents equations for estimating pavement-condition adjustment factors for oil consumption, tire wear, maintenance and repair, and vehicle depreciation. These equations also were estimated by applying ordinary least squares regression to the adjustment factors presented in Zaniewski.[33]

Zaniewski does not provide pavement-condition adjustment factors for fuel consumption. Accordingly, the corresponding adjustment factor used for HERS v3.26 is set to one. However, the factor has been included in the code for symmetry and to allow development of such a factor in the future.

7.1.2.3 The Effect of Speed-Change Cycles

HERS calculates excess operating costs due to speed-change cycles (or speed variability) for sections which have stop signs or traffic signals. The overall formula for calculating these costs is similar to that for constant speed operating costs (see Equation 7.2) with two exceptions: the consumption rates are derived from a different set of equations, and no pavement condition adjustment factors are used. For each vehicle type (*vt*), excess operating costs per thousand vehicle-miles due to speed variability (*VSOPCST*) is estimated:

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[32] *Op. cit.*, Appendix B.
[33] *Ibid.*, Figure 5 and Tables 12, 15, and 19.

$$\begin{aligned} VSOPCST_{vt} = {} & VSFC \times COSTF_{vt} / FEAF_{vt} \\ & + VSOC \times COSTO_{vt} / OCAF_{vt} \\ & + VSTW \times COSTT_{vt} / TWAF_{vt} \\ & + VSMR \times COSTMR_{vt} / MRAF_{vt} \\ & + VSVD \times COSTV_{vt} / VDAF_{vt} \end{aligned} \qquad \textit{Eq. 7.3}$$

where:

$VSOPCST_{vt}$ = excess operating cost due to speed variability for vehicle type *vt*;
$VSFC$ = excess fuel consumption rate due to speed variability (gallons/1000 miles);
$VSOC$ = excess oil consumption rate due to speed variability (quarts/1000 miles);
$VSTW$ = excess speed tire wear rate due to speed variability (% worn/1000 miles);
$VSMR$ = excess speed maintenance and repair rate due to speed variability (% of average cost/1000 miles);
$VSVD$ = excess depreciation rate due to speed variability (% of new price/1000 miles);
$COSTF_{vt}$ = unit cost of fuel for vehicle type *vt*;
$COSTO_{vt}$ = unit cost of oil for vehicle type *vt*;
$COSTT_{vt}$ = unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$ = unit cost of maintenance and repair for vehicle type *vt*;
$COSTV_{vt}$ = depreciable value for vehicle type *vt*;
$FEAF_{vt}$ = fuel efficiency adjustment factor for vehicle type *vt*;
$OCAF_{vt}$ = oil efficiency adjustment factor for vehicle type *vt*;
$TWAF_{vt}$ = tire wear efficiency adjustment factor for vehicle type *vt*;
$MRAF_{vt}$ = maintenance and repair efficiency adjustment factor for vehicle type *vt*; and
$VDAF_{vt}$ = depreciation adjustment factor for vehicle type *vt*.

These equations were also derived from Zaniewski, and are only applied to sections with stop signs or traffic signals. The equations are shown in Exhibits E-9 through E-15 in Appendix E.

Signals and stop signs (as a group) are assumed to be uniformly spaced on each section. (This assumption is also used in the speed model.) Sections with both signals and stop signs are treated as having all signals at one end of the section and all stop signs at the other end. The two portions of the sections are analyzed separately, producing separate estimates of excess costs per 1000 cycles for the stop-sign and traffic signal portions of the section.

For each section, the estimates of excess costs per 1000 cycles are converted to excess costs per 1000 miles by dividing by the average distance between stops for stop signs and traffic signals. For traffic signals, this denominator reflects an adjustment for the probability of actually being stopped at a traffic signal. If both stop signs and traffic signals exist on the section, the sum of the excess costs for the two parts of the section is used.

7.1.2.4 The Effect of Curves

HERS uses the original Zaniewski tables[34] and equations derived from those tables for estimating excess operating costs due to curves. Two-dimensional linear interpolation of table values is used for sections with average effective speed below 55 m.p.h., and equations fit to the tables are used for sections with average effective speed above 55 m.p.h. On sections with zero degrees of curvature, excess costs are set to zero.

For medium and high speeds (generally above 40 m.p.h.), the Zaniewski values for excess costs due to curves with one degree of curvature are higher (and sometimes substantially higher) than those due to curves with two degrees of curvature. The values for one degree of curvature were deemed to be excessive and were ignored in estimating the equations for average effective speeds above 55 m.p.h. Similarly, the questionably high values for one degree of curvature were modified to more reasonable values in the tables used for sections with average effective speeds below 55 m.p.h.

7.1.2.4.1 Sections With AES Below 55 M.P.H.

HERS uses the individual Zaniewski tables for the effects of curves on fuel consumption, tire wear, and maintenance and repair. (The effects of curves on vehicle depreciation and oil consumption were assumed to be negligible by Zaniewski.) During program initialization, the values in these tables are:

1. Multiplied by exogenously specified factors representing improvements since 1980 in fuel consumption, tire wear, and maintenance and repair;
2. Multiplied by exogenously specified unit prices; and
3. Summed.

The result is a single table of excess costs due to curves for each vehicle type (in dollars per 1000 vehicle miles) as a function of curvature and speed (up to 55 m.p.h.). For individual sections, excess costs due to curves for each vehicle type are estimated using average effective speed and curvature on the sections and using two-dimensional linear interpolation between entries in the table.

7.1.2.4.2 Sections with AES Above 55 M.P.H.

For sections with average effective speeds equal to or greater than 55 m.p.h., HERS uses equations fit to the Zaniewski values given for speeds of 55-70 m.p.h. and two degrees of curvature or more. Equations for use with sections having two or less degrees of curvature were devised to match the modified table values. Similar to the overall formula for constant-speed operating costs, HERS calculates the excess cost due to curves (*COPCST*) for each vehicle type on sections with average effective speed greater than 55 m.p.h.:

$$\begin{aligned} COPCST_{vt} = {} & CFC \times COSTF_{vt}/FEAF_{vt} \\ & + 0.01 \times CTW \times COSTT_{vt}/TWAF_{vt} \\ & + 0.01 \times CMR \times COSTMR_{ct}/MRAF_{vt} \end{aligned} \qquad \textit{Eq. 7.4}$$

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[34] *Ibid.*, Appendix A, Tables A.73-A.80.

where:

$COPCST_{vt}$ = excess operating cost due to curves for vehicle class *vt*;
CFC = excess fuel consumption rate due to curves (gallons / 1000 miles);
CTW = excess tire wear rate due to curves (% worn / 1000 miles);
CMR = excess maintenance and repair rate due to curves (% of average cost / 1000 miles);
$COSTF_{vt}$ = unit cost of fuel for vehicle type *vt*;
$COSTT_{vt}$ = unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$ = unit cost of maintenance and repair for vehicle type *vt*;
$FEAF_{vt}$ = fuel efficiency adjustment factor for vehicle type *vt*;
$TWAF_{vt}$ = tire wear adjustment factor for vehicle type *vt*; and
$MRAF_{vt}$ = maintenance and repair adjustment factor for vehicle type *vt*.

The equations used to produce *CFC*, *CTW*, and *CMR* are shown in Exhibits E-16 through E-22 of Appendix E.

7.1.2.5 Total Operating Costs

The HERS operating cost process is implemented as two nested loops. The outer loop propels the model through each vehicle type in turn. The inner loop is executed twice, once in each direction for each vehicle type. The calculation of the three categories of operating costs is performed within this inner loop. When operating costs in both directions for all vehicle types have been calculated, the model weights the costs using the procedures in paragraph 6.4, ”The Fleet Composition Model,” to arrive at the total operating cost per vehicle mile over the section.

7.1.3 Safety Costs

The HERS safety analysis is a three-step procedure:

1. Estimate numbers of crashes using separate procedures for each of six facility types;
2. Apply functional-class-specific injury / crash ratios and fatality / crash ratios to estimate numbers of injuries and fatalities; and
3. Multiply by appropriate cost parameters to produce estimates of the total cost of crashes.

The procedures for estimating the number of crashes are described and documented in the next paragraph. The subsequent paragraph, 7.1.3.2, ”Fatalities and Injuries,” presents the injury / crash ratios and fatality / crash ratios. Paragraph 7.1.3.3, ”Secular Trends,” develops estimates, for use by HERS, of the extent to which recent secular declines in crash rates, fatality / crash ratios, and injury / crash ratios are due to factors not analyzed by HERS. In paragraph 7.1.3.4, ”Costs of Crashes,” data from a recent report by the National Highway Traffic Safety Administration (NHTSA) is used to update HERS’ estimates of costs per injury and property damage costs per crash, as well as to provide estimates of the cost of travel-time delay per crash.

7.1.3.1 Crash Rates

HERS estimates the numbers of crashes and crash rates using separate procedures for three types of rural facility and three types of urban facility. The facility types distinguished are:

- freeways (by design);
- multi-lane roads and streets; and
- two-lane roads and streets.

The freeway procedures are used for all divided roads[35] with four or more lanes and full access control, and also for all one-way roads with two or more lanes and full access control. These procedures are used for these roads regardless of functional system. For all other facilities with four or more lanes and all other one-way facilities with two or three lanes, the “multi-lane” procedures are used, again regardless of functional system. Finally, the “two-lane” procedures are used for all two-way facilities with fewer than four lanes and for all one-lane facilities.

Five of the procedures are slightly modified versions of procedures recommended by Richard Margiotta based on an extensive review of the literature.[36] The sixth procedure is derived from the results of an analysis by Vogt and Bared[37] that was performed after the completion of Margiotta’s work.

All procedures were modified to produce estimates of crash rates per 100 million vehicle-miles of travel (VMT) and calibrated to crash-rate data for 1995. The six procedures (after calibration) are described in paragraphs 7.1.3.1.1 through 7.1.3.1.6, and the calibration is described in paragraph 7.1.3.1.7.

7.1.3.1.1 Rural Two-Lane Roads

The procedure for estimating crashes on rural two-lane roads develops separate estimates of crashes within 250 feet of an intersection and crashes on segments between intersections. Both sets of estimates are developed using equations based on those developed by Vogt and Bared.[38] These estimates are then combined:

$$CRASH = 1.056 \times (CNINT + CINT) \qquad \textit{Eq. 7.5}$$

where

$CRASH$ = total number of crashes on the section per 100 million VMT;
$CNINT$ = non-intersection crashes per 100 million VMT;
$CINT$ = crashes occurring within 250 feet of an intersection, per 100 million VMT on the section;

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[35] For the purpose of the safety analysis, a divided road has a positive barrier median or a median width of at least four feet. This definition is slightly narrower than the HPMS definition of a divided (FHWA, *Highway Performance Monitoring System Field Manual*, Appendix I, pp. I-1 and I-8, January 1998). The HPMS definition, which is used by the HERS capacity procedures, also classifies roads with curbed medians of any width as being divided. Because narrow curbed medians provide relatively limited protection from median crossing, our safety procedure treats roads with curbed medians and median widths of less than four feet as being undivided.

[36] Richard Margiotta, *Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process*, prepared by COMSIS Corporation and Science Applications International Corporation for FHWA, September 1996, Chapter 2.

[37] Andrew Vogt and Joe Bared, “Accident Models for Two-Lane Rural Segments and Intersections,” presented at the TRB Annual Meeting, January 1998.

[38] *Ibid.*

and 1.056 is the calibration factor developed in paragraph 7.1.3.1.7, "Calibration." The procedures for estimating $CNINT$ and $CINT$ are presented below.

7.1.3.1.1.1 Non-intersection Crashes

The equation for estimating non-intersection crashes is based on an equation developed by Vogt and Bared using Highway Safety Information System (HSIS) data for Minnesota and Washington.[39] The HERS equation is:

$$\begin{aligned} CNINT = {} & 100 \times ADJSL/SLEN \qquad \textit{Eq. 7.6} \\ & \times \exp(0.72 - 0.085 \times LW - 0.059 \times SHW + 0.067 \times RHR + 0.0085 \times DD \\ & + 0.44 \times CCGR) \\ & \times \left(\sum_i LCURV_i \times \exp(0.045 \times CURV_i)\right) / SLEN \\ & \times \left(\sum_i LGRD_i \times \exp(0.011 \times GRD_i)\right) / SLEN \end{aligned}$$

where

$SLEN$ = section length (in miles);
$ADJSL$ = section length adjusted to exclude segments within 250 feet of an intersection;
LW = lane width (in feet);
SHW = shoulder width (in feet);
RHR = roadside hazard rating (3.0);
DD = driveway density (per mile) (3.7 for rural type of development, 50 for dense development);
$CURV_i$ = average degrees of curvature in HPMS curve class i;
$LCURV_i$ = total length (in miles) of all curves in curve class i;
GRD_i = average percent grade in HPMS grade class i;
$LGRD_i$ = total length (in miles) of all grades in grade class i; and
$CCGR$ = crest curve grade rate in percent per hundred feet (zero for flat terrain, 0.03 for hilly terrain, and for mountainous terrain).

In Equation 7.6, HERS uses the factor of 100 to convert the estimate of crashes from being expressed per million VMT (as in Vogt and Bared) to being expressed per 100 million VMT in HERS.

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[39] *Ibid.*, p. 6. Vogt and Bared also use the data from Minnesota and Washington separately to develop two additional equations for non-intersection crashes (p. 5).

The ADJSL / SLEN factor adjusts the estimate of non-intersection crashes to reflect only travel that occurs more than 250 feet from an intersection. (The procedure treats crashes occurring within 250 feet of an intersection as intersection crashes.) For this purpose, *ADJSL* is obtained from *SLEN* by subtracting 500 / 5,280 times the number of intersections; if the result is negative, *ADJSL* is set to zero. This adjustment enables the HERS procedure to avoid producing unreasonably high estimates of total crashes for sections with moderate to high numbers of intersections per mile.[40]

Vogt and Bared use a dummy variable, *STATE*, to distinguish between Minnesota and Washington data. In Equation 7.6, *STATE* has been set to 0.5 (effectively weighting data from both states equally), and the term corresponding to *STATE* has been combined with the constant term to produce a modified constant term (0.72).

The value used in Equation 7.6 for the roadside hazard rating (*RHR*) is 3.0, which approximates the average value for all sections used in the Vogt and Bared analysis.

The values used for driveway density (*DD*) are assumed to vary by type of development. For rural development, driveway density should be somewhat below the median for rural types of development, and for dense development it should be appreciably higher. The median values in the data used by Vogt and Bared are 3.73 for Minnesota and 6.12 for Washington; the means are 6.58 and 10.12, respectively; and the maxima are 85.1 and 100, respectively. This data suggests that it is appropriate to set *DD* to 3.7 where development is rural and to set it to 50 where development is dense. When these values are used with 1995 HPMS data, the VMT-weighted average value of DD is 8.29, just slightly below 8.35, the unweighted average of the means for Minnesota and Washington. (The value of 50 for dense development implies an average of 211 feet between driveways.)

The values for crest curve grade rate (*CCGR*) were also based on a judgmental review of Vogt and Bared data. In their data, the median values for this variable were 0.024 in Washington and 0.037 in Minnesota, suggesting that 0.03 is a reasonably typical value for hilly terrain. Similarly, the maximum value was 2.0 in Washington (and 0.89 in Minnesota). Since most crests can be assumed to have *CCGR* values that are appreciably below the maximum, a typical value of 0.4 was assumed for mountainous terrain. Finally, for flat terrain, *CCGR* values are likely to be zero or close to zero; accordingly, a value of zero was used.

Finally, if necessary, the HPMS-coded lengths of curves ($LCURV_i$) are scaled so that their sum equals the coded section length (*SLEN*); and, if necessary, a corresponding adjustment is made to the lengths of the grades ($LGRD_i$).[41]

7.1.3.1.1.2 Intersection Crashes

Vogt and Bared used HSIS data for Minnesota to develop separate equations for estimating crashes at three-legged intersections and crashes at four-legged intersections. The HPMS data-

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[40] Vogt and Bared did not incorporate an *ADJSL/SLEN* adjustment in their analysis. The inclusion of this adjustment in the HERS equation would, by itself, reduce HERS' estimate of total crashes on rural two-lane roads. However, since the HERS estimates are calibrated to 1995 data, the actual effect of the adjustment is to increase the size of the calibration factor (1.056 in Equation 7.5), leaving the estimate of total crashes unchanged but shifting some crashes from sections with high numbers of intersections per mile to sections with lower numbers of intersections per mile.

[41] The adjustments are made in the HERS preprocessor and are applied to all sections for which curves or grades are coded. (Previously, adjustments were made when the total length of curves (or grades) exceeded coded section length but not when they were less than coded section length.)

base does not distinguish between three and four-legged intersections, but it does distinguish between:

1. Intersections with traffic signals;
2. Intersections with stop signs on the sample section; and
3. All other intersections.

To avoid double-counting, HERS assigns all crashes at the second type of intersection to the intersecting road and all crashes at the third type to the sample section. A portion of crashes at intersections with traffic signals are assigned to the sample section using assumptions presented subsequently.

HERS treats all signalized intersections as four-legged intersections. “Other” intersections (i.e., Type 3 intersections) are treated as a mix of three- and four-legged intersections by using a weighted average of the two Vogt and Bared equations. The weights used are 0.55 for three-legged intersections and 0.45 for four-legged intersections.[42] Since all crashes at intersections with stop signs are assigned to the intersecting road, crashes at these intersections are not estimated.

With the above assumptions, estimates of the number of crashes at intersections are obtained from the following equations:

$$CINT = \frac{10^8}{VMT} \times (CSINT + COINT4 + COINT3) \qquad \textit{Eq. 7.7}$$

$$\begin{aligned} CSINT = {} & 0.2 \times NSIG \times FSICAS \\ & \times \exp(-7.74 + 0.64 \times \ln(ADT1) + 0.58 \times \ln(ADT2) \\ & + 0.33 \times CCGR - 0.053 \times ADJIA + 0.11 \times ND) \end{aligned} \qquad \textit{Eq. 7.8}$$

$$\begin{aligned} COINT4 = {} & 0.2 \times 0.45 \times NOINT \\ & \times \exp(-7.74 + 0.64 \times \ln(AADT) + 0.58 \times \ln(ADT2) \\ & + 0.33 \times CCGR - 0.053 \times ADJIA + 0.11 \times ND) \end{aligned} \qquad \textit{Eq. 7.9}$$

$$\begin{aligned} COINT3 = {} & 0.2 \times 0.55 \times NOINT \\ & \times \exp(-11.48 + 0.82 \times \ln(AADT) + 0.51 \times \ln(ADT2) \\ & + 0.26 \times CCGR + 0.036 \times DC + 0.027 \times SPDLIM \\ & + 0.18 \times RHR3LI + 0.24 \times PRTL) \end{aligned} \qquad \textit{Eq. 7.10}$$

where *CINT* and *CCGR*[43] have been defined above and the other variables are:

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[42] The database used by Vogt and Bared contained data for 389 three-legged intersections and 327 four-legged intersections. The weights used were obtained by reducing the latter figure by an estimate of the number of signalized intersections (based on 1995 HPMS data), all of which are treated as four-legged intersections by the HERS procedure.

[43] We considered the possibility that crest curve grade rate and average curvature would have lower values in the vicinity of an intersection than they would have for the section as a whole. However, this hypothesis was not supported by the data in Vogt and Bared.

VMT = vehicle miles traveled on the section in one year;
CSINT = annual crashes at signalized intersections;
COINT4 = annual crashes at "other" four-legged intersections (i.e., intersections with neither signals nor stop signs on the sample section);
COINT3 = annual crashes at "other" three-legged intersections;
NSIG = number of signalized intersections;
FSICAS = *AADT/(ADT1+ADT2)* = fraction of total *AADT* on the inventoried section;
ADT1 = at signalized intersections, *AADT* on the road with the higher traffic volume;
ADT2 = at any intersection, *AADT* on the road with the lower traffic volume;
ADJIA = "adjusted intersection angle" (2.0);
NOINT = number of "other" intersections;
AADT = Annual Average Daily Traffic;
ND = number of driveways within 250 feet of a given intersection = (500 / 5,280) x *DD*;
DC = average degrees of curvature on the section;[44]
SPDLIM = speed limit (mph);
RHR3LI = roadside hazard rating for three-legged intersections (2.1); and
PRTL = probability that a three-legged intersection has a right-turn lane (0.42).

In the case of signalized intersections, *AADT* on intersecting roads is assumed to vary with the functional class of the road section being analyzed. In the case of principal arterials, the intersecting road is assumed to carry less traffic than the section in question, so *ADT1* is set to *AADT* and *ADT2* is assumed equal to one-half *AADT*. In the case of major collectors, the reverse is assumed, so *ADT2* is set to *AADT* and *ADT1* is assumed equal to twice *AADT*. For minor arterials, traffic volumes on both roads are assumed (on average) to be equal, so *ADT1* and *ADT2* are both set to *AADT*.

Crashes at signalized intersections are allocated to the inventoried section and to the intersecting roads in proportion to their relative traffic volumes. Thus, *FSICAS* (fraction of signalized-intersection crashes attributed to the inventoried section) is two-thirds for principal arterials, one-half for minor arterials, and one-third for major collectors.

"Other" intersections are unsignalized intersections which do not have stop signs on the inventoried section. These sections are assumed to have stop signs on the intersecting roads and relatively low volumes on these roads. For these intersections *ADT2* is assumed to be the lesser of 500 and one-half *AADT*. All crashes at these intersections are allocated to the inventoried section (and all crashes at intersections with stop signs on the inventoried section are allocated to the intersecting roads).

If the total number of intersections (signalized, stop sign, and "other") exceeds 20 per mile, the number of each type of intersection is scaled so that the total is reduced to 20 per mile and the scaled-down numbers are used for *NSIG* and *NOINT* in the above equations (and also for deriving *ADJSL* for use in Equation 7.6).

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[44] See preceding footnote.

Vogt and Bared define "adjusted intersection angle" (*ADJIA*) to be $(\alpha - 15)^2/100$, where α is the departure of the intersection angle from 90°, measured in degrees. This variable equals 2.25 when $\alpha = 0°$ or 30°, equals zero when $\alpha = 15°$, is below 2.0 when α is between 1° and 29°, and exceeds 2.25 when $\alpha > 30°$. The Vogt and Bared data for α suggests that 2.0 is a reasonable average value for *ADJIA*.

Vogt and Bared assigned roadside hazard ratings of one to seven for conditions on the main road within 250 feet of an intersection. The average value of these ratings for three-legged intersections, 2.1, has been adopted as the default value for the corresponding variable (*RHR3LI*) in Equation 7.10. Similarly, the default value of 0.42 assumed for the probability that a three-legged intersection has a right-turn lane (*PRTL*) represents the fraction of such intersections with right-turn lanes in the data used by Vogt and Bared.

The factor 0.2 in Equations 7.8 through 7.10 is used to transform the corresponding Vogt and Bared equations, which estimate intersection crashes over a five-year period, into equations that produce estimates of the expected numbers of annual crashes.

7.1.3.1.2 Rural Multilane Roads

The equation for estimating the number of crashes per 100 million vehicle-miles on rural multilane roads is:

$$\begin{aligned} CRASH = {} & 132.2 \times AADT^{0.073} \\ & \times \exp(0.131 \times RHRRML - 0.151 \times AC + 0.034 \times DDRML \\ & + 0.078 \times INTSPM - 0.572 \times RPA + 0.0082 \times (12 - LW) \\ & - 0.094 \times SHLDW - 0.003 \times MEDW + 0.429 \times (DEVEL - 1)) \end{aligned} \qquad \textit{Eq. 7.11}$$

where:

RHRRML = roadside hazard rating for rural multilane roads (2.45);
AC = 1 for sections with (full or partial) access control,
= 0 for other sections;
DDRML = driveway density (per mile) for rural multilane roads (0.41 for rural type of development, 5.6 for dense development);
INTSPM = intersections per mile (maximum =10);
RPA = 1 for rural principal arterials and rural Interstate,
= 0 for lower functional systems;
LW = lane width, in feet (between 8 and 13 feet);
SHLDW = right shoulder width, in feet (maximum = 12 feet);
MEDW = 50 if positive barrier median,
= median width, in feet, otherwise (maximum = 50); and
DEVEL = type of development (1 for rural, 2 for dense).

Equation 7.11 is a modified version of an equation for estimating crashes on rural highways that was fit to Minnesota HSIS data for rural four-lane roads by Wang, Hughes and Stewart.[45] The following modifications were made to the estimated equation:

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[45] Jun Wang, Warren Hughes and Richard Stewart, *Safety Effects of Cross-Section Design of Rural Four-Lane Highways*, FHWA Report FHWA-RD-98-071, May 1998, Equation 6.

- The equation has been divided by 365 times daily VMT and multiplied by 100 million in order to produce estimates of crashes per 100 million vehicle-miles instead of annual crashes.
- The coefficient (132.2) is the product of the coefficient from the original equation (0.0002), the above adjustment factor (273,973), and a calibration coefficient (2.4123, see paragraph 7.1.3.1.7, "Calibration").
- A factor, $(\text{section length})^{0.073}$, has been dropped from the equation since there does not appear to be any reason for crash rates to vary with section length.
- Signalized intersections (which were excluded from the original analysis) have been assumed to have the same influence on crash rates as unsignalized intersections (though this assumption may actually underestimate their influence).
- For want of HPMS data on turn lanes for rural sections, the original equation's distinction between intersections with turn lanes and those without turn lanes has been dropped and the two terms combined.[46]
- The value, 2.45, used for roadside hazard rating (RHRRML) approximates the average value of the ratings used by Wang, Hughes and Stewart.
- Values used for driveway density were obtained by multiplying the corresponding values used for rural two-lane roads by 0.112 (0.112 is the approximate ratio of driveway density on two-lane rural roads in Minnesota used by Bared and Vogt to the driveway density on four-lane roads in Minnesota used by Wang, Hughes and Stewart).
- Lane width (which was found not to be a significant variable in the original analysis[47]) has been assumed to have one-tenth as much influence as it has for rural two-lane roads (cf. Equation 7.6); this assumption appears to be more realistic than assuming that crash rates are totally unaffected by lane width.
- Maximum values of 12 feet for right shoulder width and 50 feet for median width have been assumed, as recommended by Margiotta;[48] increases in shoulder and median widths beyond these values are likely to have appreciably smaller effects on crash rates than would be indicated by the exponential form of Equation 7.11.
- A maximum value of ten has been assumed for INTSPM (intersections per mile). A summary of data used in the original analysis indicates it is unlikely that any of the sections analyzed in deriving Equation 7.11 had more than ten intersections per mile.[49] The equation is relatively sensitive to INTSPM: a value of ten multiplies the result by 2.2; a value of 20 would multiply the result by 4.8.[50]
- A barrier median is assumed to have the same effect on crash rates as a 50-foot median. (Only one of the sections originally studied had a barrier median, so this effect could not be analyzed.)

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[46] The coefficient (0.078) of the combined term was obtained as a weighted average of the original coefficients, using data from Wang, Hughes and Stewart to obtain weights representing the approximate number of intersections with turn lanes per mile (0.22) and the approximate number of intersections without turn lanes per mile (0.74).

[47] The variable actually used by Wang, Hughes and Stewart was width of road surface.

[48] *Op. cit.*, Figure 2.9.

[49] Wang, Hughes and Stewart, *op. cit.*, Table 2.

[50] The current HPMS database has a moderate number of sections with 20 or more intersections per mile.

- The HPMS and HERS variable "type of development" (rural dense or rural rural) is assumed to be a reasonable proxy for the "area location type" variable (rural municipal or rural non-municipal) used in the original analysis, though the match may be imperfect. ("Rural municipal" may include some small urban places that would be coded as "urban" by HPMS and HERS, and it may exclude some small rural developments that would be coded as "rural dense" by HPMS and HERS.)

7.1.3.1.3 Rural Freeways

The equation for estimating the number of crashes per 100 million vehicle-miles on rural freeways is:

$$CRASH = 17.64 \times AADT^{0.155} \times \exp(0.0082 \times (12 - LW)) \qquad \textit{Eq. 7.12}$$

This equation incorporates a lane-width factor into an equation originally developed by Persaud[51] for four-lane freeways and calibrated to HPMS data for all rural freeways. The effect of lane width (*LW*) is assumed to be the same as that assumed for other rural multilane roads. The variables used by this equation have been defined previously.

Persaud's equation actually estimates crashes per mile per year. Equation 7.12 was derived from Persaud's equation by multiplying by section length, dividing by annual VMT (equal to 365×AADT×section length), multiplying by 108, and multiplying by the estimated calibration factor (0.8442).

Persaud also derived a separate equation for rural freeways with more than four lanes. However, for any value of AADT, the equation for freeways with more than four lanes produces appreciably higher crash rates than the equation for freeways with four lanes, implying that crash rates vary inversely with congestion. This result is inconsistent with those of most other analyses.[52, 53]

7.1.3.1.4 Urban Freeways

The equation for estimating the number of crashes per 100 million vehicle-miles on urban freeways is:

$$\begin{aligned} CRASH = {} & (154.0 - 1.203 \times ACR + 0.258 \times ACR^2 - 0.00000524 \times ACR^5) \qquad \textit{Eq. 7.13} \\ & \times \exp(0.0082 \times (12 - LW)) \end{aligned}$$

where ACR = AADT divided by two-way hourly capacity and the other variables have been defined previously. This equation incorporates a lane-width factor into an equation developed

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[51] B. N. Persaud, *Roadway Safety: A Review of the Ontario Experience and of Relevant Work Elsewhere*, prepared for the Ministry of Transportation, Ontario, 1992.

[52] See B. Persaud and L. Dzbik, "Accident Prediction Models for Freeways," *Transportation Research Record* 1401, 1993.

[53] For low values of AADT (less than 24,000), crash rates were also found to be higher on freeways with more than four lanes in FHWA's *Highway User Investment Study* (as reported in *HPMS Analytical Process,* Volume II, Technical Manual, 1987, page IV-41 and Appendix J). However, this result is of little significance since very few freeways with such low values of AADT have more than four lanes. To enable HERS and the AP to avoid assuming that adding lanes to four-lane freeways will increase crashes, Margiotta recommended that only Persaud's equation for four-lane freeways be used.

by Margiotta[54] using results from Tedesco, *et. al.*,[55] and Margiotta and Cohen.[56] The effect of lane width is assumed to be the same as that assumed for rural multilane roads.

7.1.3.1.5 Urban Multilane Surface Streets

The equation for estimating the number of crashes on urban multilane surface streets and on urban expressways lacking full access control is:

$$CRASH = A \times AADT^{B} \times NSIGPM^{C} \qquad \textit{Eq. 7.14}$$

where:

A, B, and C = values from Table 7-5; and
NSIGPM = number of signals per mile.

The value of NSIGPM, the number of signals per mile, has a minimum value of 0.1 and a maximum value of eight. This equation was derived from an equation for estimating annual crashes per mile that was estimated by Margiotta[57] using data from Bowman and Vecellio.[58] The derivation involved multiplying Margiotta's equations by section length, dividing by annual VMT, multiplying by 108, and incorporating calibration factors. The upper and lower limits on the number of signals per mile were recommended by Margiotta.

Table 7-5. Parameters for Crash-Rate Equation for Urban Multilane Surface Streets

Type of Section	A	B	C
Two-Way with Left-Turn Lane	95.1	0.1498	0.4011
One-Way, or Two-Way with a median: 1) wider than 4 feet, or 2) curbed, or 3) a "positive barrier"	82.6	0.1749	0.2515
Otherwise	115.8	0.1749	0.2515

7.1.3.1.6 Urban Two-Lane Streets

For two- and three-lane urban streets, crashes are estimated using the equation:

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[54] Richard Margiotta, *op. cit.*, pp.15-19, 25 and 28.

[55] Shelby A. Tedesco, *et. al.*, "Development of a Safety Model to Assess the Impact of Implementing IVHS User Services," *Proceedings of the IVHS America 1994 Annual Meeting*, April 1994.

[56] Richard Margiotta and Harry Cohen, *Roadway Usage Patterns: Urban Case Studies*, prepared by Science Applications International Corporation and Cambridge Systematics for Volpe National Transportation Systems Center, June 1994.

[57] *Op. cit.*, pp. 19-22, 25 and 29.

[58] Brian L. Bowman and Robert L. Vecellio, "Effect of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety," Transportation Research Record 1445, 1994, pp. 169-179. This source actually provided data only for roads with raised medians, roads with two-way left-turn lanes, and other undivided roads. (Roads with two-way left-turn lanes are considered to be divided roads in the safety literature and are treated as such in this report; however, they are classified as undivided in the HERS and HPMS capacity analyses.)

$$CRASH = -19.6 \times \ln(AADT) + 7.93 \times (\ln(AADT))^2 \qquad \text{Eq. 7.15}$$

This equation was developed by using ordinary least squares regression to fit a function of this form to the data shown in Table 7-6 and multiplying by the calibration factor in Table 7-7. The r^2 for this regression is 0.99.

Table 7-6. Data Used for Estimating Crash Rates for Urban Two-Lane Streets

AADT Range	Mean Value of AADT Within Range[a]	Crashes per 100 Million VMT[b]
< 4,000	1,978	345
4,000 - 7,999	5,739	490
8,000 - 15,999	11,101	590
> 15,999	20,417	660

[a] Weighted average mean value obtained from the 1995 HPMS database for streets to which the "two-lane urban streets" procedure is applied (i.e., all one-lane urban streets and two-way urban streets with two or three lanes).

[b] Crash rates used in original HERS safety procedure.

7.1.3.1.7 Calibration

The crash-rate equations were calibrated in two steps.

In the first step, the equations used by the six procedures presented above were calibrated separately to crash rates for the corresponding highway types. These rates were obtained by Margiotta[59] as a VMT-weighted average of rates developed by Zegeer and Williams[60] using data for four states from the HSIS. The rates used are shown in the first column of Table 7-7, "Crash Rates Used for Calibration."

In the second step, the six calibration factors were scaled uniformly to produce an overall rate of 309.7 crashes per 100 million VMT. This rate was obtained by multiplying an estimate of total crashes in 1995 from the National Highway Traffic Safety Administration's General Estimates System (GES)[61] by an undercapture correction factor of 1.12[62] and dividing by national VMT in that year.[63] [64] The calibration factors produced by this two-step procedure are shown in the

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[59] Margiotta, *op. cit.*, pp. 7-8.

[60] C.V. Zegeer and C. Williams, *Calculation of Accident Rates by Roadway Class for HSIS States*, University of North Carolina Highway Research Center, June 1994. The four states used were Illinois, Maine, Minnesota and Utah. This source contains crash rates for five states. However, rates for the fifth state, Michigan, are appreciably higher than those for the other four states (for rural areas, they are, on average, twice as high). Accordingly, Michigan data were excluded from our calibration.

[61] National Highway Traffic Safety Administration, *Traffic Safety Facts - 1996*, Table 1.

[62] Lawrence J. Blincoe and Barbara M. Faigin, *The Economic Cost of Motor Vehicle Crashes, 1990*, NHTSA, Report DOT HS 807 876, 1992, as quoted in Ted R. Miller, Diane C. Lestina and Rebecca S. Spicer, "Highway Crash Costs in the United States by Driver, Age, Blood Alcohol Level, Victim Age, and Restraint Use," *Accident Analysis and Prevention*, Vol. 30, No. 2, 1998.

[63] FHWA, Highway Statistics - 1995, Table VM-1.

Table 7-7. Crash Rates Used for Calibration[a]

Facility	Crashes per 100 million VMT	Calibration Factor
Rural		
Freeway	68.0	0.8842
Multilane	146.6	2.4123
Two Lane	163.8	1.0557
Urban		
Freeway	131.0	1.1453
Multilane		
Divided	439.1	
Median		0.9367
Two-Way Left-Turn Lane		0.7494
Undivided	554.8	1.3131
Two-Lane	378.7	0.8743

[a] Derived from rates developed using Highway Safety Information System data for Illinois, Maine, Minnesota and Utah. Separate rates were developed for each state by C.V. Zegeer and C. Williams (*Calculation of Accident Rates by Roadway Class for HSIS Status*, University of North Carolina Highway Research Center, June 1994). The above rates are VMT-weighted averages of these rates developed (using 1994 HPMS data) by Richard Margiotta (*Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process*, prepared by COMSIS Corporation and Science Applications International Corporation for FHWA, September 1996, Table 2.3).

right column of Table 7-7, "Crash Rates Used for Calibration." These factors are included in Equations 7.5 through 7.15 as presented in paragraphs 7.1.3.1.1 through 7.1.3.1.6.

The calibration factor for urban two-lane streets results from the replacement of the step function previously used by a continuous function and from a decline in crash rates between 1988 and 1995. (The step function was last calibrated using 1988 data.) The calibration factors for urban multilane streets incorporate separate calibration factors developed by Margiotta[65] for the three types of multilane streets distinguished.

The other calibration factors generally represent differences, that are not explained by any of the independent variables, between the crash rates observed in the data used in developing the orig-

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[64] No adjustment was made for differences in overall crash rates between the nine functional systems covered by HPMS sample-section data and the three systems (rural minor arterials and the two local systems) that are not covered. To the extent that crash rates on the latter systems may be lower than average, our calibration procedure may result in a slight upward bias in the HERS estimates of crashes on the nine systems covered by HERS. Since the other three systems account for only 15 percent of national VMT, the effect of this bias should be fairly small.

[65] *Op. cit.*, pp. 25 and 29.

inal equations and the HSIS and national crash rates used in the calibration process. The high calibration factor for rural multilane roads is due to very low average crash rates in the HSIS data used by Wang, Hughes and Stewart in their analysis of crash rates on rural multilane roads. The factor for rural two-lane roads incorporates an upward adjustment to counter the effect of the ADJSL / SLEN factor that we added to Equation 7.6 (see 7.1.3.1.1.1, "Non-intersection Crashes").

7.1.3.2 Fatalities and Injuries

The HERS safety procedure estimates fatalities and nonfatal injuries as being directly proportional to the number of crashes, with separate ratios used for each functional system. The ratios were obtained by:

- taking estimates of fatality and crash rates per 100 million vehicle-miles by functional system for 1995;[66] and
- dividing by corresponding estimates of the number of crashes per 100 million vehicle-miles by functional system produced by the new HERS procedure for estimating numbers of crashes described in the preceding chapter.[67]

The resulting ratios are shown in Table 7-8, "Fatality and Injury Rates."

Table 7-8. Fatality and Injury Rates

Functional System	Fatalities per Crash	Injuries per Crash
Rural		
Interstate	0.01408	0.4546
Other Principal Arterial	0.01685	0.6317
Minor Arterial	0.01362	0.5610
Major Collector	0.01370	0.6261
Urban		
Interstate	0.00382	0.4908
Other Freeway or Expressway	0.00396	0.3640
Other Principal Arterial	0.00273	0.4113
Minor Arterial	0.00237	0.3401
Collector	0.00257	0.3496

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[66] FHWA, *Highway Statistics, 1995,* Table FI-1.

[67] An alternate approach for obtaining ratios by highway type (instead of by functional system) was also investigated. This approach used a calibration process that was more complicated than the one finally adopted, along with HSIS data on numbers of crashes, fatalities and injuries by highway type in six states, and corresponding estimates of 1995 VMT obtained from HPMS sample-section data. However, the HSIS estimates of the numbers of crashes on rural multilane roads (and, in particular, undivided rural multilane roads) in these states were found to be inconsistent with the corresponding HPMS estimates of VMT in these states, making it impractical to calibrate the equations appropriately.

7.1.3.3 Secular Trends

Over time, the rates of injuries and fatalities in highway crashes have shown steady declines. In the past twenty years, fatalities per 100 million vehicle-miles have declined at an average annual rate of about four percent, and nonfatal injuries have declined at an average rate of about 2.25 percent.[68] Although highway improvements have contributed to this decline, several other factors have been major contributors. These include improvements in: vehicle designs; emergency medical care; and driver behavior (including reductions in drunk driving).

In order to allow HERS to incorporate the effects of these secular trends into its forecasts of crashes and crash costs, the safety model allows the user to specify annual percentage declines in:

- the rate of crashes per 100 million vehicle-miles;
- the ratio of injuries to crashes; and
- the ratio of fatalities to crashes.

Estimates of annual crashes for 1988 and subsequent years are available from NHTSA's General Estimates System (GES).[69] These values, when combined with FHWA's estimates of annual fatalities and nonfatal injuries,[70] indicate that, over the 1988-1995 period, the average annual rates of decline have been 1.0 percent for the ratio of (nonfatal) injuries to crashes and 1.3 percent for the ratio of fatalities to crashes, and the rates of decline since 1990 have been appreciably higher. Since the ratios developed in paragraph 7.1.3.2 are for 1995, the decline in these ratios is assumed to begin in 1996. The year of the data used for calibrating the fatality and injury ratios (currently 1995) is provided to HERS as a parameter and should be changed by the user whenever these ratios are changed.

Obtaining a forecast rate of decline to be applied to crash rates presents a somewhat greater problem. Combining the GES estimates of annual crashes since 1988 with FHWA estimates of annual VMT[71] produces estimates of crashes per 100 million vehicle-miles that drop from 340 in 1988 to 266 in 1993, rise more slowly to 277 in 1995, and decline very slightly to 276 in 1996. The average annual rate of decline between 1988 and 1995 (the time period used for estimating the decline rates for the fatality and injury ratios) is 2.6 percent, but a focus on more recent data would produce an appreciably lower annual rate of decline (and an *increase* if only data since 1993 is used[72]).

As the above discussion implies, data for the last few years suggests that there may be some weakening in the long-term trends toward reductions in crash, fatality and injury rates. It is not yet clear whether this weakening represents a temporary or permanent change in the secular

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[68] Derived from FHWA, *Highway Statistics Summary to 1995*, July 1997, Tables FI-210 and FI-220.

[69] National Highway Traffic Safety Administration, *Traffic Safety Facts – 1996*, Table 1.

[70] FHWA, *op. cit.* Estimates of 1996 fatalities and injuries (from Highway Statistics, Table FI-1) were excluded from this analysis because of inconsistencies between the FI-1 data and the FI-210 and FI-220 data. The latter data is currently being revised.

[71] *Ibid.*, Table FI-200; and FHWA, *Highway Statistics, 1996, Table VM-1.*

[72] In another test, the new HERS crash-estimation procedures were applied without a temporal adjustment to 1993 and 1996 HPMS data for 42 states. The procedures indicate a 0.6 percent increase in crash rates over this three-year period, apparently because of increased congestion. (All six procedures produce estimated crash rates that vary with AADT or AADT per lane.) However, the increase produced by the HERS procedures is appreciably lower than the 3.7 percent increase indicated for this three-year period by the GES and FHWA data.

rates of decline in the crash, fatality and injury rates. In preparing data for the 1999 Conditions and Performance Report, the rate of decline was set to zero (no decline).

7.1.3.4 Costs of Crashes

The HERS safety model estimates crash costs as the sum of the value of lives lost and the costs of injuries, property damage, and delay to other highway users. The value of lives lost is estimated by multiplying fatalities by the U.S. Department of Transportation's estimate of the value of life (currently $2.7 million). Unit costs for estimating the three other components of crash costs have been derived in large part from information contained in a recent National Highway Traffic Safety Administration (NHTSA) study of crash costs in 1994.[73]

7.1.3.4.1 Unit Costs of Crashes in 1994

HERS' estimates of injury costs are derived from estimates of comprehensive costs per injury developed by Ted Miller in 1991[74] and updated to 1994 dollars by NHTSA.[75] These estimates, which are based on the willingness-to-pay concept used by HERS, are provided by the Maximum Abbreviated Injury Scale (MAIS).[76] They range from $10,840 for MAIS Level 1 to $2,509,310 for MAIS Level 5 (and $2,854,500 for fatal injuries). Weighting the estimates for non-fatal injuries by the relative frequency of injuries of each severity[77] produces an overall estimate of $47,657 per police-reported injury.

Corresponding estimates of property-damage costs per crash and travel-delay costs per crash were obtained by dividing the NHTSA estimates of total 1994 costs of these two types[78] by an estimate of crashes in 1994 that is consistent with the 1995 estimate used to calibrate the HERS crash-estimation procedures.[79] This step produced overall costs-per-crash estimates of $7,164 for property damage and $605 for travel delay.

The next series of steps in the development of unit cost factors for use by the HERS safety model involved using the above overall estimates of unit costs for injuries and property damage to develop estimates by functional system. This was accomplished by:

1. Using the new HERS procedures and 1994 HPMS data to estimate crashes, injuries and fatalities by functional system in 1994;

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[73] Lawrence J. Blincoe, *The Economic Cost of Motor Vehicle Crashes, 1994,* NHTSA, 1996.

[74] Ted R. Miller, *et. al.*, *The Costs of Highway Crashes,* The Urban Institute, 1991.

[75] Blincoe, *op. cit.*, Table A-1. These estimates of comprehensive costs, based on willingness to pay, are, on average, roughly three times the NHTSA estimates of economic or "human capital" costs summarized in Table 1 of the Blincoe report.

[76] An alternative to using costs by MAIS is the use of costs by police-reported "KABCO" code (killed; A, B or C injury; property damage only). Estimates of comprehensive costs by KABCO code are available in Ted R. Miller, Diane C. Lestia, and Rebecca S. Spicer, "Highway Crash Costs in the United States by Driver Age, Blood Alcohol Level, Victim Age, and Restraint Use," *Accident Analysis and Prevention*, Vol. 30, No. 2, 1998. However, these estimates probably should not be used with crash data from small numbers of states, since the source observes that KABCO coding varies appreciably across states.

[77] Blincoe, *op. cit.*, Table 3.

[78] *Ibid.*, Table 1.

[79] The resulting estimate of 1994 crashes, 7.28 million, was obtained by applying an undercapture correction factor of 1.12 (see paragraph 7.1.3.1.7) to the NHTSA GES estimate of crashes in 1994.

2. Using unindexed values of HERS' original 1988 estimates of unit costs of injuries and property damage by functional system to obtain national estimates of unit costs implied by the original unit costs; and
3. Dividing the new estimates (in 1994 dollars) by those produced using 1988 unit costs.

This last step produced scale factors of 3.1062 for injury costs and 1.2532 for property damage costs. These scale factors were then applied to the 1988 HERS estimates of unit costs by functional system to produce a revised set of unit costs for injuries and property damage. The revised unit costs are shown in Table 7-9.

Table 7-9. Injury and Property-Damage Costs

Functional System	Injury Cost per Injury (1994 dollars)	Property-Damage Costs per Crash (1994 dollars)
Rural		
Interstate	$ 52,800	$ 5,000
Other Principal Arterial	68,300	6,300
Minor Arterial	55,900	6,300
Major Collector	77,650	6,300
Urban		
Interstate	55,900	6,300
Other Freeway or Expressway	46,600	7,500
Other Principal Arterial	49,700	7,500
Minor Arterial	40,400	7,500
Collector	31,100	6,300

Delay costs vary with AADT per lane. HERS uses the equation:

$$DELCC = \frac{0.0886 \times AADT}{LANES} \times CRASH \qquad \text{Eq. 7.16}$$

where

DELCC = cost of delay due to crashes (per 100 million VMT);
CRASH = crash rate on the section (per 100 million VMT); and
LANES = number of lanes.

The coefficient (0.0886) was set so that, when applied to 1994 data, HERS would produce an overall average cost of delay that matches the above estimate of $605 per crash.

The assumption that the delay cost of crashes is linear with a simple measure of traffic volume (AADT per lane) undoubtedly understates the complexity of this relationship. Hence, this simple procedure is likely to underestimate the delay cost of crashes on congested roads and to overestimate this cost on uncongested roads.

The estimate of the delay cost of crashes is included in HERS' estimates of crash costs and not in its estimates of travel-time costs. Similarly, HERS' estimates of average speed excludes the small effect (less than 0.2 mph) of delay due to crashes. HERS' estimate of the delay cost of crashes in 1994 is $1.96 per 1,000 vehicle-miles – about 1.5 percent of total estimated crash costs and less than 0.5 percent of estimated travel time costs.

7.1.3.4.2 Indexing the Costs of Crashes

HERS allows the costs of property damage, delay and injuries to be indexed from 1994 dollars to dollars of a subsequent year using separate, user-supplied index values. For property-damage costs, an appropriate index to use is the Consumer Price Index (CPI) component for automobile body work.[80] Using 1994 as a base year, the 1997 value of this index is 1.126, so property-damage costs per crash in 1997 are estimated as being 12.6 percent higher than in 1994.

For travel delay, the index used should be the same one as is used for the value of time, but the base year for the travel delay index would be 1994 (instead of 1995, the year currently used for value of time). The index currently being used for this purpose is the U.S. Bureau of Labor Statistics (BLS) Employment Cost Index (which reflects total compensation of all civilian workers).[81] Using 1994 as a base year, the 1997 value of this index is 1.089.

Injury costs have previously been indexed by HERS using the CPI component for medical care. However, since the HERS estimates of the comprehensive costs of injuries are based on willingness to pay, rather than on economic costs (which include medical costs), the cost of medical care may not be the most appropriate basis for indexing injury costs. A measure of perceived wealth or earnings ability is probably a better indicator of changes in willingness to pay. For simplicity, HERS uses the BLS Employment Cost Index for this purpose (as well as for indexing the cost of delay); therefore the 1997 value of this index is also 1.089.

7.2 Agency Costs and Benefits

For agencies in charge of building and maintaining highways, HERS recognizes two potentially accruing benefits resulting from improving a highway section:

- a reduction in the cost of routine maintenance resulting from resurfacing or reconstruction of pavement; and
- a reduction in the cost of the next improvement resulting from the improved condition of the section when that improvement is implemented.

The second type of benefit is referred to as the "residual value" of the improvement. The estimation of residual value is discussed at some length in conjunction with the presentation of the HERS benefit-cost analysis procedure under paragraph 4.6, "Residual Value." The HERS proce-

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[80] U.S. Bureau of Labor Statistics, Consumer Price Index – All Urban Consumers, Series ID CUUR0000SETD01, Motor Vehicle Body Work, http://stats.bls.gov/sahome.html (U.S. city average, not seasonally adjusted).

[81] U.S. Bureau of Labor Statistics, Employment Cost Index, Series ID: ECS10001I, Total Compensation of All Civilian Workers, http://stats.bls.gov/sahome.html (seasonally adjusted).

dure for estimating the other type of agency benefit, reductions in maintenance costs, is presented below. These benefits take their place in the numerator of the benefit-cost equation.

In HERS, all improvements are analyzed over a benefit-cost analysis (BCA) period that begins at the midpoint of one funding period and ends at the midpoint of some subsequent funding period. To simplify the analysis of maintenance expenditures, a "maintenance cost (MC) period" is defined as a period beginning at the midpoint of a funding period and ending at the midpoint of the next funding period. Estimates of pavement maintenance expenditures over each MC period are then derived from PSR estimates for the beginning and end of each period.

7.2.1 Maintenance Costs for Flexible Pavements

Estimates of maintenance costs per lane-mile for flexible pavements have been developed by Witczak and Rada[82] as a function of PSR and structural number (SN). Their results are presented in Table 7-10, "Maintenance Costs for Flexible Pavements." The middle column of this table presents estimates of maintenance costs (in 1984 dollars) incurred per lane-mile during periods when PSR (PSI in the exhibit) drops from 4.5 to 4.0, from 4.0 to 3.5, etc. The last column shows estimates of cumulative maintenance costs per lane-mile for a section that starts with a PSR of 4.5 and has various indicated terminal PSRs ranging from 4.0 to 1.5. These estimates are independent of the time required for the deterioration to occur.

Regressing the values for cumulative maintenance costs shown in Table 7-10 against the values for PSR (or PSI) and SN yields the following equation:

$$\begin{aligned} COST = {} & 4427.24 - 1989.7 \times PSR + 223.57 \times PSR^2 + 7996.11 \times SN \\ & - 3594.56 \times SN \times PSR + 403.99 \times SN \times PSR^2 \end{aligned} \qquad \textit{Eq. 7.17}$$

where:

PSR = terminal PSR;
SN = structural number; and
$COST$ = where cost is cumulative maintenance cost per lane-mile, in 1984 dollars, for the time over which the pavement is deteriorating from an initial PSR of 4.5 to the terminal PSR.

The R^2 for the above equation exceeds 0.9999.

Equation 7.17 can be modified to produce cost estimates in 1988 dollars by multiplying all coefficients by 1.2118, the ratio of the 1988 and 1984 values of FHWA's Cost Index for Highway Maintenance and Operation.[83]

To estimate maintenance costs per lane-mile on any section during a period beginning at time *i* and ending at time *f*, Equation 7.17 is evaluated using the section's PSR at times *i* and *f*, and the

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[82] Matthew W. Witczak and Gonzalo R. Rada, *Microcomputer Solution of the Project Level PMS Life Cycle Cost Model*, University of Maryland, Department of Civil Engineering, prepared for Maryland Department of Transportation, State Highway Administration, Baltimore, Md., December 1984, Chapter 4.

[83] U.S. Department of Transportation, Federal Highway Administration, *Highway Statistics: 1988*, U.S. Government Printing Office, Washington, D.C., 1989, Table PT-5.

Table 7-10. Maintenance Costs for Flexible Pavements[a]
(1984 Dollars)

Final PSI	Maintenance Cost Between PSI Levels ($/lane mile)	Cumulative Cost ($/lane mile)
Low SN / traffic: (SN = 2.16)		
4.0	221.57	221.57
3.5	767.03	988.60
3.0	1314.95	2302.55
2.5	1859.47	4163.02
2.0	2413.74	6576.76
1.5	2957.34	9534.10
Medium SN / traffic: (SN = 3.60)		
4.0	339.10	339.10
3.5	1174.05	1513.15
3.0	2012.72	3525.87
2.5	2845.76	6371.63
2.0	3604.98	10066.61
1.5	4526.45	14593.06
High SN / traffic: (SN = 5.04)		
4.0	456.63	456.63
3.5	1581.05	2037.38
3.0	2710.50	4748.18
2.5	3832.04	8580.22
2.0	4976.21	13556.43
1.5	6095.55	19651.98

[a] Source: Matthew W. Witczak and Gonzalo R. Rada, *Microcomputer Solution of the Project Level PMS Life Cycle Cost Model*, University of Maryland, Department of Civil Engineering, prepared for Maryland Department of Transportation, State Highway Administration, Baltimore, MD., December 1984, p. 132

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difference between the two results is obtained. The general form of the HERS equation to provide this result, MCOST, in 1988 dollars, is:

$$MCOST = -(2411 + 4355 \times SN) \times (PSR_f - PSR_i) + (270.9 + 489.6 \times SN) \times (PSR_f^2 - PSR_i^2) \quad \text{Eq. 7.18}$$

This equation (Equation 7.18) would produce negative values of $MCOST$ whenever $PSR_i > PSR_f \geq 4.5$. To avoid this undesirable effect, 4.5 is substituted for any PSR values above 4.5. The resulting costs can be adjusted to dollars of another year. To index the 1988 dollars to 1997 dollars for use in the 1999 *Conditions and Performance Report*, a factor of 1.231 was used for rural sections and 1.242 for urban sections.

7.2.2 Maintenance Costs for Rigid Pavements

In the absence of readily available information about maintenance costs for rigid pavements, HERS assumes these costs are identical to those for flexible pavements with a structural number (SN) of 5.625. This is the SN of flexible pavements with a thickness of 5.5 inches, the thickest flexible pavement considered by HERS.

7.3 External Costs

The HERS model includes estimates of the costs of damages from vehicular emissions of air pollutants in its calculation of benefits and disbenefits resulting from the implementation of an improvement. HERS uses the following equation to calculate the average cost of air pollutant emissions generated per vehicle mile:

$$EmCost = EC + EF_1 \times AES + EF_2 \times AES^2 + EF_3 \times AES^3 + EF_4 \times AES^4 + EF_5 \times AES^5 + EF_6 \times AES^6 \quad \text{Eq. 7.19}$$

where:

EmCost = Emission cost per vehicle mile;
EC = Emission constant value;
EF_n = Emission factor *n*, where *n* is 1 through 6; and
AES = Average effective speed.

The selection of the emission constant *EC* and the emission factors EF_n depends upon

- the functional class;
- the year for which emission values are being calculated; and
- whether the “high” or “medium” estimate of damage from emissions has been selected by the user.

Urban minor arterials and urban collectors share the same set of emission constant and emission factor values: otherwise, each functional class has a unique set of emission constant and emission factor values. Differences in these values reflect differences in the mix of vehicle types that typically use each functional class, differences in the rates at which specific types of vehicles emit various air pollutants, and differences in the density of development typically found along facilities of different functional classes. The emission constant and emission factor values for each functional class change during each successive five-year period, reflecting projected reductions in the rates at which all types of vehicles emit air pollutants and changes in the composition of the U.S. vehicle fleet. These periods are:

- pre - 2000
- 2001 - 2005
- 2006 - 2010
- 2011 - 2015
- 2016 and beyond

A more complete discussion of the derivation of the emission factor values is contained in Appendix F, ”Detailed Description of Procedures for Incorporating Air Pollution Costs in HERS.” The constant and factor values used for each roadway functional class and five-year period are presented in Appendix G, ”Factors For Emissions Equations.”

7.4 Capital Cost of Improvements

HERS requires estimates of highway improvement costs to be included in the analysis of investment options. In the case of the pavement, widening and alignment improvements currently considered by HERS, these costs are all initial costs; i.e., they are incurred at the time the improvement is implemented. When analyzing the economic attractiveness of a potential improvement, the improvement cost is used as the denominator in the benefit-cost equation.

This paragraph contains three parts. The first presents the initial costs of pavement and widening improvements used by HERS.

The second part presents the HERS procedure for estimating the initial cost of alignment improvements. This cost is estimated for those portions of a section that must be reconstructed on a modified alignment in order to bring the section's alignment up to design standards. The cost is sensitive to the extensiveness of the required alignment improvement as well as to the physical characteristics of the section. This cost is added to the cost of pavement and widening improvements to obtain the full initial cost of any improvement that includes alignment improvements.

The final part of this paragraph presents the procedure used to estimate the improvement costs of correcting substandard conditions on urban freeways.

All figures for improvement costs presented in this chapter are expressed in 1997 dollars.[84] Users wishing output expressed in another year dollars can adjust these costs individually or all costs can be adjusted uniformly using a cost index. FHWA's Composite Bid Price Index for Fed-

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[84] For the 1999 *C&P Report*, costs for improvements on existing alignments were entered in 1995 dollars and indexed to 1997 dollars using factors of 1.09 (rural) and 1.068 (urban). Alignment-related costs and the costs of upgrading substandard urban freeways were entered in 1988 dollars and converted to 1997 dollars using factors of 1.231 (rural alignment), 1.496 (urban alignment), and 1.242 (substandard freeways).

eral-Aid Highway Construction[85] may be used as the basis for adjusting improvement costs to dollars of another year.

7.4.1 Pavement and Widening Improvements

HERS distinguishes seven kinds of pavement and widening improvements (described in Exhibit 3-1, "Kinds of Improvement"). In HERS, the costs of pavement and widening improvements are derived from the costs computed for the HPMS Analytical Process. The HERS costs include both improvement and right-of-way (ROW) costs, but do not include costs such as unusual cut and fill operations, excessive number of structures, or non-construction costs.

The scaled estimates of cost per lane-mile (for construction and ROW, combined) used by HERS are shown in Table 7-11, "Capital Improvement Costs." These costs are expressed in 1997 dollars but can be scaled to any other-year dollars by the user.[86]

HERS also distinguishes between the costs associated with adding lanes when conventional widening is feasible (normal cost lanes), and when more expensive methods will be required (high cost lanes). The 1997 costs used in HERS to develop the 1999 *C&P Report* only distinguished between normal cost lanes and high cost lanes on urban sections. (The output statistics report rural high cost lanes, but they are priced at the same rate as normal cost lanes.) It should be noted that HERS uses a single estimate of improvement costs per lane-mile, rather than separate estimates for construction and ROW costs.

HERS uses five methods to compute the cost of pavement and widening improvements. The method used depends upon the type of improvement being implemented. The calculations are presented in Table 7-12.

Note that for some sections, the initial widening feasibility code allows adding lanes at both high and normal cost at the same time. The normal cost used is the one which would be used if no high cost lanes were included in the improvement.

The length of the improvement is included in the equations shown in Table 7-12 rather than the length of the section, since when a portion of a section receives an alignment improvement, those costs are calculated separately and added to the costs for the portion of the section improved on the existing alignment.

7.4.2 Alignment Improvements

In HERS, any of the pavement and widening improvements listed in Table 7-11 can be combined with alignment improvements. The initial cost of any such improvement is obtained by developing separate cost estimates for the portion of the section that would be reconstructed on a modified alignment and the portion (if any) that would continue to follow the existing alignment.

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[85] Office of Infrastructure, Office of Program Administration, *Price Trends for Federal-Aid Highway Construction,* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., quarterly.

[86] Costs shown are derived from the improvement cost file (IMPRCOST.DAT) used in preparation of the 1999 *Conditions and Performance Report* (which reports on the 1997 highway system). In this file, these improvement costs are entered in 1995 dollars: here, they have been indexed to 1997 dollars.

Table 7-11. Capital Improvement Costs

(Thousands of 1997 Dollars per Lane-Mile)

	Reconstruct & Add High Cost Lanes	Reconstruct & Add Normal Cost Lanes	Reconstruct & Widen Lanes	Reconstruct	Major Widening at High Cost	Major Widening at Normal Cost	Minor Widening	Resurface & Improve Shoulders	Resurface
Rural Interstate									
Flat terrain	558	558	629	524	351	351	284	195	110
Rolling terrain	653	653	694	540	374	374	305	206	106
Mountainous terrain	752	752	920	766	493	493	419	252	136
Rural Other Principal Arterial									
Flat terrain	704	704	536	458	360	360	278	135	69
Rolling terrain	728	728	603	518	402	402	306	147	69
Mountainous terrain	1036	1036	790	647	750	750	436	201	101
Rural Minor Arterial									
Flat terrain	611	611	413	326	355	355	231	136	58
Rolling terrain	665	665	520	444	491	491	242	138	62
Mountainous terrain	899	899	811	582	623	623	320	172	97
Rural Major Collector									
Flat terrain	538	538	471	334	338	338	186	95	33
Rolling terrain	590	590	571	413	336	336	196	104	38
Mountainous terrain	789	789	730	569	574	574	261	133	48
Urban Sections									
Freeways/Expressways	8256	3550	2604	1595	8380	3674	1546	462	215
Other Divided	4910	1961	1603	909	5250	2302	852	316	144
Other Undivided	3468	1268	1394	831	3917	1717	902	276	163

Total improvement costs for the section are obtained as the sum of the two separate cost estimates.

The procedures for determining the alignment modifications to be made, estimating the cost of these modifications, and combining this cost with the improvement cost for the remainder of the section are presented below. The development of these procedures is presented in a separate report prepared by Cambridge Systematics[87].

Table 7-12. Improvement Cost Calculations

Improvement Type	Cost Calculation
Reconstruct & Add High Cost Lanes *and* Major Widening at High Cost on rural sections	$COST = ((LANES_{exist} + LANES_{norm}) \times COST_{norm} + LANES_{high} \times COST_{high}) \times IMPLEN$
Major Widening at High Cost on urban sections	$COST_{tot} = (LANES_{norm} \times COST_{norm} + LANES_{high} \times COST_{high}) \times IMPLEN$
Major Widening at Normal Cost on urban sections	$COST_{tot} = LANES_{norm} \times COST_{norm} \times IMPLEN$
Reconstruct & Add Normal Cost Lanes	$COST = (LANES_{exist} + LANES_{norm}) \times COST_{norm} \times IMPLEN$
All Other Improvement Types	$COST_{tot} = LANES_{exist} \times COST_{norm} \times IMPLEN$
where: $LANES_{exist}$ = the number of lanes before improvement; $LANES_{norm}$ = the number of lanes being added at normal cost; $LANES_{high}$ = the number of lanes being added at high cost; $COST_{high}$ = the cost of adding a lane at high cost; $COST_{norm}$ = the cost of the improvement when no high cost lanes are being added; $COST_{tot}$ = the total cost of the improvement; $IMPLEN$ = the length of the improvement.	

7.4.2.1 Modifying Section Alignment

In HERS, an alignment improvement generally results in improving all of a section's substandard curves and grades to the design standard (as specified in Table 3-11, "Default Design Standards For Curves and Grades"). The exception to this statement occurs during the first loop of a funding period when HERS considers only the least expensive improvement necessary to correct any unacceptable conditions. During this loop, if curves or grades are unacceptable, but not both, HERS selects an improvement that improves only curves or only grades to the design standard (and, if sufficient funds are available, a more aggressive improvement that improves both curves and grades to design standards is considered during the second loop).

For any section, improvement of substandard grades is presumed to result in replacing all segments whose grade is substandard by segments with grades that just meet the design standard for the section. The total length of these segments before improvement is denoted LVERT, and the corresponding length after improvement is denoted LAFTV. In HERS, LAFTV is taken to be equal to LVERT.

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[87] Cambridge Systematics, Inc., *FHWA Highway Economic Requirements System: Alignment Improvement Costs*, prepared for Jack Faucett Associates and the Federal Highway Administration, Washington, D.C., April 1991.

Similarly, for any section, improvement of substandard horizontal curves is presumed to result in replacing all segments whose curvature is substandard by segments whose curvature just meets the design standard. The total length of these segments before improvement is denoted LHORIZ, and the corresponding length after improvement is denoted LAFTH. Straightening of horizontal curves generally results in a slight reduction in overall roadway length but an appreciable increase in the length of the somewhat straightened curves. In HERS, the former effect is ignored, while the latter effect is estimated by calculating LAFTH:

$$LAFTH = \mathbf{MIN}\left(SLEN, \sum_{I} \frac{C_i}{C_{ds}} L_i \right) \qquad \text{Eq. 7.20}$$

where

$SLEN$ = original length of the section (miles);
L_i = total length of curves in class *i*;
C_i = average curvature of curves in class *i*;
C_{ds} = average curvature of curves in class that just meets the design standard;

and the sum is taken over all substandard classes of curves. In order to maintain the total length of the section, the lengths of all curves that were not originally substandard are scaled downward (with no change in their curvature).

The total length of the segments with modified alignment, LNEW, is taken to be the sum of LAFTV and LAFTH, or, if this sum is greater than the entire length of the section, LNEW is set to the original length of the section. In the latter event, there must be some portion of the section that must be reconstructed both to eliminate substandard grades and to eliminate substandard curves. This portion is designated LBOTH and is equal to LAFTV + LAFTH - LNEW.[88]

For sections that have both substandard grades and substandard curves, the HPMS data base provides no information about the extent of any overlap. The above definition of LBOTH reflects the assumption that there is normally no overlap, and that, when an overlap exists, it is as small as possible. This assumption is considered to be reasonable (because of the safety problems that would result from sharp curves located on steep grades). However, to the extent that this assumption does not hold, it increases the length of road to be reconstructed on a modified alignment and thus tends to increase the estimated cost of the alignment improvement.

7.4.2.2 Cost of Improving Alignment

Improvement costs for segments with modified alignment are obtained by estimating costs for clearing and grubbing, earthwork, drainage, structures, pavement, right-of-way, guard rails and curbs, fencing, painting, and lighting. The procedures used for estimating each of these cost components were developed by Cambridge Systematics (*op. cit.*) and are summarized below. Unit costs, in 1997 dollars, used by these procedures are shown in Table 7-13, “Unit Costs Used for Rural Alignment Cost Computation,” and Table 7-14, “Unit Costs Used for Urban Alignment Cost Computation.” Parameter values used in Equations 7.21 through 7.25 are shown in Table

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[88] The HERS variables LBOTH, LAFTV and LAFTH correspond to the quantities Lboth, (Lafter(v) -Lboth), and (Lafter(h) - Lboth), respectively, in the Cambridge Systematics report (*op. cit.*, pp. 4-2 through 4-4).

7-15, “Parameter Values for Alignment Cost Computation.” The unit costs may be converted as a group to dollars of any other year using FHWA's Composite Bid Price Index for highway construction, or converted individually using the component indexes for excavation, structures, surfacing with Portland cement concrete, and resurfacing with bituminous concrete.[89]

7.4.2.2.1 Clearing and Grubbing

Site preparation consists of clearing and grubbing. The total cost of clearing and grubbing, TCCG, is estimated:

$$TCCG = PCG(1, terrn) \times RW^{PCG(2,\, terrn)} \times UCCG \times LNEW \qquad \textit{Eq. 7.21}$$

where:

RW = roadway width after improvement (feet) (equals the number of lanes times the lane width, plus twice the right-shoulder width, plus the median width);
$LNEW$ = total length of the realigned segments (miles);
$UCCG$ = unit cost of clearing and grubbing (dollars per square yard);
$terrn$ = terrain type; and
$PCG(j,terrn)$ = estimated parameters that vary with terrain type (see Table 7-15).

7.4.2.2.2 Earthwork

For flat terrain (terrn = 1), total earthwork costs, TCEW, are estimated:

$$\begin{aligned} TCEW = {} & PEW(1, 1) \times RW^{PEW(2,\, 1)} \times [PEW(3, 1) + WET \times PEW(4, 1)] \\ & \times UCEW(1) \times LNEW \end{aligned} \qquad \textit{Eq. 7.22}$$

and total earthwork costs for rolling or mountainous terrain are estimated:

$$TCEW = UCEW(terrn) \times PEW(1, terrn) \times RW^{PEW(2,\, terrn)} \qquad \text{Eq. 7.23}$$

$$\times \left\{ \begin{array}{l} [PEW(3, terrn) + e^{PEW(4,\, terrn) \times [ARGV - PEW(5,\, terrn)]}] \\ \quad + [PEW(3, terrn) + e^{PEW(4,\, terrn) \times [ARGH - PEW(5,\, terrn)]}] \\ \quad \times (LAFTH - LBOTH) \end{array} \right\}$$

where:

RW = roadway width after improvement (feet);
$LNEW$ = total length of the realigned segments (miles);
WET = 1 in wet climate zones, 0 in other climate zones;

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[89] Office of Infrastructure, *op. cit.*

Table 7-13. Unit Costs Used for Rural Alignment Cost Computation[a]

(1997 Dollars)

Clearing and Grubbing	$ 1.77 per square yard
Earthwork:	
Flat terrain	$ 5.66 per cubic yard
Rolling terrain	5.66
Mountainous terrain	6.65
Drainage:	
Narrow pipe culverts	$ 67.48 per foot
Wide pipe culverts	135.32
Small box culverts	612.64
Wide box culverts	1440.75
Structures	$ 903,122 each
Guard rails and curbs:	
Curbed median or shoulder	$ 152,518 per mile
Guard rail or concrete median	188,933
Guard rail at shoulder	184,401
Fencing	$ 97,005 per mile
Lighting	$ 674,578 per mile

Painting of Traffic Lanes (per mile)
Number of Lanes

2	4	6	8
$17,835	$29,577	$38,269	$43,218

Pavement Costs (per square yard)

Layer Thickness (inches)	Aggregates	Asphaltic Concrete	Portland Cement Concrete
2		$5.99	
3		6.99	
4	$3.99	9.53	
6	5.77	14.01	$18.080
7			20.91
8	7.66	19.67	22.75
9			24.82
10			28.36
12	11.49		33.09
13	13.76		
15			40.18

Surface treatment (for light pavement sections): $ 2.09

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[a] Source: Cambridge Systematics, Inc. *FHWA Highway Economic Requirements System; Alignment Improvement Costs*, prepared for Jack Faucett Associates and the Federal Highway Administration, Washington, D.C., April 1991, Appendix D. Adjusted to 1988 dollars by applying a factor of 0.96; 1988 dollars adjusted to 1997 dollars by applying a factor of 1.231.

Table 7-14. Unit Costs Used for Urban Alignment Cost Computation[a]

(1997 Dollars)

Clearing and Grubbing	$ 2.15 per sq. yard
Earthwork:	
Flat terrain	$ 6.88 per cubic yard
Rolling terrain	6.88
Mountainous terrain	8.08
Drainage:	
Narrow pipe culverts	$ 82.01 per foot
Wide pipe culverts	164.46
Small box culverts	744.53
Wide box culverts	1750.90
Structures	$ 1,097,539 each
Guard rails and curbs:	
Curbed median or shoulder	$ 185,351 per mile
Guard rail or concrete median	229,606
Guard rail at shoulder	224,098
Fencing	$ 117,888 per mile
Lighting	$ 819,796 per mile

Painting of Traffic Lanes (per mile)
Number of Lanes

2	4	6	8
$ 21,674	$ 35,944	$ 46,508	$ 52,522

Pavement Costs (per square yard)

Layer Thickness (inches)	Aggregates	Asphaltic Concrete	Portland Cement Concrete
2		$7.29	
3		8.50	
4	$4.85	11.58	
6	7.02	17.02	$21.98
7			25.42
8	9.31	23.91	27.65
9			30.16
10			34.47
12	13.96		40.21
13	16.73		
15			48.83

Surface treatment (for light pavement sections):	$ 2.54

[a] Source: Cambridge Systematics, Inc. *FHWA Highway Economic Requirements System; Alignment Improvement Costs*, prepared for Jack Faucett Associates and the Federal Highway Administration, Washington, D.C., April 1991, Appendix D. Adjusted to 1988 dollars by applying a factor of 0.96; 1988 dollars adjusted to 1997 dollars by applying a factor of 1.496.

Table 7-15. Parameter Values for Alignment Cost Computation[a]

	j	Flat	Rolling	Mountainous
PCG	1	685.00	685.00	636.00
	2	1.07	1.07	1.14
PEW	1	439.00	399.00	853.00
	2	1.0	1.10	1.30
	3	1.0	1.00	1.00
	4	2.22	-0.49	-0.25
	5	---	0.50	1.50
ANBC		0.40	0.55	1.53
ANPC		1.93	2.90	3.35
PDR	1	1.25	3.92	2.22
	2	1.10	0.84	0.90

[a] Source: Cambridge Systematics, Inc. *FHWA Highway Economic Requirements System: Alignment Improvement Costs*, prepared for Jack Faucett Associates and the Federal Highway Administration, Washington, D.C., April 1991, Chapter 3, Equations 3.1- 3.8.

UCEW(terrn) = unit cost of earthworks (dollars per mile);
ARGV = average road gradient after improvement of segments whose alignment is being modified to eliminate substandard grades; this will be the average gradient of grade class that just meets the design standard;
ARGH = average road gradient after improvement of segments whose alignment is being modified to eliminate substandard curves; this will be the average road gradient of all segments that currently meet the design standard; and
PEW(j,terrn) = estimated parameters that vary with terrain type (see Table 7-15).

7.4.2.2.3 Drainage

Total cost of drainage culverts, TCDR, is estimated:

$$TCDR = [ANBC(terrn) \times UCBC(s) + ANPC(terrn) \times UCPC(s)] \times PDR(1, terrn) \times RW^{PDR(2,\, terrn)} \times LNEW \qquad \text{Eq. 7.24}$$

where:

ANBC(terrn) = average number of box culverts per mile, by terrain type;
ANPC(terrn) = average number of pipe culverts per mile, by terrain type;
UCBC(s) = unit cost of box culverts (dollars per mile) by size s (small or large);
UCPC(s) = unit cost of pipe culverts (dollars per mile) by size s (narrow or wide); and
PDR(j,terrn) = estimated parameters that vary with terrain type (see Table 7-15).

Large box culverts and wide pipe culverts are used in wet climate zones; small box culverts and narrow pipe culverts are used in other climate zones.

7.4.2.2.4 Structures

The total cost of new structures, TCSTR, is estimated by obtaining the number of structures per mile on the original section and multiplying by the length of the segments with modified alignment and by the average cost of a new bridge:

$$TCSTR = \frac{NSTR}{SLEN} \times LNEW \times ACSTR \qquad \text{Eq. 7.25}$$

where:

LNEW	=	total length of the realigned segments (miles);
SLEN	=	original length of the section (miles);
NSTR	=	number of structures on the original section; and
ACSTR	=	average cost of a new bridge (dollars).

7.4.2.2.5 Pavement

The cost of pavement depends upon pavement type, the number of pavement layers, and their thickness.

The pavement type used for the portion of a section being reconstructed on a modified alignment is determined by the type of pavement the section had before being improved. Rigid pavement is used for alignment improvements to sections with rigid or composite (flexible over rigid) pavement, and flexible pavement is used otherwise.

For low-type flexible pavement (used for rural collectors that carry no more than 1000 vehicles per day[90]), a surface treatment on a four-inch aggregate base and a four-inch aggregate sub-base is assumed.

For other flexible pavements, a wider range of options exists. For these pavements, the thickness of the asphaltic concrete surface layer is obtained from Table 8-6, “Pavement Thickness After Improvement,” and the structural number (SN) is obtained from Equation 8.1 (or set to the original value of SN for the section, if that value is higher). SN is then used to classify the pavement section type as being light ($SN \leq 3.0$), medium ($3.0 < SN \leq 4.5$), or heavy ($SN > 4.5$). An asphaltic concrete base is assumed for sections with an existing asphalt base, and an aggregate base is assumed otherwise. An aggregate sub-base is assumed whenever an aggregate base is used or when the pavement section type is classified as heavy; otherwise, it is assumed that there is no sub-base. Finally, the thickness of the base and sub-base (if it exists) is obtained from Table 7-16.

The total cost of pavement, TCP, for the portion of the section being reconstructed is then estimated:

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[90] See Table 3-3, “Default Surface Type Criteria and Standards.”

Table 7-16. Thickness of Base and Sub-base of Reconstructed Sections[a]

Type of Pavement Section ⇓	Type of Base			
	Asphaltic Concrete		Aggregate	
	Base	Sub-base (Aggregate)	Base	Sub-base (Aggregate)
Light	6"	none	4"	4"
Medium	6"	none	8"	8"
Heavy	8"	8"	12"	13"

[a] Source: U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System *Field Manual*, Washington, D.C., Table IV-3, August 30, 1993.

$$TCP = 1760 \times PW \times \left[\sum_{i=1}^{I} UCPL(i, t) \right] \times LNEW \qquad \text{Eq. 7.26}$$

where:

PW = pavement width, in yards;
$UCPL(i,t)$ = unit cost for pavement layer i of thickness t (dollars per square yard);

and the factor of 1760 is used to convert *LNEW* from miles to yards. Flexible pavements may have from 1 to 3 layers (as described above); rigid pavements have only the surface layer.

The costs per square yard of aggregate, asphaltic concrete, and Portland cement concrete layers are shown in Tables 7-13 through 7-14 for selected thicknesses. For thicknesses not shown, the cost per square yard is obtained by linear interpolation. The exhibit also shows the cost per square yard for surface treatment for light pavement sections.

7.4.2.2.6 Right-of-Way

Total right-of-way costs, *TCROW*, are estimated:

$$TCROW = NL \times UCROW(i, j, k) \times LNEW \qquad \text{Eq. 7.27}$$

where:

UCROW = unit costs for right-of-way (in dollars per lane-mile)
indx = index to *UCROW*; For rural areas, specified by functional system and terrain type; for urban areas, by facility type.

The unit costs for right-of-way, in 1997 dollars, are shown in Table 7-17, "Right-of-Way Costs for Alignment Improvements."[91] They may be converted to dollars of another year using the appropriate FHWA price trends.[92]

Table 7-17. Right-of-Way Costs for Alignment Improvements[a]

(1997 Dollars per Lane Mile)

Rural Sections			
	Terrain		
	Flat	Rolling	Mountainous
Interstates	$ 89,863	$ 80,015	$ 71,398
Other Principal Arterials	80,015	71,398	64,012
Minor Arterials	73,860	64,012	55,395
Major Collectors	71,398	61,550	55,395
Urban Sections			
Freeways and Expressways	$ 330,616		
Other Divided Roads	332,112		
Other Undivided Roads	263,296		

[a] Source: Cambridge Systematics, Inc., *FHWA Highway Economic Requirements System: Alignment Improvement Costs*, prepared for Jack Faucett Associates and the Federal Highway Administration, Washington, D.C., April 1991, p. D-9. Costs are shown in 1997 dollars per lane mile. Values in original table were adjusted to 1988 dollars by applying a factor of 0.96; 1988 dollars adjusted to 1997 dollars by applying factors of 1.231 (rural) and 1.496 (urban).

7.4.2.2.7 Miscellaneous Costs

Miscellaneous costs estimated by HERS consist of the costs of guard rails and curbs, fencing, lighting, and the painting of traffic lines[93]. Total miscellaneous costs, TMC, are estimated:

$$TMC = LNEW \times \sum_{i=1}^{5} UMC(i,j) \qquad \text{Eq. 7.28}$$

where *UMC(i,j)* represent unit miscellaneous costs of type *i* and *j* (in dollars per mile). The parameter *i* represents the type of cost:

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[91] The costs shown in Table 7-17, "Right-of-Way Costs for Alignment Improvements," are expressed in 1997 dollars. In the improvement cost file, they are entered in 1988 dollars, and are converted to 1995 dollars by applying factors of 1.231 (rural) and 1.496 (urban).

[92] Office of Infrastructure, *op. cit.*.

[93] See Table 7-13, "Unit Costs Used for Rural Alignment Cost Computation," and Table 7-14, "Unit Costs Used for Urban Alignment Cost Computation," for the relevant unit costs.

$i = 1$ Curbs (j=1) or positive barrier (j=2) at median. These costs are assessed when the original section has curbs or a positive barrier at the median.

$i = 2$ Curbs (j=1) or guard rails (j=2) at right shoulder. On roads with shoulders: guard rails are assumed to be used over the entire segment in rural mountainous terrain, and over half the segment in rural rolling terrain and on urban freeways. On other roads, guard rails are assumed not to be used.

$i = 3$ Fencing is assessed for urban freeways only.

$i = 4$ Painting of traffic lines (j = Number of Lanes / 2).

$i = 5$ Lighting is assessed for urban sections only.

7.4.2.3 Total Improvement Cost

For any section, the total initial improvement cost for combining pavement and widening improvements with alignment improvements is obtained by combining the cost of reconstructing part of the section on a modified alignment with the cost of the pavement and widening improvements made to the remainder of the section. The former cost is obtained by combining clearing and grubbing, earthwork, drainage, structures, pavement, right-of-way, and miscellaneous costs (from Equations 7.21 through 7.28). The latter cost is obtained by multiplying the cost per lane-mile for the pavement and widening improvements (Table 7-11, “Capital Improvement Costs”) by the length of the portion of the section (if any) that would continue to follow the existing alignment (the unaligned portion being equal to SLEN - LNEW).

7.4.3 Correcting Substandard Conditions on Urban Freeways

HERS considers an urban freeway substandard if (a) it is an Interstate or Other Freeways and Expressways (that is, functional class is 11 or 12), and (b) any one of the four deficiencies listed below applies:

- the shoulders are unsurfaced;
- access control is not full
- the median type is not positive barrier; or
- the median width is less than the design standard for urban freeways and expressways by design.

For the 1999 *C&P Report*, the default value for the urban median width design standard was set to 20 feet.

HERS will correct these deficiencies only on urban freeways which are being reconstructed. Improving access control to full and improving the median width to the design standard each require a lane of right-of-way as coded in the section’s widening feasibility (WDFEAS) data item. (This data item is part of the section’s HPMS input record.) If the availability of right-of-way is limited, precedence is given first to adding lanes, then to improving access control, and last to improving median width. Improvement costs for each upgrade are estimated using the cost data in Table 7-18, “Improvement Costs - Substandard Urban Freeways.”[94]

Table 7-18. Improvement Costs - Substandard Urban Freeways

(1997 Dollars)

Improvement Type	Cost per Lane-Mile
1. Shoulder Type to "Surfaced"	$ 192,510
2. Access Control to "Full"	284,418
3. Median Type to "Positive Barrier"	150,282
4. Median Width to Design Standard	458,298

The costs in Table 7-18 were derived using the following assumptions:

- The cost for improving shoulder type to surfaced is taken as the difference between costs of resurfacing with shoulder improvement and simple resurfacing for urban freeways (Table 7-11, "Capital Improvement Costs");
- Improving access control to full assumes cost of one additional lane right-of-way (Table 7-17, "Right-of-Way Costs for Alignment Improvements");
- Median barrier costs were derived from recent work[95] and adjusted to 1997 dollars;
- The cost of improving the median width to design standard is taken as the combination of one additional lane of right-of-way (Table 7-17) and the cost for resurfacing (Table 7-11).

7.4.4 State Cost Factors

Improvement costs are further indexed by state. The cost factors are derived from *Price Trends*[96] as a three-year rolling average, and are applied to all capital costs associated with the improvement. The index values used for the 1999 *C&P Report* are presented in Table 7-19, "1997 State Cost Factors."

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[94] The costs shown in Table 7-18 are expressed in 1997 dollars. In the improvement cost file, they are entered in 1988 dollars, and are converted to 1997 dollars by applying a factor of 1.242.

[95] M. G. McNally and O. Merheb, "Impacts of Jersey Median Barriers on the Frequency and Severity of Freeways Accidents", AAA Foundation for Traffic Safety, Washington, D.C., 1991.

[96] Office of Infrastructure, *op. cit.*

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Table 7-19. 1997 State Cost Factors

State	Factor	State	Factor	State	Factor
AL	0.912	LA	1.056	OH	1.067
AK	1.725	ME	1.215	OK	1.023
AZ	0.863	MD	1.131	OR	0.977
AR	0.827	MA	1.301	PA	1.257
CA	1.096	MI	1.141	RI	0.775
CO	0.897	MN	0.904	SC	1.115
CT	0.896	MS	1.150	SD	0.713
DE	0.887	MO	0.791	TN	0.896
DC	0.923	MT	0.932	TX	0.725
FL	0.922	NE	0.981	UT	0.912
GA	1.058	NV	1.017	VT	1.287
HA	1.360	NH	0.635	VA	1.161
ID	0.567	NJ	0.808	WA	1.557
IL	1.076	NM	0.930	WV	1.165
IN	0.738	NY	1.349	WI	0.832
IA	0.707	NC	0.962	WY	0.784
KS	0.783	ND	0.862	PR	0.535
KY	1.603				

8 Effects of HERS Improvements

The effects of each HERS improvement are simulated by changing the description of the characteristics of the sample section. When evaluating potential improvements, HERS builds a temporary description of the section for each of the candidate improvements. (When analysis extends for more than a single funding period, HERS builds a series of descriptions extending to the end of the benefit-cost analysis period.) If HERS implements an improvement at the end of processing for a funding period, the altered description is saved for use in the following funding period.

HERS analyzes the effects of all improvements as if they are implemented instantaneously at the middle of a funding period instead of being spread throughout the funding period. Accordingly, by the end of a funding period, the PSR of a reconstructed section shows the effect of one-half period of pavement deterioration. The disruptive effects of improvements are not analyzed. Sections which do not undergo improvement during a funding period also have their section descriptions updated to reflect forecast changes in PSR and traffic volume. This “unimproved condition” is used as a base case in benefit-cost analysis.

Most of the effects of improvements on the “section data items” that form this description are shown in Table 8-1, “Effects of Improvements on Section Data Items -- All Sections.” The widening options in this exhibit are assumed to be accomplished without any change in rush-hour parking rules. Effects that occur only when lanes are added to rural sections are shown separately in Table 8-2, “Additional Effects of Adding Lanes on Data Items for Rural Sections.” The effects of alignment improvements on alignment-related data items (curves and grades, passing sight distance, and weighted design speed) and on pavement condition are presented in Table 8-3, “Effects on Section Data Items of Alignment Improvements.”

The additional effects of improving substandard conditions on urban freeways are presented in Table 8-4, “Effects of Addressing Substandard Conditions on Urban Freeways.” In HERS, the changes shown in Table 8-4 are implemented, if feasible, whenever a substandard urban freeway undergoes pavement reconstruction.

The effects of improvements on widening feasibility are presented in Table 8-5, “Widening Feasibility Code Adjustments.” Generally, when widening improvements are made, widening feasibility for future improvements is reduced. The exception is sections coded as having unlimited widening feasibility, for which widening feasibility is never reduced. The values shown assume that the override factor WDFOVR is set to 5, thus allowing widening in excess of the limits indicated by WDFEAS. However, the urban freeway upgrade and rural section upgrades are not affected by WDFOVR, and WDFEAS must have a value of at least 3 for an upgrade to be implemented. For these two upgrades, note that WDFEAS is checked after it has already been adjusted for the “main” improvement. (See paragraph 6.5, ”The Widening Feasibility Model,” for additional discussion.)

Table 8-1. Effects of Improvements on Section Data Items -- All Sections[a]

Section Attributes	**Improvement Type**						
	Reconstruct With More Lanes (High or Normal Cost)	Reconstruct With Wider Lanes	Reconstruct Pavement	Major Widening (High or Normal Cost)	Minor Widening	Resurface W/Shoulder Improvement	Resurface Pavement
Number of Lanes[b]	Design Number	NC	NC	Design Number	NC	NC	NC
Lane Width	DS	DS	NC[c]	DS	DS	NC	NC
Shoulder Type[d]	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	NC
Right Shoulder Width[d]	DS	DS	DS[e]	DS	DS	DS[e]	NC
Pavement Condition (PSR Value)[f]	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate
Pavement Thickness	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate	Recalculate
SN or D	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase	NC or Increase
Surface Type[g]	DS	DS	DS	DS	DS	DS	DS
Drainage Adequacy	Good	Good	Good	Good	Good	Good	Improve by 1 Code Value
Peak Capacity	Recalculate[h]	Recalculate[h]	NC[i]	Recalculate[h]	Recalculate[h]	NC[i]	NC

[a] NC = No Change, MTC = set to Minimum Tolerable Conditions, and DS = set to Design Standard.

[b] The design number of lanes is the number of lanes needed to accommodate projected traffic in the design year, and which would be added if widening were not constrained. The two constraints are widening feasibility and the maximum number of lanes allowed. This last number is user specified and can vary with functional class. For the 1999 *C&P Report,* the maximum number of lanes for all functional classes was 99.

[c] For an unpaved section the improvement reconstruct pavement results in paved lane widths equal to the MTC.

[d] Curbed sections remain curbed (with zero shoulder width) after improvements.

[e] Shoulder only widened if feasible.

[f] Changes in PSR specified in Table II-14 of HPMS/AP *Technical Manual.*

[g] If low type pavement exists, resurfacing does not change the pavement type.

[h] No change if recalculated capacity is lower than original capacity.

[i] If the shoulders are widened, the value is recalculated.

Table 8-2. Additional Effects of Adding Lanes on Data Items for Rural Sections

Data Item	Effect
Median Width	Widen to design standard or to the extent feasible.
Median Type	Set to unprotected if median width is widened and median type is currently "none."
Access Control	If median is added and access control is not full, set to partial.

Table 8-3. Effects on Section Data Items of Alignment Improvements

Data Item	Effect
Grades	Substandard grades are improved to design standard.
Curves	Substandard curves are lengthened and improved to design standard.[a]
Passing Sight Distance	(For rural two-lane highways only) improve to typical passing sight distance (from 1978 data).
Weighted Design Speed	Recalculate. If no data on curves by class, increase by 5 m.p.h.[b]
Pavement Condition	Obtain as a weighted average of the PSR on the portion of the section with modified alignment[c] and the PSR indicated in Exhibit 3.3 for the remainder of the section.

[a] The procedure used for determining the extent to which curves are lengthened is presented in Chapter 5.

[b] HERS contains code for adjusting weighted design speed when there is no data on curves by class, but HERS does not consider horizontal alignment improvements when these data are not available.

[c] The portion of the section with modified alignment equals the sum of the portions with substandard grades or curves (after lengthening) but is no greater than the length of the section.

Table 8-4. Effects of Addressing Substandard Conditions on Urban Freeways

Data Item	Effect
Shoulder Type	Improve to surfaced.
Access Control	Improve to full control if feasible.[a]
Median Type	Improve to positive barrier.
Median Width	Improve to design standard if feasible.[b]

[a] Improvement to full control is assumed to require one lane of right-of-way.

[b] Improvement of median width to design standard is assumed to require one lane of right-of-way.

Table 8-5. Widening Feasibility Code Adjustments

Original WDFEAS Code	WDFEAS Code After Improvement						
	Resurface	Resurface with Improved Shoulders	Recon-struct	Widen Lanes[a]	Add Lanes[b]	Urban Freeway Upgrade[c]	Rural Section Upgrade[d]
1 (no widening)	1	1	1	1	1	NF	NF
2 (partial lane)	2	2 or 1[e]	2 or 1[e]	1	1	NF	NF
3 (one lane)	3	3 or 2[e]	3 or 2[e]	2	1	1[f]	1
4 (two lanes)	4	4	4	3	3 or 1[g]	4, 3, or 1[h]	NA[i]
5 (three or more lanes)	5	5	5	5	5	5	5
where: NF = Not Feasible (the improvement is not made, and WDFEAS is not adjusted); NA = Not Applicable.							

[a] The adjustment is the same whether the section is resurfaced or reconstructed.

[b] The adjustment is the same whether the section is resurfaced or reconstructed, and without regard for whether the lanes are added at normal or high cost.

[c] Applies when correcting substandard conditions on urban freeways undergoing reconstruction. The model first tries to improve access control, and then to widen the median to the design standard. Neither improvement is implemented (and WDFEAS is not adjusted) if the condition is not substandard.

[d] For rural sections when lanes are added, the model will widen the median and improve access control to "partial" if feasible. Unlike the urban upgrade, a single feasibility test (and adjustment) is made for both improvements.

[e] If the shoulder is not curbed and is below the design standard, it is widened to and WDFEAS reduced.

[f] Only one improvement is implemented. Access control is preferred -- the median will only be widened if access control is already full.

[g] If two lanes are added, the WDFEAS code is adjusted to 1 (no widening feasible). If one lane is added, the WDFEAS code is adjusted to 3 (one lane may be added).

[h] Either, neither, or both of the two improvements may be needed or implemented.

[i] This value will never be tested for the rural upgrade, as a WDFEAS of 4 would have been reduced as a result of the added lane(s).

8.1 The Effects of Improvements on Pavement Thickness

This section discusses the HERS procedure for estimating pavement thickness resulting from resurfacing and reconstruction and for obtaining the corresponding structural number (SN) for flexible pavement. As discussed in paragraph 6.2, "The Pavement Deterioration Model," SN is one of the influences on the deterioration rate of flexible pavement, and the deterioration rate of rigid pavement depends directly on pavement thickness. Additionally, the cost of alignment improvements is affected by pavement thickness.

In HERS, the design life of a pavement normally is taken to be twenty years. This value can be modified by the user; however, as pavement thickness is a function of the number of ESALS forecast during the design period, modifying this variable will affect pavement thickness (and hence pavement durability). Resurfacing or reconstruction cost will be affected only to the extent that some portion of the section has its alignment improved.

The following subsections present the values of pavement thickness for reconstruction, simple resurfacing, and resurfacing and widening; and a final subsection presents the structural numbers used by HERS for reconstructed and resurfaced flexible pavements.

8.1.1 Reconstruction

Assuming that the reconstructed pavement is designed and constructed as a new pavement structure, pavement thickness is a function of pavement material and traffic load. HERS assumes that reconstruction of either rigid or composite (flexible over rigid) pavement is performed with rigid pavement, and that reconstruction of flexible pavement uses flexible pavement. Thicknesses used by HERS for reconstruction of flexible (asphaltic concrete) pavements to a medium or high-type design standard are shown in Table 8-6, “Pavement Thickness After Improvement,” as are thicknesses for reconstruction of rigid (Portland cement concrete) pavements. For low-type flexible pavement, only a surface treatment is used.

Table 8-6. Pavement Thickness After Improvement

(Inches)

Forecast ESALs over Design Life	**Pavement Type**	
	Flexible[a b c]	Rigid[d]
≤ 50,000	1.5	6.5
50,001 - 150,000	2.5	6.5
150,001 - 500,000	3.0	6.5
500,001 - 2,000,000	4.0	8.0
2,000,001 - 7,000,000	5.0	9.5
> 7,000,000	5.5	10.5

[a] American Association of State Highway and Transportation Officials, *AASHTO Guide for Design of Pavement Structures*, Washington, D.C., 1986.

[b] Thickness shown for flexible pavements are also used for resurfacing flexible pavements with a flexible overlay.

[c] For low-type pavement, assume a surface treatment only.

[d] E.J. Yoder and M.W. Witczak, *Principles of Pavement Design*, John Wiley, New York City, 1975.

8.1.2 Simple Resurfacing

HERS assumes that resurfacing is always performed using a flexible overlay. For flexible overlays over flexible, composite, or rigid pavement, the overlay thickness used by HERS varies with traffic load in the same way as for reconstruction with flexible pavement. These thicknesses are shown in Table 8-6.

8.1.3 Resurfacing with Widening Improvements

When resurfacing is combined with widening improvements, some part of the improved roadway will be built on land that is not already paved. In general, the newly paved area will be structurally compatible with the resurfaced roadway. HERS treats resurfacing with widening improvements as producing a single roadway whose characteristics are those of the original roadway after resurfacing.

8.2 The Effects of Improvements on Structural Number

HERS assumes that resurfacing or reconstruction never reduces the structural number (SN) of flexible pavement but may increase its value. To do this, a value of SN is obtained using an equation that approximates the relationship between SN and pavement thickness presented in Table IV-3 of the HPMS *Field Manual*[1]. This equation is:

$$SN = 1.5 + 0.75 \times D_f \qquad \textit{Eq. 8.1}$$

where D_f is pavement thickness, in inches. If the resulting value is less than the original value of SN coded for the section, SN is set to that value.

8.3 The Effects of Improvements on PSR

When pavement undergoes reconstruction, HERS sets its PSR to a level determined by the section's location and surface type. These values may be set by the user. Table 8-7 lists the default values.

Table 8-7. PSR Values After Reconstruction

Surface Type	Rural	Urban
High Flexible	4.6	4.6
High Rigid	4.6	4.6
Intermediate	4.4	4.4
Low	4.2	4.2

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[1] U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System *Field Manual*, Washington, D.C., Table IV-2, December 1, 1987.

For sections being resurfaced, HERS adds an increment to the PSR at the time of the improvement. This augmented PSR value is limited to maximum PSR values. These values may be adjusted by the user. The default values for incrementing PSR are shown in Table 8-8, “Increase in PSR After Resurfacing,” and the default maximum PSR limits are shown in Table 8-9, “Maximum PSR After Resurfacing.”

Table 8-8. Increase in PSR After Resurfacing

Surface Type	Rural	Urban
High Flexible	1.8	1.8
High Rigid	1.8	1.8
Intermediate	1.8	1.8
Low	1.8	1.8

Table 8-9. Maximum PSR After Resurfacing

Surface Type	Rural	Urban
High Flexible	4.3	4.3
High Rigid	4.3	4.3
Intermediate	4.2	4.2
Low	4.0	4.0

8.4 The Effects of Alignment Improvements on Pavement Characteristics

For any section, an improvement that combines pavement reconstruction with alignment improvements results in producing newly reconstructed pavement on the entire section. Such improvements produce a single type of pavement and a single PSR for the entire section.

On the other hand, improvements that combine resurfacing with alignment improvements produce a single PSR only in the (relatively rare) case in which the alignment of the entire section is improved. More commonly, such improvements produce one PSR for the portion of the section on which alignment does not change and a higher PSR on the portion that is reconstructed on a modified alignment. Furthermore, resurfacing of rigid or composite pavement is presumed to be performed with a flexible overlay (producing composite pavement), while the adjoining reconstructed pavement is presumed to be rigid. For both cases, HERS obtains a single combined PSR for the section by taking a weighted average of the PSRs on the two portions of the section, using the lengths of these portions of the section as weights. For the case in which part of the section receives a flexible overlay on composite or rigid pavement and part is reconstructed with rigid pavement, HERS uses the relative length of the two portions of the section to determine whether to treat the section as having rigid or composite pavement.

9 Model Output

HERS is capable of producing, at the user's option, an extensive variety of statistics, describing both the forecast state of the highway system and the costs and benefits of the improvements selected. This chapter describes the output produced by HERS v3.26. HERS outputs a text file suitable for printing, and separate comma-delimited text files suitable for use in spreadsheets and databases. The printable output consists of the following:

1. One page of output summarizing the state of the system at the start of the run;
2. For each funding period, one page of output summarizing the state of the system at the end of the funding period;
3. For each funding period and for the overall analysis period, one page of output summarizing how the system is forecast to change between the beginning and the end of the period; and
4. For each funding period and for the overall analysis period, up to twenty-five pages of additional output providing information on the costs and benefits associated with the selected improvements.

The output pages are presented in three layout formats, as discussed below. The first two of these formats are also available in comma-delimited layout. HERS places the printable output in a single text file named by the user in the specification file (RUNSPEC.DAT).

9.1 The System Conditions Output Format

HERS uses this format for items one through three in the above list of output pages. In addition to the run number and run description information from the RUNSPEC file, this page contains the following information for each of the nine functional systems in the HERS database, with individually produced summary forecasts for the rural system, the urban system, and for the complete system:

1. Average PSR;
2. Average IRI (inches per mile);
3. Average speed;
4. Congestion Delay (hours per 1000 vehicle-miles);
5. Total Delay (hours per 1000 vehicle-miles);
6. Total VMT;
7. Travel-time costs (dollars per thousand vehicle-miles);

8. Operating costs, listed for all vehicles combined and separately for four-tire vehicles and for trucks (dollars per thousand vehicle-miles);
9. Crash costs (dollars per thousand vehicle-miles);
10. Total user costs, which is a summation of travel-time costs, operating costs for all vehicles, and crash costs (dollars per thousand vehicle-miles);
11. Number of crashes (per 100 million vehicle miles);
12. Number of injuries (per 100 million vehicle miles);
13. Number of fatalities (per 100 million vehicle miles);
14. Annual maintenance costs (dollars per mile);
15. Average cost of pollution damage (dollars per 1000 vehicle-miles); and
16. Percent of total VMT on roads not meeting minimum tolerable conditions for:
    - pavement condition (PSR);
    - peak-hour volume/capacity ratio;
    - lane width;
    - right-shoulder width;
    - shoulder type;
    - surface type;
    - horizontal alignment;
    - vertical alignment.

The initial page of output in this format presents the conditions at the beginning of the analysis period. It also includes the number of center-line miles and the number of sections in the sample.

For each funding period, HERS produces a page of output summarizing conditions at the end of the period. This is followed by a page summarizing the changes in conditions which occurred during the funding period. This second page of output also shows the (incremental) benefit-cost ratio of the last improvement selected. If a constraint was placed on available funds, this page also displays the amount of funds spent; while, if a performance goal was specified, it compares the performance level achieved with the specified goal.

HERS produces a similar summary of the change in conditions during the overall analysis period.

HERS creates an output file named [run number].SS1 (where the file name is the same as the run number entry in the RUNSPEC file) which contains the comma-delimited version of this format. HERS generates a “page” for the initial system conditions and the conditions at the end of each funding period. Each page contains only the sixteen data items listed above (i.e., not the number of center-line miles, sections in the sample, etc.).

9.2 The "By Improvement Type" Output Format

HERS produces up to twenty-one pages of printable output in this format. This format is organized by functional class versus improvement type. The improvement type categories are duplicated: one set covers all improvements by improvement type, and the other only those improvements which include improved alignment. The user selects which pages are to be included in the printable output via switches in the RUNSPEC file. The twenty-one output pages are:

1. The total initial cost of selected improvements;
2. Lane-Miles improved;
3. Lane-Miles of mandatory improvements selected on a priority basis to address unacceptable conditions[1];
4. Lane-Miles of non-mandatory improvements not selected on a priority basis;
5. The net present value of the residual value of all improvements;
6. The average benefit-cost ratio of selected improvements;
7. Total benefits in the last year of the period;
8. Maintenance costs savings in the last year of the period;
9. User benefits in the last year of the period;
10. Travel time savings in the last year of the period;
11. Operating cost savings in the last year of the period;
12. Safety benefits in the last year of the period;
13. Crashes avoided in the last year of the period;
14. Injuries avoided in the last year of the period;
15. Lives saved in the last year of the period;
16. VMT for improved sections in the last year of the period;
17. Miles improved;
18. Miles of mandatory improvements selected on a priority basis to address unacceptable conditions;
19. Miles of non-mandatory improvements not selected on a priority basis.

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[1] In HERS, statistics pertaining to mandatory improvements selected to address unacceptable conditions are collected only for improvements that are not replaced by a more aggressive non-mandatory improvement selected on the basis of its benefit-cost ratio.

20. Lane-Miles added to the system through widening improvements;
21. Emissions costs savings in the last year of the period;

Also, the first six and the last two of these optional output pages can be requested for the overall analysis period.[2]

Each page of optional output provides values for one of the above measures by improvement type and functional system. HERS also produces summary values for all the improvement types combined, as well as for the entire rural highway system, the entire urban highway system, and the complete highway system. The first of the above optional pages also provides separate summaries of initial costs by functional system for mandatory improvements selected to address unacceptable conditions and for non-mandatory improvements.[3]

HERS creates the file [run number].SS2 to hold the comma-delimited output for this format. The comma-delimited format includes only the "all improvements" set of statistics: it does not include the data for improvements with improved alignment. The comma-delimited output set contains per funding period and overall analysis period statistics for initial cost of selected improvements and the average benefit-cost ratios of selected improvements.

9.3 The "By IBCR" Output Format

HERS produces up to four printable summary sets in this format.[4] The data is organized by functional class versus improvement type, and, within each improvement type, by incremental BCR range. Therefore, where the "by improvement type" format might show that HERS identified 4.542 billion dollars of resurfacing improvements for rural major arterials, the "by IBCR" format could show that 1.261 billion dollars were invested in improvements with BCRs greater than or equal to 6.0. HERS uses the following BCR ranges:

- 1.0-1.2;
- 1.2 - 2.0;
- 2.0 - 3.0;
- 3.0 - 4.0;
- 4.0 - 5.0;
- 5.0 - 6.0; and
- >= 6.0

The four summary sets are:

1. Capital requirements (initial cost);

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[2] For "last year of the period" statistics (items 7 through 16), the data for the last funding period would be identical to that for the overall analysis period.

[3] See preceding footnote.

[4] For this format, to refer to "pages" would be somewhat misleading, as each summary set requires more than two physical pages to print.

2. Number of sample sections improved (including duplicates);
3. Miles improved; and
4. Travel time benefits expressed as a percentage of total user benefits.

There is no comma-delimited output in this format.

Appendix A: Benefit-Cost Analysis

This appendix presents a detailed description of the benefit-cost analysis procedure used by HERS. It is divided into two major parts. The first part describes the analysis of potential improvements to a highway section for which no improvements have yet been selected for the current funding period. The second part addresses the situation that exists when an improvement is tentatively selected and describes the analysis of more aggressive improvements that might be selected to replace the first selection.

A.1 When No Improvements Have Been Selected

This section addresses the analysis of a potential improvement, I_1, on a highway section, H, for which no improvements have yet been selected during the funding period currently being analyzed. In this situation, normally, I_1 is analyzed over a BCA period that begins at the midpoint, T_1, of the current funding period and ends at the midpoint, T_2, of the next funding period. The analysis of this "normal case" is discussed in the first subsection below. Two special cases for which a longer BCA period is appropriate are discussed in subsequent subsections.

A.1.1 The Normal Case

The normal situation described above is shown schematically in Exhibit A-1, "The Effect of Improvements on Highway Conditions". In the exhibit, S_0 represents the condition or state of section H (PSR, capacity, alignment characteristics, etc.) prior to improvement at time T_1; S_1 represents the condition at time T_1 after improvement I_1 is implemented; S_2 represents the condition at time T_2 if I_1 is implemented at time T_1; and S_3 represents the condition at time T_2 if I_1 is not implemented at T_1. The two sloping lines in the exhibit are shown to be somewhat closer together at T_2 than at T_1; this will be the case for most improvements (in part because, for flexible pavement, the deterioration functions used by HERS produce a deterioration rate that declines with declining PSR).

The residual value of I_1 at time T_2 is set to the cost of an improvement (I_2 in Exhibit A-1) that would improve the section's condition from S_3 to S_2. Under most conditions, the cost of I_2, $C(I_2)$,is somewhat less than the cost of I_1, $C(I_1)$.

The procedure described above is equivalent to estimating the benefits of implementing I_1 at time T_1 relative to a base case in which a similar improvement is implemented during the next funding period at time T_2. Some observations should be made about the implications of this procedure.

First, by ending the analysis at time T_2, the procedure ignores all benefits that might result after T_2. To understand the effect of ignoring such future benefits on improvement selection, consider a section with an unusually high rate of traffic growth.

A disproportionate share of the benefits of improving such a section occurs after time T_2 and so will be ignored by our procedure. The benefits occurring during the entire life of an improvement may be sufficient to justify its implementation at time T_1, but the benefits occurring prior to T_2 may not be.

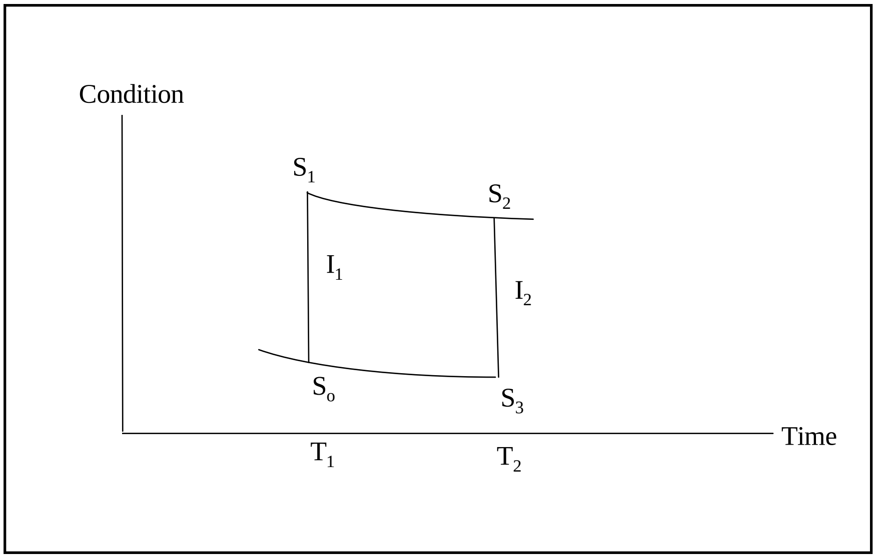

Exhibit A-1. The Effect of Improvements on Highway Conditions

In this case the HERS procedure determines that (after adjustment for differences in improvement costs) the benefits foregone by postponing this improvement until the next funding period are lower than the benefits that would be foregone if an improvement on some other section (with a slower traffic-growth rate) were to be postponed. Assuming no significant decrease in the availability of funds in subsequent periods, both improvements will eventually be implemented. The only benefits that will not be obtained are the benefits that could be obtained by improving the first section earlier -- but these benefits have been determined to be smaller than those to be obtained by improving the second section at time T_1. Thus the short BCA period enables HERS to determine when an improvement on a section with a high rate of traffic growth should be postponed until at least the next funding period -- a situation that would not be identified if a longer BCA period were used. In effect, the choice of BCA period length enables HERS to optimize the timing of improvements on sections with rapidly growing traffic.[1]

Although a short BCA period enables HERS to optimize the timing of improvements on sections with rapidly growing traffic, a short period does not guarantee that the most desirable improvement for a given section will be selected. Indeed, on a section with rapidly growing traffic, analysis over a short BCA period may result in the initial selection of a relatively nonaggressive improvement (e.g., simple resurfacing) when analysis over the normal life of the improvement would result in selection of a more aggressive improvement (e.g., resurfacing with some widening option). This situation, however, is readily handled by the next step: the evaluation of the IBCRs for selecting more aggressive improvements for the section. This evaluation (discussed in

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[1] Actually, the HERS improvement-cost procedure does not consider the disruptive effect on highway users of implementing improvements. To reduce this effect, it may be desirable to implement improvements on sections with growing traffic volumes somewhat earlier than indicated by HERS.

the following section) is performed over a BCA period representing the normal life of the just selected improvement. Any more aggressive improvement that is clearly more desirable than the selected improvement will have an IBCR over this BCA period that is higher than the BCR (over the short BCA period) of the improvement that has just been selected. Accordingly, the aggressive improvement with the highest IBCR will immediately be selected to replace the less aggressive improvement.

Another observation is that the procedure tends to be biased against improvements for which $C(I_2)$ (that is, the residual value) is appreciably less than $C(I_1)$. In HERS, there are two situations in which $C(I_2)$ can be appreciably less than $C(I_1)$.

The first situation occurs when a section whose pavement is in relatively good condition[2] is resurfaced. In this situation, HERS assumes that the PSR improvement resulting from resurfacing is capped at a maximum level (between 4.0 and 4.3). I_1 incorporates the full cost of a normal resurfacing of the section, but the improvement in pavement condition is less than the improvement that would normally occur. Accordingly, the distance between S_3 and S_2 (and between S_0 and S_1) is reduced; and the residual value of I_1 at time T_2, represented by $C(I_2)$, can be appreciably less than $C(I_1)$. In effect, the bias results from a situation in which the full improvement of resurfacing cannot be obtained. Assuming that the effect of resurfacing pavements that are in relatively good condition is being appropriately simulated, the bias against selecting such improvements appears to be completely appropriate.

The second situation in which $C(I_2)$ can be appreciably less than $C(I_1)$ occurs when I_1 involves pavement reconstruction. In HERS, pavement condition after reconstruction is independent of condition before reconstruction. Accordingly, normal reconstruction at time T_2 will bring the condition of section H appreciably above S_2. Thus, the residual value $C(I_2)$ (the cost of improving section H's condition to S_2) will be appreciably less than the normal cost of reconstruction. The result is that the procedure will be biased against selecting improvements that involve pavement reconstruction (alone or in conjunction with widening and/or alignment improvements) and in favor of selecting improvements that involve resurfacing of sections provided that the situation discussed in the preceding paragraph does not exist.

A relatively high pre-reconstruction PSR (represented by S_0 in Exhibit A-1) results in a relatively small PSR improvement, and, accordingly, a relatively low residual value. The extent of the bias against reconstruction thus varies with pre-reconstruction PSR. This bias against reconstruction, and particularly against early reconstruction, appears to be reasonable, though it may be somewhat overstated -- particularly since HERS does not have any way of representing the non-economic factors that result in early reconstruction.

A.1.2 Sections with Declining Traffic Volumes

Consider now a section on which traffic is forecast to decline. Such a decline may result from a forecasted decline in population or economic activity in the vicinity of the section, or from the expected completion of a parallel road that will divert traffic from the section in question. The HPMS database does not distinguish between these two cases. Accordingly, both cases are treated by HERS as causing traffic to decline at a uniform rate over the entire OA period.

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[2] In the current context, pavement to be resurfaced is in "relatively good condition" if it has PSR greater than 2.5 for high-type, 2.4 for intermediate-type, or 2.2 for low-type pavements.

As in the preceding subsection, let T_1 be the midpoint of the funding period being analyzed, and T_2 the midpoint of the next funding period. If a section with declining traffic is improved at T_1, a somewhat disproportionate share of the lifetime benefits of the improvement will occur by T_2. Accordingly, if the improvement is evaluated over a single funding period, from T_1 to T_2, the benefit-cost ratio obtained will be higher than if the improvement is evaluated over a longer BCA period. The shorter BCA period might thus result in the selection of an improvement that would not be selected if a longer BCA period were used. When this is the case, in effect, the analysis suggests that it is better to implement the improvement in the current funding period than in the next funding period, but that given the benefits of potential improvements on other sections it may be even better to postpone the improvement until the end of the longer BCA period.

It is concluded that, if improvements on sections with declining traffic are analyzed over a single funding period, the procedure will occasionally choose to improve such a section before the optimal time for an improvement. Accordingly, for sections with declining traffic and no unacceptable conditions, HERS uses a special procedure. HERS uses a base case that presumes that the most attractive alternative to immediate implementation of an improvement, I_1, is to postpone implementation as long as possible without resulting in increased improvement costs and without permitting the section's condition to become unacceptable. More precisely, for such a section, the BCA period is chosen:

1. If I_1 does not involve reconstruction, and if resurfacing is still practical in the next funding period, the BCA period will extend until the midpoint of the last funding period in which resurfacing is still practical if no improvement is previously implemented.[3]

2. Otherwise, the BCA period extends until the midpoint of the first funding period when the section first develops a triggering unacceptability if no improvement is implemented.[4]

For sections with a triggering unacceptability, a single-funding period BCA period is used even if traffic is declining. Such sections may require benefit-cost analysis because funds available in a given funding period for improving sections with triggering unacceptabilities are not sufficient to correct all unacceptable conditions on such sections. This may occur if the HERS user has specified an unreasonably low level of funds available for this purpose or if a large backlog of sections with triggering unacceptabilities exists at the beginning of the overall analysis period. Focusing on the latter situation, it is reasonable to presume that such sections that are not improved in any given funding period are likely to be improved in the next period. Accordingly, the BCA period used for analyzing sections with triggering unacceptabilities is taken to be one funding period long.

A.1.3 The Last Funding Period When Resurfacing is Practical

Consider the analysis of an improvement, I_1, that involves resurfacing a section whose PSR at the start of the current funding period is above the reconstruction PSR (i.e., the PSR at which resurfacing is no longer practical), but whose PSR will slip to or below this value by the start of the

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[3] Since reconstruction is appreciably more expensive than resurfacing, the assumption is made that, for an improvement being given serious consideration for implementation at time T1, it will rarely (if ever) be desirable to postpone the improvement until resurfacing is no longer practical (i.e., until pavement reconstruction is required).

[4] For sections with declining traffic volumes, pavement condition is the only possible reason for a section's condition to decline from acceptable to unacceptable.

next funding period. In this case, if resurfacing is not performed at T_1 (in Exhibit A-1), any improvement implemented in the next funding period, or at any later time, must involve reconstruction. In other words, the options are to resurface at T_1 or to reconstruct at some later time.[5]

As observed previously, the HERS procedure will tend to postpone improvements requiring reconstruction for as long as possible. In this situation, reconstruction is likely to be postponed until the section develops a triggering unacceptability; i.e., until its PSR becomes unacceptable. Accordingly, in this situation, the most appropriate BCA period to use for analyzing I_1 extends until the section's PSR becomes unacceptable if no improvements are made to the section.

If the BCA period used is only a single-funding period long, the residual value of I_1 will be particularly high (due to high cost of reconstruction) and an inappropriate bias toward selecting I_1 will be created. Use of the longer BCA period avoids this bias, but it is likely that I_1 would still be selected under most circumstances. The procedure for analyzing I_1 over the longer BCA period is relatively complex and is likely to be somewhat time consuming but it appears to be worthwhile to avoid selecting I_1 inappropriately. A description of this procedure follows.

Consider the use of an extended BCA period for evaluating I_1; i.e., a BCA period that ends in the first funding period in which the section's PSR becomes unacceptable if no improvements are made to the section. To estimate the residual value of I_1 at the end of this BCA period, it is necessary to identify any improvements, in addition to I_1, that are likely to be made during the BCA period if I_1 is implemented. It is possible, but very unlikely, that more than one such improvement would be made. Accordingly, HERS assumes that no more than one such improvement will be made.

The situation in which one improvement, I_3, is likely to be made during the BCA period if I_1 is implemented is shown schematically in Exhibit A-2, "Effects of an Improvement Over Several Funding Periods". As shown in this exhibit, implementation of I_1 at time T_1 improves the section's condition from S_0 to S_1. The section's condition then deteriorates to S_4 at time T_3. A second improvement, I_3, is then implemented, improving the condition to S_5 at time T_3. The section's condition then deteriorates to S_2 at time T_2, the midpoint of the last funding period of the BCA period.

If I_1 is not implemented at time T_1, then, as shown in Exhibit A-2, the section's condition will deteriorate to S_3 at time T_2. I_2 is then defined as the improvement that raises the section's condition to S_2, the section's most likely condition at time T_2 if I_1 is implemented.

There are three special cases of the situation described above:

1. Improvement I_3 is not likely to be made until the last funding period of the BCA period. In this case, $T_3 = T_2$, and S_5 and S_2 are identical.

2. If I_1 is implemented, more than one subsequent improvement is likely before the end of the BCA period. This relatively unlikely case can be represented by a more complex version of Exhibit A-2. HERS does not now contain code for handling this case, though such code may be incorporated into a subsequent version of HERS.

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[5] HERS assumes that all improvements to be implemented during a given funding period will be sequenced so that, if the PSR of any sections to be improved will fall below the reconstruction level during the period, those sections will be improved while resurfacing is still practical.

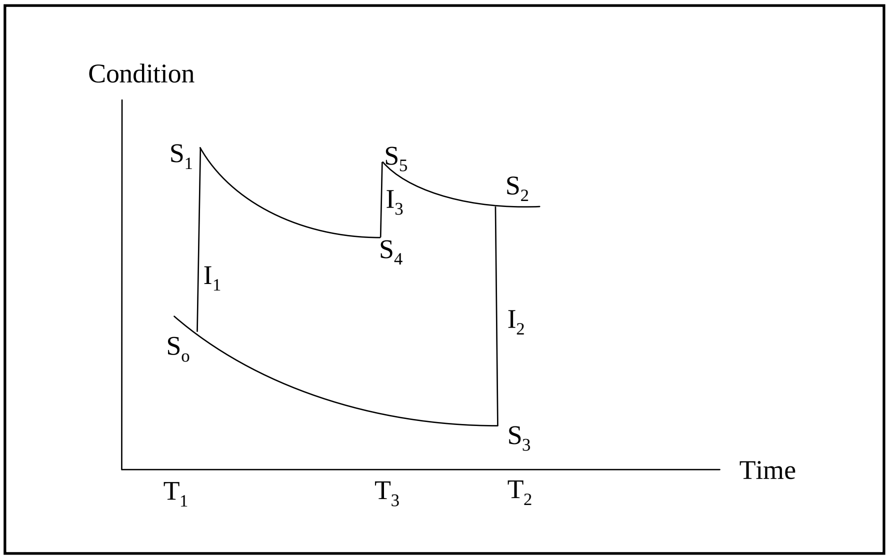

Exhibit A-2. Effects of an Improvement Over Several Funding Periods

3. If I_1 is implemented, no subsequent improvement is likely until after the end of the BCA period. This case is represented by the diagram of Exhibit A-1, “The Effect of Improvements on Highway Conditions”.

To obtain the residual value of I_1 at time T_2, it is necessary to identify I_2 and, if it exists, I_3. I_3 represents improvements “likely” to be made during the BCA period if I_1 is implemented. These improvements are identified by assuming I_1 will be implemented and using the following rules:

1. If the section's PSR drops below the reconstruction PSR before the end of the funding period following the end of the BCA period, resurfacing is “likely” in the funding period preceding the period in which the reconstruction PSR would be violated.

2. If I_1 incorporates a widening improvement intended to address a volume/capacity (V/C) ratio deficiency and, if, during the BCA period, the section's forecasted V/C ratio approximates the V/C ratio existing prior to the implementation of I_1, then widening is “likely” in the period in which this occurs. For the purpose of this rule, the forecast V/C ratio “approximates” the initial V/C ratio in that future funding period in which the forecast V/C ratio is closest to the initial V/C ratio, provided that the forecast V/C ratio in that period is below the deficiency level (DL). If the forecast V/C ratio is not below the DL in that period, then the forecast V/C ratio is considered to approximate the initial V/C ratio in the next funding period in which it is below the DL.

3. If I_1 does not incorporate a widening improvement, but the V/C ratio is forecast to become unacceptable during the BCA period, and it is feasible to reduce the V/C ratio by

widening the section, then an appropriate widening improvement is “likely” to be implemented when this occurs.

4. If Rules 2 or 3 indicate that widening is likely, Rule 1 indicates that resurfacing is likely in some earlier period than that indicated by Rules 2 or 3, and the V/C ratio will be below the DL in the period in which resurfacing is likely, then it is assumed that widening is likely to be performed at the same time as resurfacing rather than in the period indicated by Rules 2 or 3.

Once the characteristics and timing of any intermediate improvement, I_3, have been identified, a routine forecast can be made of the state, S_2, of the section at the end of the BCA period if I_1 is implemented. I_2, the improvement that will move the section from S_3 to S_2, can then be determined. This improvement consists of pavement reconstruction (since the PSR at S_3 is below the reconstruction PSR), possibly combined with a widening option and/or alignment improvements.

To estimate the cost of I_2, any widening or alignment improvements are analyzed separately from reconstruction; i.e., I_2 is treated as containing a reconstruction component and, possibly, a second component consisting of widening or alignment improvements. Since the PSR at S_2 is necessarily below the PSR achieved by normal reconstruction, the cost of the reconstruction component of I_2, $C(Recon(I_2))$, should be less than the cost of simple reconstruction. Accordingly, the cost of the reconstruction component of I_2 is estimated from the formula

$$C(Recon(I_2)) = \frac{PSR(S_2) - PSR(S_3)}{PSR_{Recon} - PSR(S_3)} \times C(Recon) \qquad \textit{Eq. A.1}$$

where PSR_{Recon} is the PSR normally resulting from reconstruction, and $PSR(S_i)$ is the PSR at S_i.

Unlike pavement improvements, widening and alignment improvements are effectively permanent. Accordingly, if I_2 contains a widening/alignment component, it must bring the section's width and alignment to the state produced by I_1 and I_3. The cost of the widening/alignment component of I_2 is thus estimated by taking the normal cost of reconstruction with the appropriate widening and alignment options and subtracting the normal cost of simple reconstruction. This cost is added to the cost of the reconstruction component of I_2 to produce the estimated cost of I_2.

Finally, the residual value of I_1 at time T_1 (beginning of the BCA period) is obtained by discounting the costs of I_2 and I_3 (implemented at times T_2 and T_3, respectively) back to time T_1 and subtracting the former value (discounted cost of I_2) from the latter value.

A.2 When An Improvement Has Already Been Selected

This section considers the analysis of a potential improvement, I_4, on a highway section, H, for which some lesser improvement, I_1, has already been selected during the analysis of the current funding period. This analysis determines whether it is desirable, from a benefit-cost standpoint, to implement I_4 instead of I_1. In HERS, I_4 may differ from I_1 in one or more of the following ways[6]:

A. I_4 incorporates a widening option but I_1 does not.

B. I_4 incorporates a more aggressive widening option than I_1.

C. I_4 incorporates an alignment option that is not incorporated into I_1.

To simplify the discussion, the above possibilities are addressed in the following sequence:

1. Only "A" exists. (See paragraph A.2.1.)
2. Only "B" exists. (See paragraph A.2.2.)
3. "C" exists either alone or in conjunction with "A" or "B". (See paragraph A.2.3.)

(It may be noted that, by definition, "A" and "B" cannot exist simultaneously.)

In all three cases, the HERS procedure obtains the incremental benefit-cost ratio, IBCR, of I_4 relative to I_1 in the same way as it obtained the benefit-cost ratio of I_1 relative to the base case. This IBCR is obtained over an appropriate timeframe determined on the basis of the following discussion.

A.2.1 Adding a Widening Option

Consider the case in which I_1 consists of either resurfacing or reconstruction, possibly combined with alignment improvements, and I_4 consists of I_1 plus a widening option.

Prior to the selection of I_1, I_4 will have been evaluated by comparing the merits of implementing I_4 in the current funding period or deferring its implementation for one period. Once I_1 has been selected, however, a single-period deferral normally would not be appropriate for I_4. Instead, the appropriate comparison is between implementing I_4 (instead of I_1) during the current period or deferring implementation until the next period in which a pavement improvement would "normally" be selected for the section.

Several alternatives exist for identifying the next period in which such a pavement improvement would "normally" be required. In HERS, if I_1 involves reconstruction, this funding period, F_3, is taken to be the last future period in which it will be possible to resurface the section; otherwise it is taken to be the future period in which the PSR of the section will have declined to approximately the PSR that exists prior to the implementation of I_1. This definition, presented more precisely below, is adequate for HERS, though it is somewhat less than ideal. In particular, depending upon funding availability, the PSR at which pavement improvements are selected for sections with a given set of conditions may increase or decrease over the course of a HERS run.

On the basis of the above discussion, the analysis period for evaluating I_4 is defined to run from the midpoint, T_1, of the current funding period to the midpoint, T_2, of F_2, the next funding period during which a pavement improvement would "normally" be implemented on the section. If I_1 involves reconstruction, F_2 is taken to be the last future period in which resurfacing will still be possible. Otherwise, with two exceptions, F_2 is taken to be that future period in which the forecast PSR is closest to the PSR existing prior to the implementation of I_1. The exceptions are: (1) if the PSR in the indicated future period is above the resurfacing deficiency level, then the first

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[6] A fourth type of difference would occur if a PSR range is defined within which benefit-cost analysis is used to choose between resurfacing and reconstruction. In concept, HERS should have the capability of analyzing this situation. However, the current HPMS database does not contain information that could be used as the basis for such an analysis (e.g., the height and slope of the pavement crown).

period that is below that level is used instead; and (2) if the PSR at the end of the indicated period is less than the unacceptability level, and that is not the first period in which the unacceptability level is violated, then the first period during which the PSR becomes unacceptable is used. The HERS assumptions about minimum pavement deterioration rates effectively limit the length of the analysis period to a typical maximum of 10 to 20 years.

The base case against which I_4 is compared is the implementation of I_1 at time T_1. The residual value of I_4 at time T_2 is normally equal to the cost of implementing the widening option under consideration at time T_2 (instead of at time T_1) in conjunction with an appropriate pavement improvement minus the cost of implementing the pavement improvement alone.

A.2.2 Replacing One Widening Option With Another

Under some relatively restricted circumstances, the improvement identification procedure presented in Chapter 3 identifies two alternative widening options, “widen lanes” and “add lanes,” as warranting analysis for implementation on a given section in a given funding period. When two widening options are identified, it is quite likely that improvements incorporating the less extensive of the two options will have higher benefit-cost ratios than improvements incorporating the more extensive option. Hence, the less extensive widening option will likely be selected for implementation before the more extensive one. When this occurs, an incremental benefit-cost analysis is required to determine whether the extra cost of implementing the more extensive option instead of the less extensive one is warranted.

As observed at the beginning of the preceding paragraph, the circumstances under which multiple widening options are identified for analysis are relatively restricted. Therefore, it is undesirable for HERS to have special code for handling this case. Accordingly, when an incremental BCA is required to determine whether an improvement incorporating one widening option should be replaced by an improvement incorporating a more extensive widening option, HERS performs the analysis over the same timeframe used when the addition of a widening option is considered (discussed in the preceding section). The IBCR produced by this analysis will likely be lower than the one that resulted in selecting the less extensive widening option, but it may be high enough to cause the more aggressive improvement to be selected if sufficient funds exist.

A.2.3 Adding Alignment Options

The final case to be considered is the one in which I_1 is any selected improvement, and I_4 is any potential improvement that includes all options incorporated into I_1 and also involves an alignment option that is not in I_1. I_4 may include a widening option regardless of whether I_1 does; if both improvements include widening options, I_4's widening option may be identical to or more aggressive than I_1's. Let O represent the set of options in I_4 that are not in I_1.

In this case, if the options represented by O are not implemented (in conjunction with I_1) during the current funding period, the next funding period in which they might be implemented in a cost-effective manner is the next period that the section normally requires a pavement or widening improvement. F_2, the next funding period during which a pavement or widening improvement is “normally” implemented, is defined in the same way as it is defined in the section above (Adding a Widening Option). Then the appropriate BCA period for I_4 starts at the midpoint of the current funding period and ends at the midpoint, T_2, of F_2.

The base case against which I_4 is compared is the implementation of I_1 at T_1. The residual value of I_4 at time T_2 is equal to the cost of implementing the options represented by O at time T_2

(instead of at time T_1) in conjunction with an appropriate pavement improvement and any additional widening that may be appropriate at T_2, minus the cost of implementing an improvement that brings the condition of the section to the same final state.

APPENDIX B

Induced Traffic and Induced Demand

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“Induced” is a term implying that a particular condition is indirectly caused by another condition. In the case of traffic volumes, the term arose from the phenomenon that improvements to a highway—especially capacity improvements—seemed to result in more traffic choosing to use the road than would be the case if the highway were not improved. To an economist, this is an example of demand elasticity. Simply recognizing that travel demand is elastic, however, is not sufficient to reconcile the conflicting views of engineers, planners, and environmentalists. On one side are those who argue that transportation facilities are provided to serve land uses and support economic activity; on the other are those who claim that whatever capacity is provided soon fills up to the same level of congestion, gaining nothing. The truth can be better understood by defining induced demand in a way that uses the concept of elasticity.

This appendix describes the concepts guiding several modifications that were made to the HERS model for the 1997 *Conditions and Performance* report to Congress. With minor exceptions noted below, the model implements the concepts as they are described here.

B.1 Concepts of Induced Demand

Frequent references are made in transportation planning to the concept of induced demand, but the term remains ambiguous. The intent here is to define the relevant concepts, and show how they can represent demand for purposes of benefit-cost evaluation of capital improvement projects.

Exogenous Demand Factors

Historically, demand forecasts in urban transportation planning have been based on exogenous variables such as land use, population, employment, and income. Once these

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variables are measured or estimated, the result is a "point" estimate for traffic volume at a future date. Demand, in this sense, is influenced by neither transportation infrastructure nor money price, but is determined entirely by exogenous factors.

If demand is determined by forces beyond the control of the transportation planner, then failure amounts to not having adequate facilities to handle it, and the planner is simply a messenger. Alternatively, if the facility creates its own demand, the planner is just furthering the careers of planners.

Demand Fills Capacity

A contrasting concept has emerged, claiming that additional capacity stimulates corresponding increases in demand. This concept embodies the "build it and they will come" idea—or a belief in the existence of "latent demand," which suggests that there are willing buyers who will express their demand for travel once the service is offered.[1] In growing urban areas, the evidence from recent decades seemed to support this interpretation.

Although the idea has not been implemented as a formal forecasting method, the implication is that demand is entirely *end*ogenous. If true, the policy choice is whether to permit travel to grow or to suppress it.

Elastic Demand

Perhaps the first recognition that demand responded to endogenous factors was the assertion that congestion is self-regulating, implying an automatic balancing of supply and demand. More recently, the economist's concept of demand being a relationship between price and quantity demanded has become accepted, if not necessarily applied in practice. From this perspective, all endogenous changes in volume are movements along the demand curve, whether they are called latent, induced, or something else. If "price" is generalized to include travel time, operating costs, and accidents, then changes in capacity and alignment alter the "price" and thereby cause movements along the demand curve.

Overall, then, travel demand is the result of a combination of both exogenous factors that determine the location of the demand curve, and endogenous factors that determine the price-volume point along the demand curve.

B.2 Short Run versus Long Run

The short run can be any period of time over which something remains fixed. What is fixed might be the capacity of a highway, fuel efficiency of the vehicle fleet, locations of employment, or anything else that changes slowly. The long run is enough time for these

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[1] For an interpretation of latent demand, see Small (1992), pp. 112-116, or Small, Winston, and Evans (1989)

characteristics to change. In transportation planning, the short run typically is assumed to be about 1 year, but the dividing line depends upon the practical context.

Short-Run Elasticity

Demand elasticity is the responsiveness of quantity demanded to changes in price. Price is generalized for travel demand to include travel time, operating costs, and accidents, as well as user charges.[2] Everything included in this generalized price is an endogenous factor with respect to induced traffic. An increase in capacity that lowers travel time, for example, results in additional travel if the elasticity is not zero.

Short-run demand elasticity tends to be lower (i.e., less elastic) than long-run elasticity, because more opportunities to increase or reduce consumption can be developed over the long run than in the short run, while short-run options do not diminish in the long run. If the price of fuel goes up, for example, highway travelers can reduce fuel consumption by taking fewer trips and chaining trips together, by carpooling to share expenses, by driving in ways that achieve better mileage, and by taking a larger share of trips on transit. In the long run they also can switch to more fuel-efficient vehicles, and change their workplace and residence locations. If the price stays high, vehicle manufacturers will develop and produce more fuel-efficient vehicles, and better transit service may be offered.

Long-Run Elasticity

Though the distinction between short-run and long-run demand is really a continuum rather than two discrete states, the separation is useful both conceptually and for modeling purposes. In Figure B-1, two short run demand curves are shown in relation to their common long run demand curve (the latter indicated by a dashed line). Demand could be for a facility, a corridor, or even travel in a region. At a “long run” price of p_1 the volume is v_1 and the short run demand curve D_1 applies, such that changes in the price cause changes in volume along this demand curve in the short run. If the price drops to p_2, for example, then volume will increase to a flow of $v_{1,s}$. If the price stays at that level for the long run, then the short run demand curve will shift outward to D_2, resulting in the volume v_2 at that price. If the price were then to go back up to p_1, volume would only drop to $v_{2,s}$ in the short run, but eventually back to v_1 in the long run.

For example, secular declines in real fuel prices have led to increases in the size and weight of vehicles and concomitant declines in their fuel economy; if the price of fuel were to increase, gasoline consumption would drop but the vehicle fleet would take time to evolve to a more fuel-efficient average. Changes are not necessarily completely reversible—knowledge gained from research leading to advances in technology in, for example, fuel efficiency, is not lost when the need is lessened, but its application tends to diminish.

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[2] The generalized price embodied in HERS includes time, operating costs, and accidents, but no user charges *per se*. The implications of this omission are discussed in greater depth in Appendix D.

Induced Traffic versus Induced Demand

A similar distinction can be made between induced *traffic* (or induced travel) and induced *demand*, by applying the short-run and long-run concepts. It is assumed that demand is fixed in the short run, so changes in volumes are the result of movements along the demand curve; but in the long run, the short-run demand curve can shift. In this way, these terms are defined so that induced traffic is a movement along the *short-run* demand curve, while induced demand is a movement along the *long-run* demand curve, or an endogenous *shift* in the short-run demand curve.

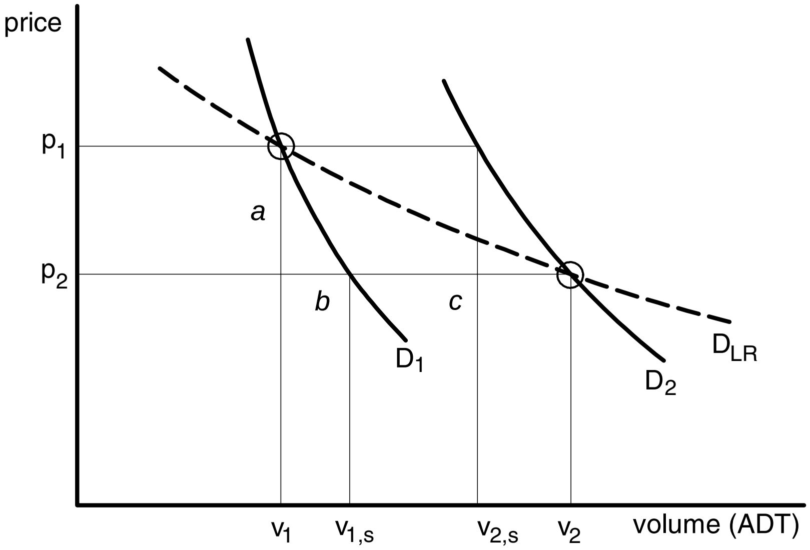

Figure B-1. Long Run Demand With Short Run Demand Curves.

In Figure B-1, no time direction is implied on the horizontal dimension; the shape of the long-run demand curve does not mean that price declines over time. Nor are the short-run demand curves necessarily ordered from one to two; demand could start at D_2 and then shift to D_1. The diagram shows only the relationship between price and volume under short-run and long-run conditions.

Disaggregation of Long Run Elasticity

Long-run elasticity—as with any other demand elasticity—is a ratio of the percentage of change in quantity demanded to the percentage of change in the price of the good. Referring to Figure B-1, the first circled point at (p_1,v_1) is taken to represent a point on both the short-run and long-run demand curves. The second circled point at (p_2,v_2) represents the long-run result of a price change, which lies on the previous long-run demand curve but also on a new short-run curve. The arc elasticity between the two points is

$$e_{LR} = \frac{\%\Delta v}{\%\Delta p} = \frac{\Delta v}{\Delta p} \times \frac{p_1}{v_1} = \left(\frac{v_2 - v_1}{p_2 - p_1}\right) \times \frac{p_1}{v_1} \qquad [1]$$

where e_{LR} is the long run elasticity of demand. If the following simplifications are made for ease of presentation,

$$\begin{aligned} a &= p_2 - p_1 \\ b &= v_{1,s} - v_1 \\ c &= v_2 - v_{1,s} \end{aligned} \qquad [2]$$

as shown in Figure B-1, then the long run elasticity can be represented as

$$e_{LR} = \frac{b+c}{a} \times \frac{p_1}{v_1} = \left(\frac{b}{a} \times \frac{p_1}{v_1}\right) + \left(\frac{c}{a} \times \frac{p_1}{v_1}\right) \qquad [3]$$

where the first term in parentheses is the short run elasticity (e_{SR}) and the second term is the shift in the demand curve over the long run, represented as an elasticity. Thus the long run elasticity is the sum of the e_{SR} and a purely long run component which will be called the long run share, e_{LRS}, defined as

$$e_{LRS} = \left(\frac{c}{a} \times \frac{p_1}{v_1}\right) = \left(\frac{v_2 - v_{1,s}}{p_2 - p_1}\right) \times \frac{p_1}{v_1} \qquad [4]$$

so

$$e_{LR} = e_{SR} + e_{LRS} \qquad [5]$$

The e_{LRS} component can be interpreted in the same way as a normal elasticity, and can be empirically measured as the difference between the short run elasticity and the long run elasticity estimated for the appropriate time period.[3]

B.3 Induced Traffic

As defined above, induced *traffic* is a movement along the short-run demand curve. Common usage of the term “induced” suggests additional traffic—that is, an increase in volume. Decreases might be called disinduced, deterred, or discouraged traffic. For present purposes, the term refers to any endogenous change, whether positive or nega-

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[3] See Taplin (1982) for theory.

tive. Increased congestion or higher tolls, other things being equal, will cause a reduction in volumes. If this occurs in the short run, this is negative induced traffic.

Some of the possible sources of induced traffic include the following:

- Diverted traffic that changes its route to the improved facility;
- Rescheduled traffic that previously used the facility at a different time, spreading or contracting the peak;
- Shifts from other modes, which might or might not have used the facility before, and which include changes in occupancy;
- Destination shifts, resulting from facility improvement; and
- Additional travel by persons already using, or in the market for, the facility.

Demand forecasts for a new or improved facility always include at least some of these sources, although such estimates seldom explicitly recognize a generalized price as the explanatory variable and do not produce a schedule of price-volume combinations.

Partial and General Equilibrium Demand Curves

All demand curves portrayed in this analysis are assumed to be general equilibrium demand curves, even those for the short run. They include traffic shifted to or from other modes or from alternative facilities. A partial equilibrium demand curve, as represented

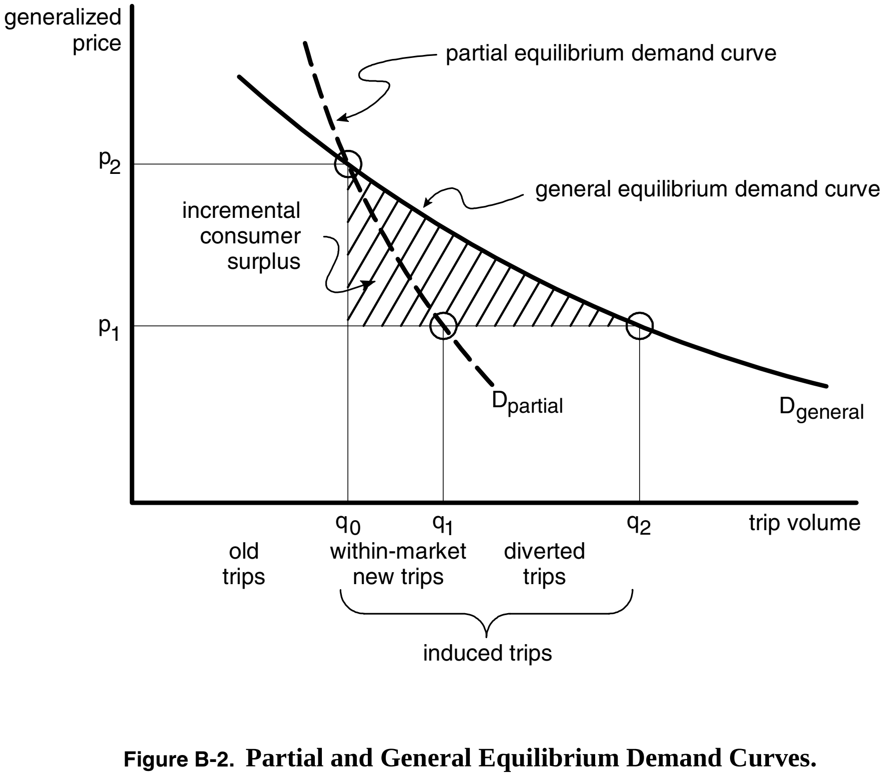

Figure B-2. Partial and General Equilibrium Demand Curves.

in Figure B-2, includes only the travel for those already in the market, whether they are currently taking trips or not (e.g., a person who did not travel at all in this corridor but who chose to do so after the price was reduced, and not by shifting a trip from another time or place). If the demand curve includes diverted travelers (from other modes, routes, times, or destinations), then it will be more elastic than the corresponding partial demand curve because more options are offered. Thus some of the (short run) induced travel comes from new trips by persons already in the market, and some comes from trips diverted from other markets.

For every point on the general equilibrium demand curve there is a corresponding partial demand curve, representing the hypothetical demand that would occur if there were no substitution between markets. If the price were raised, for example, from a point on the general equilibrium demand curve, a movement up the partial demand curve would imply that the travelers could not divert to another time or facility. Not surprisingly, such a demand curve cannot be observed in practice.

Because demand forecasts usually include diverted trips, practical demand forecasts are aimed implicitly at constructing (or locating points on) a general equilibrium demand curve. If the demand is for a single facility, then induced traffic will appear large relative to previous volumes, because most of the change in trips will be from diverted trips. At the regional level, induced traffic—if it were actually estimated—would be a smaller share of total traffic growth, because only trips diverted from other regions, plus substitutions between transportation and other goods, make up the induced share. For project evaluation, diverted travel and other components of induced demand, as measured in consumer surplus, represent the net valuation of systemwide impacts.[4]

“Gross” versus “Net” Induced Traffic

In Figure B-2, all of the movement along the general equilibrium demand curve stimulated by the reduction in price from p_0 to p_1 is labeled “induced trips.” A portion of this induced traffic is labeled “diverted trips.” If the diverted trips are removed from the total “gross” induced traffic, the residual might be called “net” induced traffic. Some analysts prefer that the term induced be restricted to mean *net* induced trips, and the others be left as diverted trips.[5]

For some purposes, this usage has an appeal, but the distinction is a difficult one to make. A trip between the same origin and destination but using a different route is clearly a diverted trip, but trips at other times, or to other destinations are less obvious. If the improved facility prompts a person to go to a movie instead of renting a video, and the video store is much closer, is this induced or diverted? Suppose the person would have walked to the video store. Or suppose the person would have had the video delivered, and the van would have used the same facility before it was improved. What can be observed directly is that more vehicles use the facility after it is improved, and that trips in the region do not go up by as large an amount as the volume on the improved

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[4] See Dargay and Goodwin (1995), Mackie (1996), and Williams and Yamashita (1992).

[5] Examples include Dowling (1994), Heanue (1997). Holder and Stover (1972) and SACTRA (1994).

facility. Labeling which particular travel is "new" and which is "diverted," however, is difficult and probably not necessary.

Schedule Delay and Peak Shifting

As noted earlier, changes in the generalized price may lead to changes in schedule. Peak congestion can be at least partially avoided by leaving earlier or later than preferred. A reduction in peak travel time will cause some travelers to join the peak because the cost to them of schedule delay (departing at a different time than preferred) is less then the new peak delay.[6] Induced traffic, therefore, can be diverted from other times as well as other routes.

If the demand curve represents both peak and off-peak, then the elasticity will be lower than if peak is separated from off-peak. Because the two periods are so closely interrelated (off-peak demand depends upon peak price, and vice versa), separating them for benefit-cost purposes can be tricky, but this is one way to include benefits from reducing schedule delay.

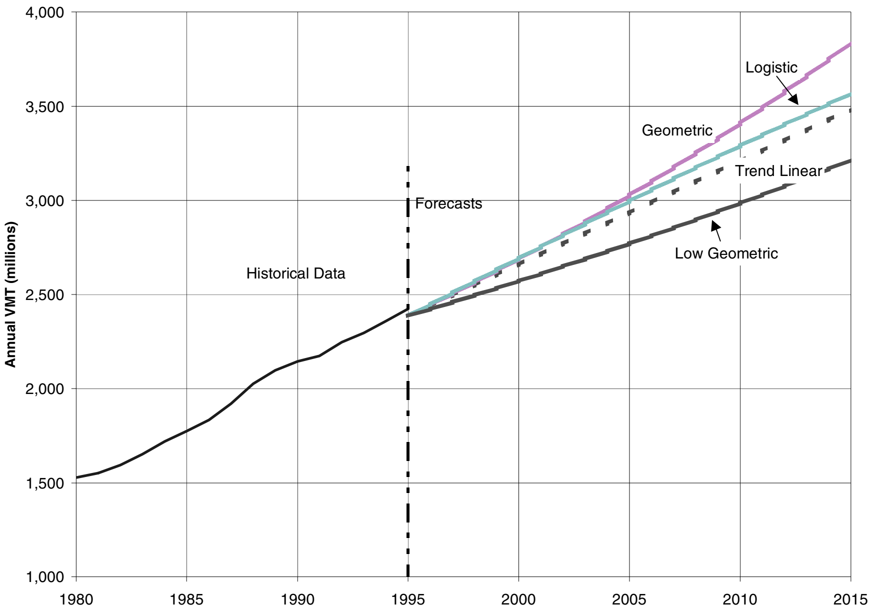

Figure B-3. **Alternative Long Run Travel Forecasts**

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[6] See Small (1992).

B.4 Induced Demand

For purposes of evaluating costs and benefits, the overall analysis period for a project (generally the project lifetime, e.g., twenty years) is broken into a series of discrete time periods, during each of which the demand curve is assumed to be fixed. A baseline long range forecast is used to establish the short run demand curve for each period.

Baseline Demand Forecast

A demand forecast is a functional relationship between time and traffic volume, assuming a set of conditions. *Exogenous* conditions include population growth, economic growth, land use patterns, and available substitute transportation alternatives. *Endogenous* conditions include capacity, level of service (LOS), and user fees. For the present analysis, all endogenous factors are represented in the generalized price. Both capacity and LOS, for example, would both be subsumed under travel time cost and included in the generalized price.

The baseline long-run demand forecast assumes a generalized price, as well as whatever exogenous factors are thought to be relevant by the forecaster. Alternative forecasts might be constructed under different assumptions, as shown in Figure B-3. One such forecast is selected for constructing the short run demand curves.

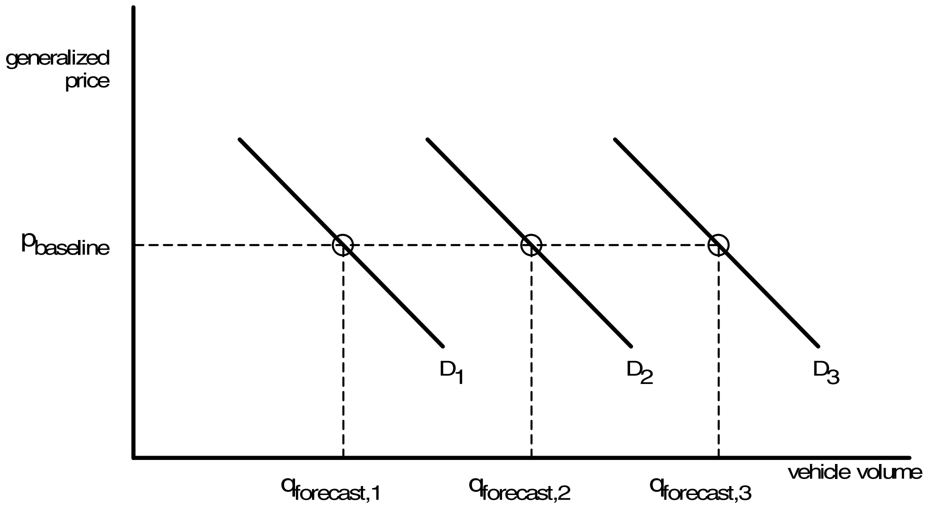

Figure B-4. **Baseline demand forecast for several periods**

Breaking the Forecast Into Discrete Periods

The distinction between long-run induced demand and short-run induced travel is implemented by constructing a short-run demand curve for each of the shorter demand periods (e.g. 1-5 years), and allowing the initial curve to shift, depending upon previous improvements. The forecast becomes a series of discrete points—shown circled in Figure B-4—that provide the calibration points for the associated short-run demand curves. The short-run demand curve can be a straight line calibrated with an elasticity, a constant elasticity demand curve, or some other functional form that can be fitted to a single price-quantity combination. The elasticity chosen should be appropriate to the length of the demand period.[7]

A single, fitted short-run demand curve is shown in Figure B-5, along with other relevant prices and volumes. The price from the previous period $p_{final,\ t-1}$ is adjusted to account for traffic growth, pavement wear, accident rates, and user fee changes that have occurred since the previous period. The result is $p_{no\ improvement}$. Alternative improvements for the current period are evaluated, and, if any are feasible, the best is implemented. This leads to the $p_{improved}$ price, which becomes the initial price for the next demand period. If no improvement is selected, the unimproved price carries into the next period.

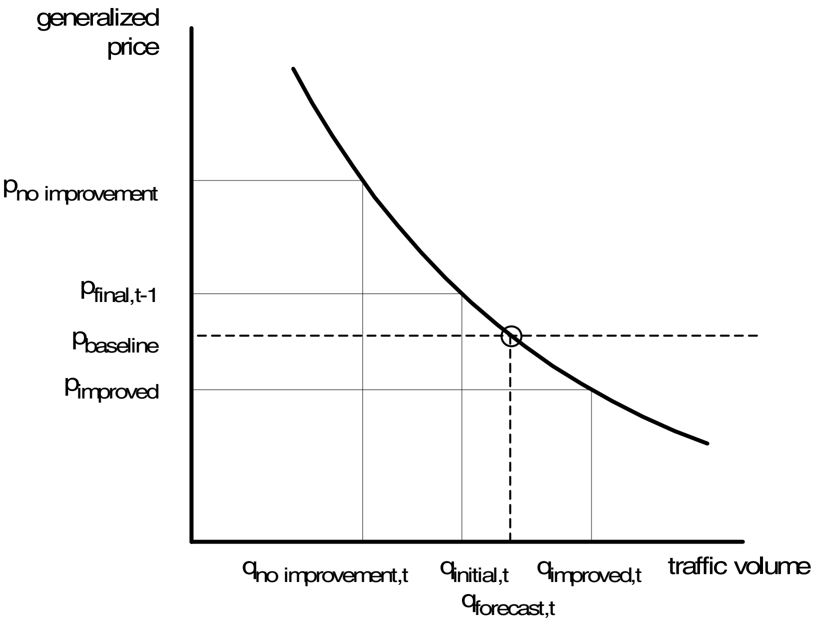

Figure B-5. **Short Run Demand Showing Prices With and Without Improvements.**

Long Run Shifts in the Demand Curve

Evolution of demand in the long run is built upon what takes place in the short run. Operationally, induced *demand* is defined to be the shift in the short run demand curve caused by the price in the previous period. If the price in all previous periods is the same as the baseline price, then the demand curve is fitted to the baseline forecast for that period. If an improvement is made in one period that reduces the price below the baseline price, this leads to a shifting of the demand curve outward, according to the percent by which the price in the previous period is below the baseline price. If no improvement is made, the price increases relative to the baseline forecast price, and the demand curve

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[7] Currently, the demand period or “funding period” in HERS is five years, so the short run elasticity should be selected to allow for adjustments that can be expected to take place within that span of time.

shifts inward in the next period. These two possibilities are shown in Figure B-6. For example, a price of $p_{no\ improvement}$ will shift the subsequent demand curve inward from $q_{forecast}$ by a percentage equal to $(p_{baseline} - p_{no\ improvement}) \times e_{LRS}$.

The relationship between the difference in price of the final, improved—or not improved—price and the baseline price, for one period, and the horizontal shift in the demand curve in the next period, is governed by the long-run share e_{LRS}, as described above.[8] There is no long run demand curve as such, but the shift attributed to induced demand is a displacement of the short run demand calibration point along the baseline price line.

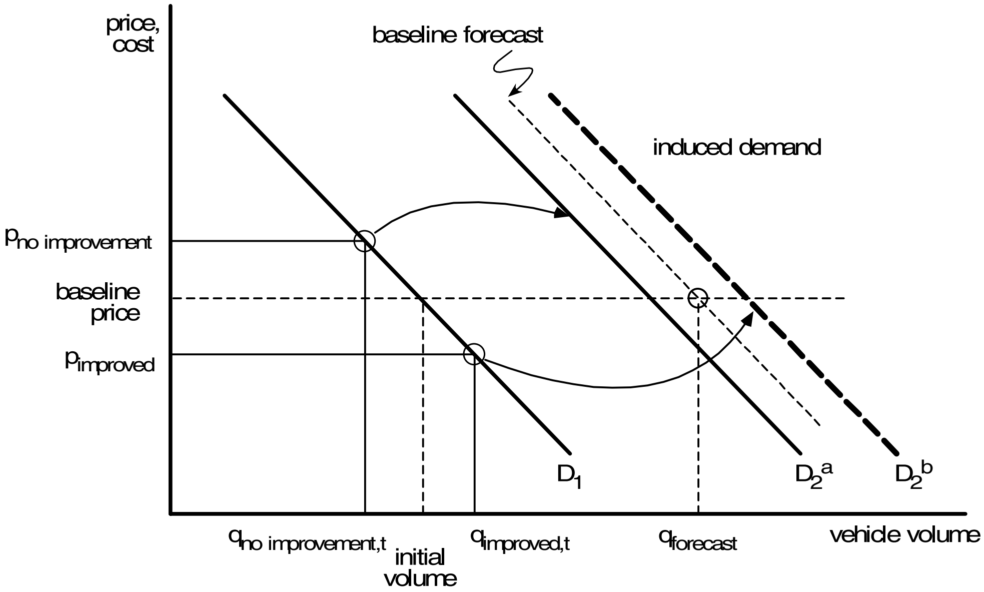

Figure B-6. **Long Run Induced Demand Shift From One Period to the Next.**

Incorporating induced demand, then, allows each period's demand curve to be a function of the previous period's investment, since it affects price to the user. Investment that keeps the price in each period below the baseline price for the baseline forecast produces demand curves that shift farther and farther outward, compared with the baseline forecast. Similarly, if improvements are not made and price is allowed to rise in each period (e.g., due to congestion, pavement roughness, and accidents), the demand curve will be shifted continually inward relative to the baseline.

The magnitude of this shift—the sensitivity of long-run demand to investment and pricing—is determined by the e_{LRS} parameter. The shorter the time period for the short run, the lower should be the long-run elasticity shift from period to period. If the long-run induced demand parameter is zero, the location of each short-run demand curve would

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[8] See "Disaggregation of Long Run Elasticity" on page B-4.

be determined by the baseline forecast, without regard for which—if any—improvements were made in any demand period. Short-run movements along the demand curve still could occur, depending on the short-run price elasticity, but there would be no cumulative endogenous effects from one period to the next. Alternatively, with a high e_{LRS}, induced demand could alter the baseline forecast, even to the point of potentially offsetting the trend of the initial forecast, such leading to growth in demand (from keeping the price low) despite a declining forecast, or causing a decline in demand despite a growth forecast (traffic is deterred by congestion and bad pavement, a consequence of no improvements).

Getting to the Long Run

Empirical estimates of the two elasticities depend upon the length of the short-run time period and the rate of adjustment to changes in price. The length of time between a change in conditions and a new equilibrium is somewhat arbitrary, because other conditions change before equilibrium is reached; however, the process is one of accelerating initial response followed by gradual refinement. In the context of highway volume adjustments in response to changes in the generalized price of travel, the short run is up to a year. The long run—allowing for changes in residence and workplace locations—begins within a year but may not run its course for upwards of 20 years. Such changes are not likely to be motivated solely by changes in transportation prices, but may take transportation user costs into account when the change is made for other reasons (e.g., new job, change in income, change in family).

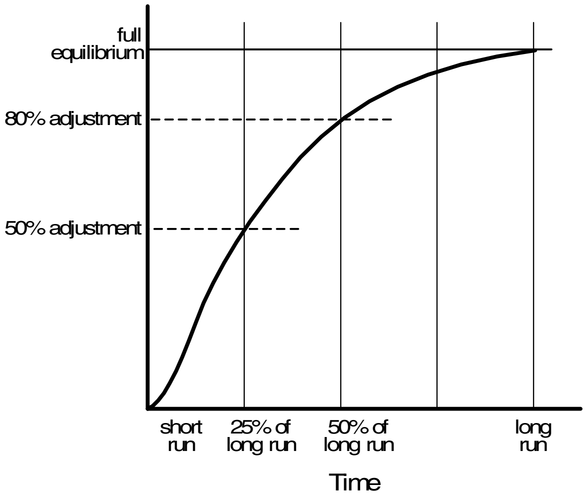

Figure B-7. Path to Long Run Equilibrium.

An approximate adjustment curve is shown in Figure B-7. Although the curve is not fitted to specific data, it reflects the generally observed pattern that roughly half the adjustments take place within about a quarter of the time to long run equilibrium.[9] If the full long-run adjustment period is 10 to 20 years, then half the long-run elasticity occurs within the first 2.5 to 5 years. There might be some accelerating adjustment in the first year, as shown, based on the idea that responses don't occur until consumers become sure the price change will stick, or until they begin feeling its effects.

Empirical Estimates of Short and Long Run Elasticities

Many studies have estimated travel-demand elasticities, but one of the difficulties in interpreting these results is the uncertainty of the time frame that is applicable to the data. Another confounding problem is the ambiguity of the base of the observed elasticity; because most of the empirical cases observe a change in a small component of the total price of travel, the base for computing the percentage change in price often is not obvious and might not be given explicit treatment. The potential differences are large (e.g., a factor of three or more).[10]

The parameter sought is the elasticity of vehicle travel with respect to its own price, including user fees, operating costs, and travel time. Studies undertaken to date suggest that short-run elasticities tend to fall in a -0.5 to -1.0 range, and long-run elasticities from -1.0 to -2.0; a within-period short-run elasticity for a 5-year period would thus be -0.6 to -1.0 and the between-period elasticity from -1.0 to -1.6, yielding an e_{LRS} of about -0.4 to -1.0.

Interpreting Demand Forecasts

Two aspects of the demand forecast are of particular interest. One is how to impute a presumed price to the baseline forecast. The second is whether long-run feedback of transportation investments on the demand curve has been incorporated into the forecast.

- Baseline Price. Although the generalized price behind a demand forecast is seldom made explicit, such attributes as LOS and accident rates may be, and others can be guessed. Pavement quality is probably assumed to be good, and operating costs are typical for the conditions (terrain, vehicle type, congestion). The current LOS can be assumed as a default.

- Long-Run Demand Feedback. Constructing or expanding a facility will induce some travel in the long run even if the price is unchanged from the baseline. Therefore, the baseline forecast should include growth in travel that will result from traffic-generating activities that locate to take advantage of the services provided by the facility at the baseline price. The long-run elasticity amplifies this effect up or down, but does not substitute for it.

If forecasts are based on historical patterns over a time horizon of half a dozen years or more, then the feedback effect implicitly is built in. Whether it needs to be made explicit or refined is an open question, but the impacts of errors in out-year forecasts are suppressed somewhat by discounting.

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[9] Cambridge Systematics, and JHK Associates (1979), Dowling Associates (1993), Dowling and Colman (1995), Goodwin (1998). Hansen (1995), Hansen, Gillen, Dobbins, Huang, and Puvathingal (1993), Kroes, Daly, Gunn, and Van der Hoorn (1996), and Pells (1993) study the time lag in response to highway capacity increases; Cairns, et al. (1998) study responses to reductions in capacity.

[10] The empirical evidence and methods for estimating highway travel demand elasticities are covered in Appendix C.

B.5 Summary

Some of the ambiguity and confusion that surrounds the discussion of induced demand might be dispelled by applying the following definitions and principles:

(1) The term *induced* means a movement along a travel demand curve as a result of changes in *endogenous* factors, which can be represented as components (time, running cost, money) of a generalized price.

(2) The measurement of induced travel is dependent upon the *market* for which the demand curve is defined; induced travel defined at the facility level will include traffic diverted from parallel routes, while induced travel at the regional level will include only trips that are new to the region.

(3) A useful distinction can be made between short-run demand and long-run demand. Movement along the *short*-run demand curve amounts to *induced traffic*. However, movement along the long-run demand curve constitutes a *shift* in the short-run demand; this can be called *induced demand*.

(4) Benefit-cost evaluation of projects requires that baseline demand forecasts be adjusted to take into account induced demand, both short and long run; simply stated, improvements that change user costs should be evaluated in the light of whatever changes in volume will actually occur. Such demand curves are referred to as general-equilibrium demand curves.

(5) If the short-run elasticity is zero, then traffic volumes are unresponsive to changes in price within a single demand period, and the demand curve is vertical. If the elasticity of the long-run share (i.e., excluding short-run effects) is zero, then there are no long-run effects (e.g., no investment in highway-related facilities or land-use changes) stimulated by highway pricing and investment policies. Empirically, neither of these conditions seems to apply.

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APPENDIX C

Demand Elasticities for Highway Travel

Douglass B. Lee, Jr.

An elasticity summarizes a large amount of information in a single number. Levels and distribution of incomes, price levels of the specific good and of substitute and complementary goods, preferences and tastes, transaction costs, etc., can, *ceteris paribus*, affect the measured value of any particular demand-price elasticity. The elasticity concept normalizes for the measurement scales (e.g., pounds or kilograms, dollars or pesos) and price levels (to the degree that the demand curve is constant elasticity), but other factors are ignored or implicitly averaged. Although the price elasticity of travel demand is frequently mentioned in discussion, there is no direct empirical measurement of elasticity with respect to the price of highway travel, and there are several alternatives about even what that price consists of.

The review and synthesis presented in this Appendix was conducted for the purpose of establishing values for use in the HERS model to represent the short-run elasticity of demand on a given highway section, and to estimate the long-run share parameter used for estimating induced demand, as described in Appendix B. For the 1999 *Conditions and Performance* report to Congress, the values selected were -1.0 for short-run elasticity, and -0.6 for the long-run elasticity supplement, giving a full long-run elasticity of -1.6.

C.1 Theory

The Meaning of Elasticity

As an empirical measure, an elasticity is a microeconomic aggregate: it summarizes demand in a specific market at a point in time, at or near the prevailing price and quantity. A market could be a highway facility, a corridor, or an entire region. A point in time

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might be a peak hour, or a daily average. The basic concept can be represented as an arc elasticity between two demand points,

$$e = \frac{\%\Delta v}{\%\Delta p} = \frac{\Delta v}{\Delta p} \times \frac{p_0}{v_0} \qquad [1]$$

where v_0 = initial traffic volume and p_0 = initial price. Elasticity can be thought of as a measure of slope normalized for the arbitrary measurement scales of p and v, and, indeed, the form to the right of the second equal sign is a slope multiplied by the initial demand point. If the derivative of the demand curve is substituted for the slope, the elasticity is instantaneous at the given point, rather than over an arc. For exposition, the arc form will be used, but the principles apply to either form.

Transferability

For a different time point on the same facility, a different group of users may respond differently to a change in price, because they have different incomes, demographic characteristics, and tastes. Moreover, prices in related markets (e.g., parallel facilities) may be different. If comparing different facilities, the above may be different, as well as differing substitute alternatives (routes, carpool and transit options, destinations, schedule options). Different days, seasons, regions, and forms of "price" all limit the transferability of an elasticity measured in one context to another context.

Hence—unlike the speed of light or the age of a rock—there is no underlying true number waiting to be discovered. Similar circumstances are likely to exhibit roughly similar elasticities, but the most important characteristics of these circumstances need to be made explicit. Given the nature of the empirical evidence, selecting appropriate values must rely heavily upon *a priori* reasoning.

Price, Output, and Market

The basic economic model of exchange reconciles supply and demand in a market, using price. The "price" is the market value of the resources given up by the buyer and received by the seller, accomplished in modern markets by means of some form of money that both parties agree to use as representing valuable resources. The market of interest in the present context is highway travel, measured as vehicle miles of travel (VMT). A single market has a single price, so a highway market could be a street length between intersections at a specific time of day. The concept of a market can be applied more broadly, however, to consist of a facility whose demand is averaged over the day, or a network of facilities. Elasticities will generally be larger (elastic) the more alternatives (route shift, time of day shift, add or forego trip) are available, and smaller (inelastic) the more broadly the market is defined (e.g., region versus facility). For present purposes, the focus is on a single facility, and its daily VMT.

Money Price

If the price measure were limited to the money price paid by the user to obtain the services of the highway, then such characteristics as travel time, pavement roughness, risk of accident, scenery, and curves and grades would be attributes of the service. Such a money price (assuming the user had access to a vehicle) would be a multi-part price consisting of vehicle registration fee, drivers' license fee, excise taxes on fuel and tires, and tolls.

This formulation of the highway market has limited usefulness for several reasons. Primarily, the fees paid are a small part of the total cost to the user of highway travel, and attributes of the good (such as travel time) dominate the choice rather than price. Because travel is a derived demand, at least some of the attributes can be thought of as part of the cost to be minimized, including time and operating costs as well as user fees.

Generalized Price and Its Components

Hence, an alternative formulation is to treat some of the attributes as disutilities, and translate them into a dollar price. Operation of the vehicle, travel delay, and tolls are thus all costs to the user, or components of the price. In practice, the only way to estimate the demand elasticity of highway travel is to build up total travel demand elasticity from elasticities of the components of user costs.

Three relationships are central to estimating total demand elasticities from component elasticities: the component's own-price elasticity, the correspondence of a change in the price of the component to a change in the price of travel, and the expansion from the component to the total elasticity.

Price Elasticity for a Component

If *X* is a component of the price of travel, and we observe its own price elasticity, then

$$e_X = \frac{\Delta q_X}{\Delta p_X} \times \frac{p_X}{q_X} \qquad \textbf{[2]}$$

where e_X is the demand price elasticity of good *X*, Δq_X is the change in the quantity of *X* that is consumed (e.g., gallons of fuel), Δp_X is the change in the price of the good (e.g., the price of gasoline at the pump), p_X is the initial price of the good, q_X is the initial quantity of the good, and $\Delta q_X / q_X$ is the percent change in the quantity of good *X*. This is a relationship between the price of the component and *its* consumption, not the consumption of the overall good of which *X* is a component.

Leakage from Component to Total

Higher fuel prices, for example, are partly absorbed in improved fuel mileage, so that the percentage reduction in fuel consumed is greater than the percentage reduction in VMT. The extent of this "leakage" between the component price elasticity and travel demand elasticity depends upon the component, and the possibilities for economizing on the component other than by reducing travel. A change in the price of a component of travel cost is not exactly an equivalent change in the price of travel, and less so in the long run. In general,

$$e_{T,X} = \sigma \times e_X, \quad \sigma \le 1 \qquad \textbf{[3]}$$

where $e_{T,X}$ = elasticity of travel demand with respect to a change in the price of *X*, and σ = a shrinkage factor representing the share of a reduction (or change) in consumption of X that consists of reduction in travel. A $\sigma = 1$ implies that the component and travel are necessarily consumed in fixed proportions.

Expansion From Component to Total

If the elasticity of VMT with respect to a part of the price is known, then the elasticity of total travel demand is simply an expansion from the part to the whole,

$$e_T = \frac{e_{T,X}}{p_X/p_T} = \frac{\sigma e_X}{p_X/p_T} \qquad [4]$$

where e_T = demand elasticity for travel (the overall good), p_T is the price of travel, and the component elasticity e_X is substituted using **[3]**. The bottom of the right-hand side is the share of the component in the total price of travel. For example, if the elasticity of gasoline consumption with respect to its own price is -0.25, and the shrinkage factor is 0.6 (from changes in fuel efficiency), then the elasticity of *travel* with respect to gasoline price is -0.15. If fuel is 20% of the cost of travel, then the implied demand elasticity is -0.75 with respect to the total price of travel.

C.2 Empirical Estimation of Price Components

From Evidence to Application

Because generalized price is being used rather than narrower money price, the analysis proceeds in two major steps: first, each of the components of generalized price (operating cost, time, etc.) is studied for what the empirical evidence says about the total vehicle price elasticity; and second, the total vehicle price elasticity is applied to specific contexts where various elasticity components (route change, forgo trip, etc.) may or may not be available as substitutes. The overall process is represented in Figure C-1.

Empirical studies are mainly oriented toward changes in one component of price; these studies can be extrapolated to the full price. Once a total price elasticity is determined, then that value must be adjusted to apply to a specific context such as a highway section. For use in the 1999 *Conditions and Performance* report, the section-level effects are assumed to cancel each other, on average, and the overall price elasticity is used for sections. The evidence and analysis presented here pertain primarily to passenger travel, although freight movement can be expected to respond in similar ways.

It is important to remember that the analysis concerns vehicle-trips, not person-trips. Although persons make the decisions for vehicles, vehicle trips are more readily observed, and the price typically applies to vehicle travel rather than to person trips.

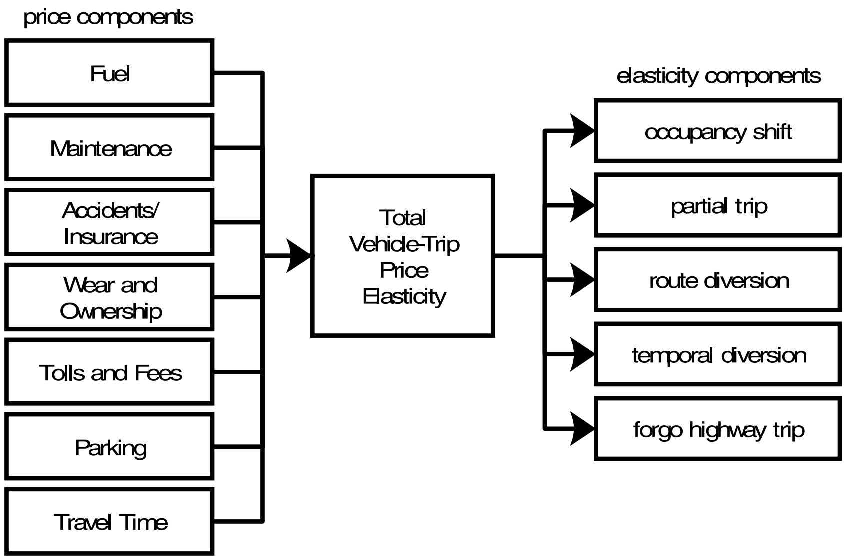

Figure C-1. **Primary analytical steps in generating project-specific elasticities.**

Construction of Travel Demand Elasticities from User Cost Components

The methodological strategy for moving from information about the components of user cost or "price" to travel demand elasticity is represented in Figure C-2 and described below:

(1) The first step is an accounting problem to define the user cost categories for which data have been collected and tabulated, matched with those for which elasticities have been or could be measured. The units are in dollars per vehicle mile of travel.

(2) Because price per VMT—even by component—is an average of unlike conditions (large and small cars, urban and rural traffic), a more robust result is obtained by considering several different data sources and reconciling the numbers. Again, the choice of measure must match whatever is used or implied in empirical elasticity estimates.

(3) A major source of uncertainty in expanding from component to total price is which components should be included in the "price" to the user. Possibilities range from using only short- run variable out-of-pocket costs that the user "perceives," to all costs paid by the user including travel time.

(4) Within this range of uncertainty, low and high percentage shares can be calculated for each of the price components.

(5) Empirical estimates of any relevant elasticity estimates can be combed from the literature, formal or informal. Not all components are suitable for estimating elasticities empirically (e.g., accidents), and some that are suitable may not have been the subject of published estimates.

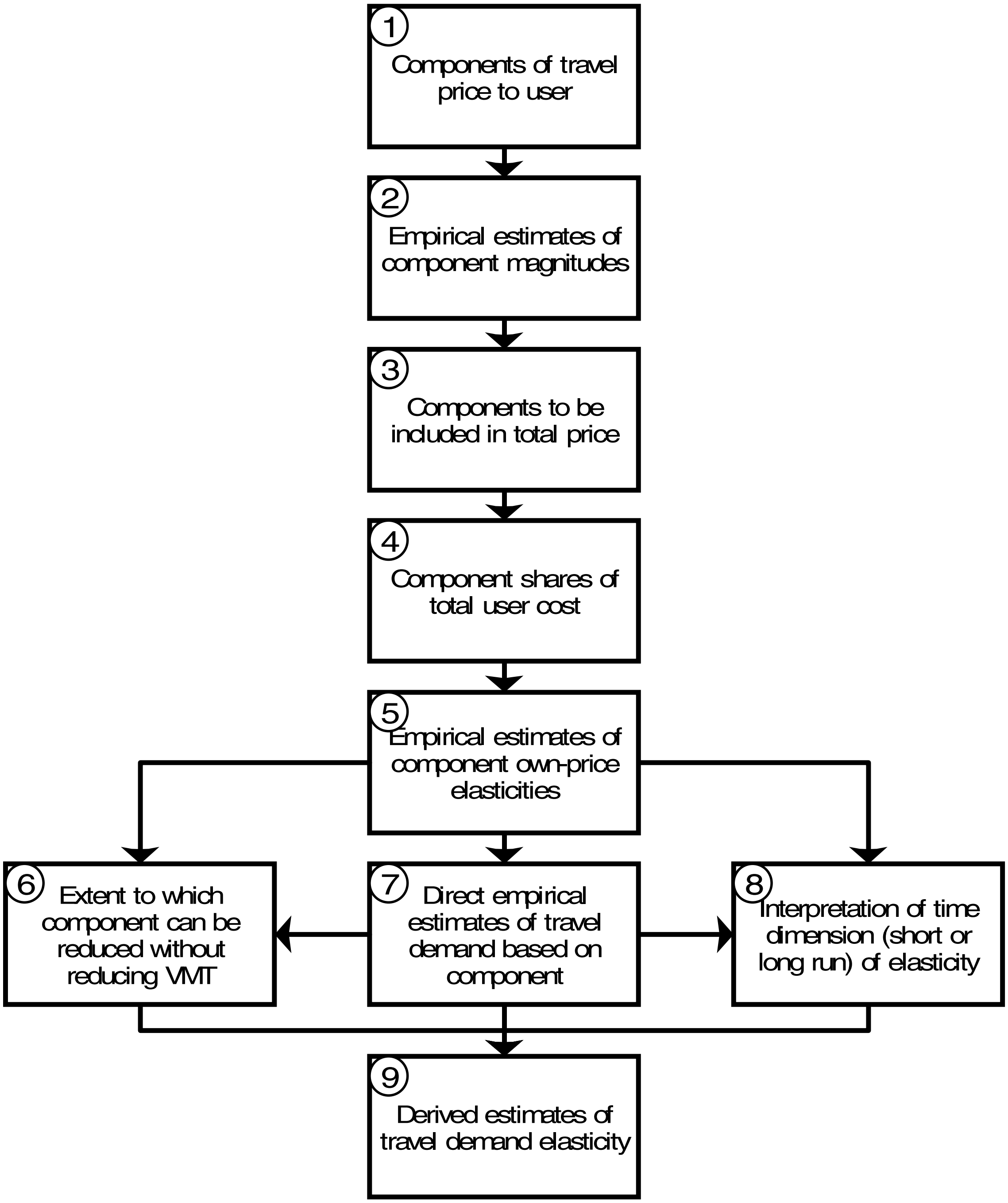

Figure C-2. **Method For Building Travel Demand Elasticities From Price Components.**

(6) Given an own-price elasticity estimate for a component, and its share in the total price, the next problem to be resolved is the extent to which a change in the consumption of the component results in the same percentage change in VMT, i.e., the shrinkage factor.

(7) For those instances in which a travel demand elasticity has been estimated from changes in the price of the component, the component elasticity can be inflated directly to the total demand elasticity; this information can also be compared to any own-price elasticities to assess the "leakage" into non-VMT changes.

(8) All of the empirical elasticity estimates must be interpreted along several dimensions, the most important being whether it is a short-run or long-run estimate. Many published estimates are ambiguous regarding the time span covered.

(9) The above information, subject to its range of uncertainty, can be distilled into estimates of short-run and long-run travel demand elasticities based on generalized price.

These steps are explained and implemented in more detail below.

Accounting Framework for Price Components

Seven categories of user cost are listed in Table C-1. They are intended to be non-overlapping and exhaustive. Fortunately, this set of categories is generally consistent with various estimates of user costs. The purpose of these categories is to be able to combine them in subsets that provide alternative measures of the "price," to distinguish fixed from variable costs as a means for defining the relevant costs, to match with empirical estimates of costs, and to match up with empirical elasticity estimates.

Table C-1. User Cost Accounting Framework

Category	Scope
Fuel	gasoline, diesel fuel, or other fuel consumed by motor vehicles, including taxes
Maintenance	oil, parts, periodic maintenance, unscheduled maintenance, tires, excise taxes
Accidents and Insurance	costs of accidents (internal), insurance administration and profit
Vehicle Wear and Ownership	wear and tear, additional depreciation, financing, sales and excise taxes
Tolls and Fees	tolls, registration fees, license fees
Parking	cost of parking to the user at work, shopping or other
Travel Time	dollar value of time spent in traveling

Estimates of Component Shares

Estimates of national averages for the cost components of highway travel are provided in Table C-2. All are intended to cover internal costs borne by users, omitting externalities, since elasticities necessarily must be based on internal costs. Four sources are presented, each of which offers a different orientation:

Table C-2. Estimates of Components of User Cost ($/VMT)

Component	Back-of-Envelope	Delucchi	Runzheimer	FHWA
(1) Fuel	0.058	0.069	0.067	0.061
(2) Maintenance	0.087	0.073	0.052	0.053
(3) Accidents and Insurance	0.087	0.133	0.070	0.070
(4) Wear and Ownership	0.125	0.142	0.248	0.127
(5) Tolls, Fees	0.002	0.015	0.003	0.009
(6) Parking	0.022	0.004	0.019	0.013
(7) Time	0.306	0.344	0.344	0.344
Total Variable	0.232	0.275	0.189	0.184
Total Monetized	0.381	0.436	0.459	0.333
Total Variable w/ Time	0.538	0.620	0.495	0.490
Total Internal	0.687	0.780	0.765	0.639

Notes:

(1) Fuel -- BoE assumes $1.15 for fuel (including excise taxes) and 19.7 miles per gallon average fuel economy for all passenger vehicles (FHWA 1996 Highway Statistics); Delucchi value is sum of fuel costs, oil company producer surplus, and fuel taxes (Delucchi, 1998), divided by total 1991 US annual VMT of 2,172 billion (Highway Statistics); Runzheimer values are extracted by applying their 1998 percentage distribution of costs for and intermediate car to their estimates of annual fixed ($6,934) plus operating costs ($2,240) of a Ford Taurus (Runzheimer, 1997, 1998); FHWA values are for an intermediate sedan, including fuel taxes, at $1.196 per gallon (Jack Faucett Associates, 1991).

(2) Maintenance -- BoE based on assumed value of $1,000 per year for oil, tires, parts, and maintenance, and an average annual mileage for passenger vehicles in 1996 of 11,492 (Highway Statistics); Delucchi estimates national expenditures on maintenance, including in-house government and private fleet maintenance, and sales taxes, but excluding external property damage, divided by national VMT (see Fuel); Runzheimer and FHWA are same as for fuel.

(3) Accidents and Insurance -- BoE assumes $1,000 per year per vehicle for insurance and accidents, divided by average mileage (see Fuel); Delucchi's estimates include insurance administration, accidents paid by users, and pain and suffering "inflicted on oneself," but not external costs; Runzheimer and FHWA same as for Fuel.

(4) Wear and Ownership -- BoE assumes a capital cost of $12,000 over 5 years, and average passenger car mileage (see Fuel); Delucchi estimates private ownership costs, excluding sales tax, divided by total US VMT (see Fuel); Runzheimer and FHWA same as Fuel.

(5) Tolls and Fees -- BoE takes 1996 total toll payments nationally of $4 billion (Highway Statistics) divided by 1996 US VMT of 2,360 (Highway Statistics); Delucchi omits user fees as transfers, so a rate of 1.5 cents per VMT is inserted; Runzheimer estimates registration fees only; FHWA includes parking with tolls, but no adjustment is made here.

(6) Parking -- BoE assumes $1 per day per vehicle for 250 days per year, over 11,492 annual miles (see Maintenance); Delucchi's values combine paid private parking and public parking; Runzheimer provides only a residual "Other" category; FHWA includes tolls with parking.

(7) Time -- BoE uses 60% of US DOT (1997) "personal" wage rate of $17 and 1.2 persons per vehicle at an average speed of 40 mph; Delucchi values time in three categories -- paid time that is delay, paid uncongested time, and unpaid time whether delay or not; neither Runzheimer nor FHWA include time costs, so the Delucchi value is used.

(1) Back-of-Envelope: The value for the particular component is estimated from a few aggregate totals, rates, and averages. This approach provides a reality check on whether other results are plausible.

(2) Delucchi:[1] In his research, Delucchi has made original estimates of national totals for most of the components for 1991, broken down finely enough to permit aggregation along several dimensions. For each item, he provides a low and high estimate, which are averaged here. His estimates are unique for including many imputed values, such as travel time, uncompensated accident costs borne directly by users, and accident costs paid from sources other than insurance.

(3) Runzheimer:[2] The Runzheimer International Corporation is a consulting firm that collects data on highway vehicle costs and other business expenses, and compiles these into planning and forecasting estimates for business use. Their "intermediate vehicle" is a full size sedan used 20,000 miles per year and traded in after three years.

(4) FHWA:[3] Up until 1991, the Federal Highway Administration intermittently contracted for tabulations of cost components for various types of highway passenger vehicles, and published the numbers. The most recent set is based on data collected in Maryland.

The sources and methods for tabulating the various price components are described in the notes to the table.

Components Included in the "Price"

Several criteria might be considered for guiding the definition of total price:

(1) Out-of-pocket costs: These include fuel, maintenance, parking, tolls, vehicle wear, variable insurance, and other variable costs to the user that are affected by whether a given trip is taken or not.

(2) Full, average, or long-run costs: Ownership costs and the annual portion of insurance might be added to out-of-pocket costs.

(3) Generalized cost or generalized price: All variable and fixed costs, plus travel time, can be included.

(4) Perceived cost: Costs might be limited to those the user explicitly recognizes in making the decision to take a trip or use a vehicle.

Generalized price is preferred from a theory standpoint, because it allows all components of cost to be fused into a single dimension. Pragmatically, the relevant price is also affected by (a) how other elasticities have been measured empirically, for comparison, and (b) how elasticity is used in the model or analytic procedure into which the parameter is inserted.[4] With proper interpretation, different measured elasticities can be used to estimate a model parameter that is defined or based differently from the empirical sources.

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[1] Delucchi (1997).

[2] Runzheimer International (199, 1998)

[3] Jack Faucett Associates (1991)

[4] The HERS model uses a generalized price including time, operating costs, and accidents, but not user fees; demand is aggregated over peak and off-peak (therefore no time diversion) and applies to a single facility (therefore the elasticity includes route diversion).

Perceived price is an attempt to identify the components of price that are consciously recognized by the user, as a basis for predicting user behavior. Whether making this intermediate variable explicit adds anything to predictive accuracy is doubtful, and, in any event, it does not provide much guidance for which costs to include. Consumers tend to respond, as a group, to attributes and magnitudes that have some significant impact on their well-being, whether consciously perceived or not.

This means that the user response depends upon what decisions are at stake. If ownership is not in question, then only variable costs may be considered, and more so in the short run. Four alternative definitions for total price are given in Table C-2, ranging from short-run monetary costs to full long-run costs including travel time. The distinction between variable and fixed is not clean: vehicle wear is variable, while ownership is fixed. Insurance is typically paid annually and has a large fixed component, although most exposure to risk is from operation.

Component Shares of Total User Cost

The several definitions of total cost yield a range of component shares, shown in Table C-3. Obviously, the range of values is quite large, depending more upon which total is used than upon the source of data. With travel time being roughly half the cost, its inclusion makes a big difference.

Table C-3. **Component Shares in Total Price.**

Component	Low Share	High Share
Fuel	8%	36%
Maintenance	9%	48%
Accidents and Insurance	7%	37%
Vehicle Wear and Ownership	18%	54%
Tolls and Fees	0%	10%
Parking	1%	10%
Travel Time	40%	62%

Empirical Estimates of Own-Price Elasticities

The number of categories drops when considering which components are suitable for empirical estimation, and more so when actual estimates are tabulated. The cost of maintenance is difficult to keep track of, and either controlled or natural experiments are hard to imagine; no such studies were found. User responses to the risk of accident based on equipment such as air bags has been used to estimate users' implicit valuation of life, but users cannot be observed reducing either their travel or their rate of accidents in response to changes in risk. Tolls, fees, and parking are clearly candidates, but apply to very specific circumstances. Direct estimates of time elasticities have been made, and indirect estimates can be derived from changes in traffic induced by changes in capacity.

Income elasticities are regarded as exogenous for purposes of estimating travel demand elasticities, by assuming that price changes are not large enough or general enough to result in a significant change in income for the average traveler.

Magnitudes of the Leakages

The size of the shrinkage factor for fuel can be seen in Goodwin's (1992) review of elasticity estimates. Table C-4 summarizes his result for studies based on fuel price changes. The numbers are juxtaposed to permit comparison of elasticities of fuel consumption (average of over 100 separate empirical values) versus elasticities of travel (about a dozen numbers), stratified by whether a time series model or a cross-sectional model was used and whether the intent was short term, long term, or ambiguous.

Table C-4. **Goodwin's Review of Fuel Price Elasticities.**

Method	Fuel or Travel	Short Run	Long Run	Uncertain
Time-series	**fuel consumption**	-.27	-.71	-.53
	travel demand	-.16	-.33	-.46
Cross-section	**fuel consumption**	-.28	-.84	-.18
	travel demand	-	.29	-0.5

Source: Goodwin (1992).

Fuel elasticities are higher than travel demand elasticities, and long term elasticity estimates are at least twice as large as short term values, as might be expected. For fuel, the shrinkage from fuel consumption to travel consumption seems to be about 0.5 to 0.9, meaning that half to ninety percent of the reduction in fuel expenditure is the result of less travel.

For other price components, the shrinkage factor is more speculative. Increases in insurance and vehicle ownership costs might result in fewer vehicles but more mileage per vehicle, with the latter less than fully offsetting the former. Increases in road roughness increase wear and tear, reduce fuel mileage, and reduce speeds. Increases in tolls directly affect the cost per vehicle mile, but, depending upon how the tolls are graduated, could alter the mix of vehicles and the time-of-day distribution.

The largest user response is likely to come from those users for whom the price change is relatively largest. A fuel price or tax increase will affect long trips and vehicles with low fuel efficiency; insurance costs deter ownership in urban areas thereby shifting the geographic distribution of vehicles; high parking costs deter short trips more than long ones; high ownership or insurance costs deter vehicles with low annual utilization.

Durations of the Short- and Long-Run Adjustment Periods

Some responses occur within days or weeks, while others may take five or ten years to reach equilibrium. To usefully interpret an empirical elasticity estimate, the time dimension must be known. If the statistical measure for an empirical estimate includes all VMT or other changes that occurred within a year of the price change, then a short-run elasticity has been estimated. Longer lag periods for the same price changes yield longer run elasticities, but separating behavioral responses from background variation gets harder with longer lags.

Several studies reviewed by Cairns, et al. (1998) reveal the degree to which individuals change their travel patterns on a daily basis. Two studies, summarized in Table C-5, are illustrative. Of a group of commuters passing a given point on a road on a given day,

Table C-5. **Travel Behavior Variability**

Location: Time Lag: Type of Travel:	Leeds 1 Week commuting	Southampton 4 months regular trips
Same behavior[a]	60%	49%
Different time	7%	5%
Different route	14%	7%
Different mode	8%	1%
Different destination	5%	13%
No trip/different trip	6%	25%

Source: Cairns, et al. (1998).

[a] travelled the same route by car within the same 2-hour time period.

60% could be found a week later within the same 2-hour block; the rest were doing something slightly or completely different. A similar study with a longer time lag showed a smaller share doing the same thing. Other studies reinforce the same conclusion: individual travel variability is high on a day-to-day basis, and more so over longer time spans. This is without any significant changes in either exogenous or endogenous factors.

One implication is that—if stability is much higher in the aggregate than in the microscopic—attempting to predict individual travel behavior is less fruitful than using aggregate elasticities for endogenous changes. Another is that, with so many individuals making changes within a short time span, the responses of travelers to changed conditions is likely to be rapid. There is not a lot of inertia in travel patterns. According to Cairns, et al. (1998), roughly 50% of the response to a change takes place within 1 to 3 years, and 90% within 5 to 10 years. Hence, long-run elasticities tend to be about twice as large as 1-year or short-run elasticities.

C.3 Conversion to Total Price Elasticity

The results of the above process are displayed in Table C-6, showing empirical estimates of component travel elasticities, along with their implied short- and long-run total travel demand elasticities. The range of possible values is wide, extending from -0.22 to -3.7 for short-run demand and -0.57 to -5.1 for long-run demand. The most plausible numbers, however, lie in the -0.5 to -1.0 range for short-run demand, and -1.0 to -2.0 for long-run demand. These elasticities apply to *vehicle* travel, not person travel, which can be considerably less elastic and still be consistent with these vehicle elasticities due to changes in vehicle occupancy and other adaptations.[5] The “low” values come from using the full generalized price, and reinforce the preference for full cost rather than subsets such as variable costs.

Table C-6. **Component and Total Travel Demand Elasticities**

	Component Elasticities		Implicit Total Travel Elasticities			
			Low		High	
User Cost Component	**SRE**	**LRE**	**SRE**	**LRE**	**SRE**	**LRE**
Fuel	-0.17	-0.33	-0.48	-0.93	-2.0	-3.9
Wear and Ownership	-0.12	-0.31	-0.22	-0.57	-0.6	-1.7
Tolls	-0.10	-0.19	-0.33	-0.63	-1.0	-1.9
Parking	-0.15		-1.17	-1.61	-3.7	-5.1
Time	-0.38	-0.68	-0.60	-1.07	-0.9	-1.7

Fuel Price Elasticities

Numerous empirical studies have estimated the price elasticity of gasoline, and a few have measured the travel elasticity with respect to fuel price. The review and summary by Goodwin described above reflects the results of these studies, and subsequent studies have tended to confirm his conclusions. Thus a value of -0.16 for short-run travel impacts and -0.33 for long-run impacts are used, with **[4]**, in Table C-6.

Ownership Elasticity

Holding exogenous factors constant, an increase in the real price of vehicles of the same quality causes a reduction in the purchases of vehicles, especially new ones. The most likely behavior response is to defer purchase of a new or better vehicle, and keep using the old one. If, however, the response is measured in the aggregate as total vehicle ownership, then fewer vehicles means less VMT, offset by the extent to which vehicles are shared.

Dargay (1998) compared several ownership and operation elasticities between the UK and France, including price elasticity and income elasticity. Converting the price elasticities to VMT elasticities, using a shrinkage factor of 0.9 and the values from Table C-3 in **[4]**, gives the results shown in Table C-6. The source of imprecision in applying ownership elasticities is the uncertain share of total cost per VMT comprised by ownership and wear-and-tear costs.

Toll Elasticities

Studies based on toll variations are somewhat inconsistent and not easily interpreted. A useful study is one by Gifford and Talkington (1996) that provides elasticity estimates for the Golden Gate Bridge in San Francisco of -0.187, based on toll variations over the days of the week as well as changes in the fee structure over several years.[6] They also review other toll elasticity studies. Because most trips are not tolled, national averages of tolls per VMT are not useful. Of trips that are tolled, $1.25 might be about average,

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[5] Cairns, et al. (1998) provide an illuminating list of examples that illustrate the many ways in which individuals and households can satisfy their travel requirements while reducing vehicle miles of travel.

[6] Harvey (1994) provides examples that are roughly consistent with Gifford and Talkington’s. Peter Samuel uses a phased-in toll increase on the Ohio Turnpike to make a back-of-the envelope calculation of trip elasticity of -0.23 and VMT elasticity of -0.15, in his *Toll Roads Newsletter* for February, 2000.

yielding a share of total costs on a 15-mile trip ranging from 10-30%. This range is used in Table C-6 instead of the range shown in Table C-3.

Elasticities in response to tolls are difficult to impute because the quality of travel, in delay time, often changes when the toll changes. For measuring elasticity, an ideal experiment is one in which travel time is constant while tolls change. Under even moderately congested conditions, a toll change results in trade-offs between money and time (value of time) as well as money and travel (price elasticity), not to mention time and travel (time elasticity). Separating these seems difficult.

Parking Price Elasticities

Shoup (1994), and Willson and Shoup (1990) review more than a dozen studies of parking pricing, including their own as well as Shoup and Pickrell (1980). From these studies it is possible to extract five case studies that provide sufficient data to construct ordinary price elasticities. In all of these examples, the price of parking was zero for the base alternative in the comparison, so the calculations in Table C-7 base the elasticity estimates on an assumed total price for travel, rather than for parking alone. The elasticity magnitudes are large even when the price change is measured against only a small share of long-run cost.

Table C-7. **Parking Total Price Elasticities**

	Trip Rate[a]		Parking Price[b]		Total Price Elasticity[c]	
Before/After Case Studies:	**Free**	**Priced**	**Free**	**Priced**	**Low**	**High**
Mid Wilshire, LA	48	30	0	58	-1.05	-3.33
Warner Center, LA	92	64	0	30	-1.65	-5.23
Ottawa CBD, Canada	94	80	0	30	-0.81	-2.56
Average					-1.17	-3.70
With/Without Case Studies:						
Century City, LA	39	32	0	23	-1.27	-4.02
Civic Center, LA	78	50	0	30	-1.95	-6.16
Average					-1.61	-5.09

Notes:

a Autos driven per 100 employees.

b Price in dollars per month.

c Full vehicle "backward" arc (low price to high) price elasticity based on 35-mile round trip average for LA reported in Willson and Shoup (1990), at an average user cost of $.22 per VMT for variable costs only (=$163 per month for the Low estimate) or $.70 for all costs including time but excluding parking (=$515 for the High estimate). Backward elasticities are lower than midpoint or forward arc elasticities for downward-sloping demand curves.

In the before/after cases, the price of parking changed at a particular work site, and the behavior responses were tracked for up to a year after parking became priced. Some of the employers had ridesharing incentive programs, which were ineffective so long as parking was free. These examples are interpreted as representative of short-run demand elasticities. The with/without cases compare similar work sites, one priced and one not. These are interpreted here as long-run elasticities, on the rationale that commuters had sufficient time to make long run adjustments. These elasticities would be higher if all employee parking were priced, because more people at more sites would be seeking ridesharing or transit arrangements.

Because parking is free to the user for 99% of all trips (over 90% of urban work trips), the average share of parking in the cost of travel to the user is not a valid base value for these elasticities. As Shoup (1994) states,

> “It is important to remember that the elasticity estimates [average 0.15] refer to commuter response to changes in only the parking price of their trip and are therefore smaller than the elasticity of demand with respect to changes in the full price of automobile trips.”(p. 159)

He gives other reasons why these estimates are low, including the likely availability of cheaper parking nearby and the inelasticity of work trip demand.[7]

Time Cost Elasticities

Several studies have tabulated traffic volumes subsequent to an increase in capacity, or occasionally in response to a decrease in capacity or change in travel time. For those based on change in capacity, the measure of elasticity is

$$e_{T,\,capacity} = \frac{\%\Delta VMT}{\%\Delta cap} \qquad \textbf{[5]}$$

where $\%\Delta cap$ = percent change in capacity, with capacity measured in lane miles. Hansen et al. (1993) estimate this elasticity for eighteen highway sections in California, and include controls for trend VMT. To transform this measure into a price elasticity requires substituting a price measure for the capacity measure, such that

$$e_T = \frac{\%\Delta VMT}{\%\Delta p} = \frac{\%\Delta VMT}{\%\Delta cap} \times \frac{\%\Delta cap}{\%\Delta p} = e_{T,\,capacity} \times \frac{\%\Delta cap}{\%\Delta p} \qquad \textbf{[6]}$$

i.e., a conversion factor is needed from the Hansen elasticity to a price elasticity, consisting of the ratio of an increase in capacity to its corresponding reduction in price. Taking time as the only component affected, the question is what are the time savings from a given added capacity? Most of Hansen’s expansions are from four to six lanes or six to eight lanes; if it is assumed that two lanes in the same direction are congested, and that adding a third will increase average speed from 40 to 60 mph[8] for at least a few years, then a 50% capacity increase is equivalent to a 33% time savings (neither the value of time nor occupancy affect this result), for a conversion factor of -1.5. Thus Hansen’s

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[7] Harvey (1994) offers examples from San Francisco and Boston airport parking, which are consistent with Shoup’s summary if Harvey’s elasticities measure the number of vehicles parking. This does not necessarily equate, however, to the same percentage reduction in VMT, because some of the deterred parking is shifted to taxi trips.

[8] This speed change implies an average savings of 0.50 minutes per VMT. Using the HERS (Chapter 6) delay equations for expressways, which model average daily delay per VMT as a function of AADT/c(apacity), a 50% increase in capacity at an AADT/c of 15 (fairly high) results in delay savings of 0.855 minutes per mile, whereas an initial AADT/c of 12 yields a savings of 0.255 per mile.

low or short-run value of about 0.25 becomes -0.375 and his high or long-run value of 0.45 becomes -0.675.

Cohen (1995) reviews several time-travel elasticity studies. The results are somewhat erratic, but generally consistent with the above. Often, some types of induced traffic are counted (e.g., new travel by users already in the market) and others omitted (e.g., route diversions). Unlike other components of user price, time cannot be economized by sharing the cost among additional vehicle occupants. Therefore, elasticity with respect to time cost should be lower than for the other components.

C.4 Conclusions

Despite the widely varying orientations, data sources, and scope of applicable empirical studies, and the fact that none was attempting to estimate total travel elasticity, the results are roughly consistent. Users respond to changes in any of the components of travel cost that are measurable, and the response starts immediately and continues over many years.

Taking the short run to be approximately a year or less, vehicle demand-price elasticity tends to fall in the range of -0.5 to -1.0, with -0.7 to -0.8 being the most likely for typical conditions. The long run may occur over twenty years, but five years is enough to cover most of the effects. long-run elasticities are about twice as high as short-run, with a range of about -1.0 to -2.0. Response to variable and obvious money costs such as parking and fuel show higher elasticities than for fixed and more hidden costs. These elasticities apply to vehicle-trips, not person-trips.

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APPENDIX D

Basic Theory of Highway Project Evaluation

Douglass B. Lee, Jr.

The criterion for making good investments is to select projects for which the net benefits are positive, i.e., incremental benefits exceed incremental costs. The major analytic steps are: define alternatives, evaluate impacts, and select the project with highest net benefits. If pricing is determined independently of marginal cost, however, pricing is exogenous and the investment evaluation is necessarily in a second-best mode.

The HERS Model

The HERS model incorporates demand elasticity and benefit-cost evaluation principles that are specific to the investment and policy alternatives typically considered at national and local levels. As highway investment concerns shift, the HERS model attempts to adapt by making explicit the variables and relationships that will permit the model to realistically address the new concerns. In doing so, the model becomes more general in its scope and more flexible in its application to questions of interest.

For the 1997 *Conditions and Performance* report to Congress, the HERS model was extended to utilize demand elasticities, such that highway improvements that lowered or raised user costs could lead to changes in travel volumes, and that over the long run the effects of improvements could be to shift the demand curve from where it might have been placed in initial forecasts (See Appendices B and C). Also, HERS was modified to estimate and take into account emissions of air pollutants, although the feature was not turned on until the 1999 report to Congress.

While HERS recognizes a “price” to the user, it does not incorporate a money price that is separate from user time and operating costs. Fuel taxes and tolls are therefore ignored, both in estimating demand and as potential policy instruments such as for congestion pricing.

This appendix presents the principles that apply generally to evaluating highway improvements, under conditions of exogenously-determined arbitrary pricing. The HERS model implements a subset of these principles. The purpose of displaying a

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broader scope is to illuminate the capabilities of the HERS model in the context of the more general theory, and to indicate the directions in which the model might be modified to extend its applicability.

D.1 Project Description

A physical facility can be represented for evaluation purposes by its unit costs with respect to traffic volume, measured as vehicle trips per hour. Three functions of volume provide the information necessary for calculating net operating benefits: average variable cost (*AVC*), marginal cost (*MC*), and price. Assuming a base alternative and one project alternative, the physical characteristics of each alternative are given by their variable cost curves, while the price curve constitutes the policies affecting how the facility is operated. All variable costs, whether monetized or not, are included. Cost and price components are assumed to be converted into a common numeraire (dollars), referred to as generalized cost or generalized price, meaning that it combines money and in-kind components on the same scale. Neither fixed costs nor fixed charges (e.g., annual vehicle license) are represented in the diagrams.

In general, at any given volume, marginal cost, average variable cost, and price to the user are all different. *MC* and *AVC* are mathematically related, and will diverge if any component of cost varies with volume (or v/c), i.e., *MC* is unequal to *AVC* if unit cost (*AVC*) goes up or down with volume. Because unit travel time costs rise with congestion, for most volume levels marginal cost lies above average cost. Price includes user charges, which are transfers and not costs, and excludes externalities and agency costs (facility wear, maintenance, and operation), which are costs that are not part of the price.

Marginal Cost

The marginal social cost curve is the guide for efficient pricing, so if $p = MC$ at all volumes, then net benefits in the short run are maximized for the facility. In this special (first-best) case, price and marginal cost are the same. As shown more generally in Figure D-1, price, represented by the price function, is not directly tied to marginal cost, labeled *MC*. Since the price function determines the quantity demanded by its intersection with the demand curve, actual volume is q_0 at a price of p, with a marginal cost of mc and an average cost of ac. The inefficiency from not pricing at marginal cost is given by the triangular area bounded by p_{mc}, mc, and p.[1]

Average Cost

Variable social costs include travel time, fuel, accidents, other vehicle wear and operating costs, damage from emissions and noise, and facility wear, maintenance, and operation (agency costs), but not fuel taxes or tolls. They are variable because they increase

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[1] The welfare loss from inefficient pricing does not enter in to the measurement of second-best benefits, but recognition of the inefficiency provides some insights when comparing second-best benefits to first-best pricing.

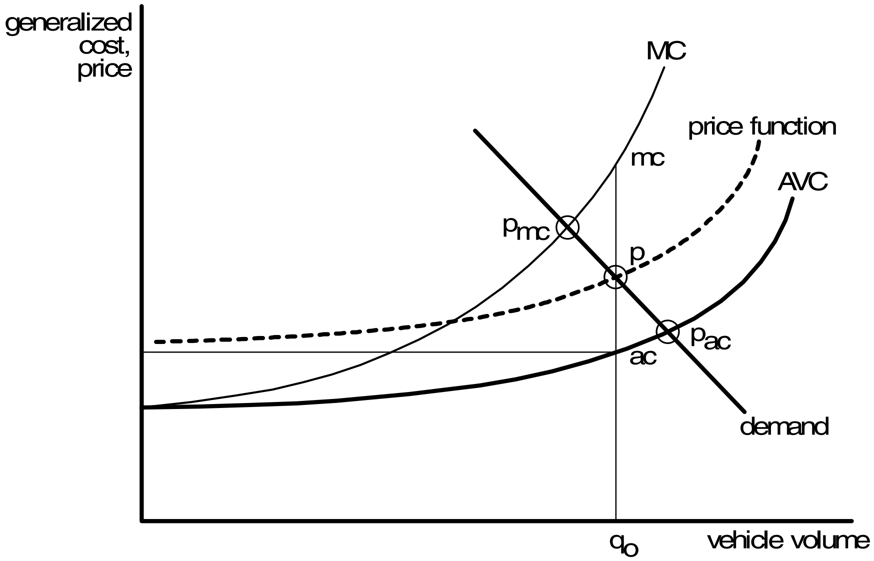

Figure D-1. **Three Functions of Trip Volume.**

with vehicle miles traveled. Their combined average unit cost per vehicle mile (*AVC*) might rise, decline, or remain constant with volume, which is a rate of flow. In fact, most of the components of variable cost vary slightly with volume, due to congestion, but the one that varies by far the most is travel time.

Because users are faced with the average rather than the marginal cost of travel time, it is frequently assumed that price and average cost are the same, but this usually is not true because of user charges, agency costs, and externalities. The *AVC* and *MC* functions are mathematically related, such that either one could be derived from the other, but it is the components of average cost that can be observed empirically.

Total variable cost can be measured either as the area under the marginal cost curve (e.g., up to q_0) or as the average variable cost (*ac*) times the volume (q_0), the latter being a rectangle, as shown in Figure D-1. This relationship will be used later.

Price

Price is the cost to the user, and includes travel time, accidents, and operating costs as well as money payments that vary with usage. The price function in Figure D-1 assumes that travel time is the main reason the generalized price varies with volume; user charges are approximately constant per vehicle mile, such as through a fuel tax.

The price function in this diagram is shown as lying above average cost. This might be the case if variable user charges exceed variable externalities and agency costs. If the reverse is true, then the price function lies below *AVC*, as shown in Figure D-2. The same relationships hold as before, although the inefficiency triangle is relatively larger. For congested conditions, it is unlikely that price will be above *MC* without a congestion-related toll, but price could be above *AVC*. Whether price is above or below *AC* depends upon the magnitude and valuation of externalities and agency costs relative to user charges.

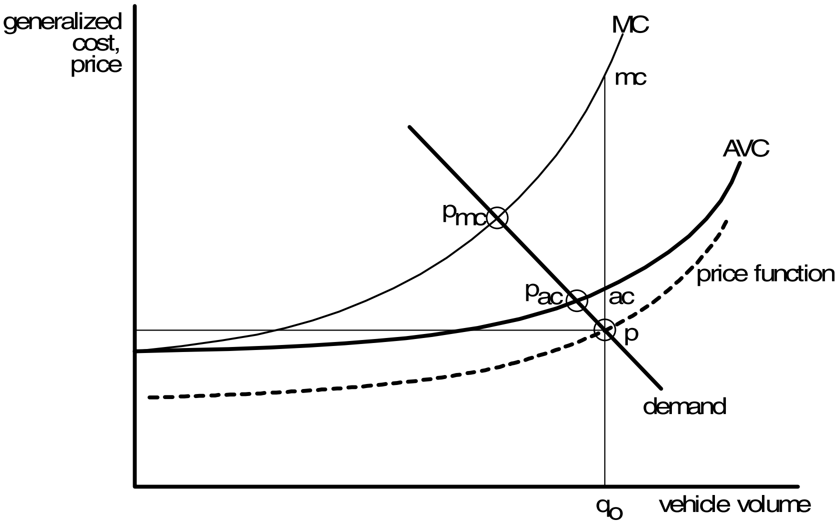

Figure D-2. Three Functions with Price Below *AC*.

Thus volume could be determined by any of the three functions, shown at the circled points in Figure D-1 or Figure D-2: by marginal cost at p_{mc}, for efficient pricing and first-best evaluation; by average variable cost at p_{ac}, which ignores actual user charges, agency costs, and externalities; or by the price function at p, which is the most general case.

Constructing the Demand Curve

The demand curve shows the quantity that will be taken by consumers across a range of prices, generalized to include time and running costs. In reality, this demand curve is constantly shifting, affected by user preferences as well as their knowledge of what conditions will actually pertain at their time of usage. For analytic purposes, the demand curve is assumed to be fixed—or represented by some average—for some period of time. An example of a demand period is the AM peak period, lasting several hours in larger urban areas. A single demand curve might represent the AM peak, or the AM and PM peaks combined; time periods do not need to be contiguous to be treated as a single demand period.

The minimum information needed to construct a demand curve is a price, a quantity, and an elasticity at that point. The price could be the average generalized price during peak periods, namely, the sum of travel time, running costs, and user fees representative of peak times.[2] The quantity is the average traffic volume for the peak, in vehicles per hour. An elasticity can be selected by comparing the project to other facilities with

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[2] See Table D-1 below, page D-10.

respect to the mix of components of price, the substitutes available, and the types of vehicles and trip purposes. Ideally, the elasticity should be compatible with the nature of the project, e.g., include diversions if the project is a single facility. The demand curve could be disaggregated into separate analyses for each market segment (e.g., trucks, commuters, recreational travelers), but some averaging is always necessary. A single demand curve for all users is assumed here.

With a single elasticity value, the functional form of the demand curve can be either straight line or constant elasticity. Given the demand point (p, q_0) in Figure D-2, only one demand curve of each type passes through that point with the given elasticity at that point. A straight line is used here.

Project Alternatives

To evaluate a project, a set of curves is needed for each of the base and the project alternatives, as shown in Figure D-3. Data for the base alternative are designated with a “0” subscript, and with a “1” for the project alternative.

The marginal and average cost functions are characteristics of the facility, resulting from its capacity, geometrics, terrain, pavement condition, and so forth. The price function is partly endogenous to the facility in that it includes some variable costs, and partly exogenous in the form of user charges and regulation. The price function could be made to go through the point p_{mc} by the correct congestion toll, in which case the facility would be operating efficiently. Another possibility is that externalities (except delay) and agency costs are exactly offset by user charges, such that the price function follows the *AC* curve. These are special cases of the general case presented here.

D.2 Single-Period Evaluation

A highway improvement—resurfacing, reconstruction, additional lanes—will change user costs by some amount, resulting in operating benefits. Reductions in running costs, travel time, and accidents are both reductions in price and real benefits. Savings in agency costs and externalities are real benefits but not included in the price, whereas savings in user fees are not real benefits. The impacts of each improvement can be estimated from its induced traffic volume (based on the price and demand curve) and variable cost savings. These net operating benefits (*NOB*) are estimated for the current period, and subsequent periods, over the lifetime of the improvements. Any improvement whose *NOB* over its lifetime exceeds its capital costs is considered feasible; among feasible improvement projects, the one generating the highest net benefits is preferred.

Short-Run Effects of Improvements

Highway improvements that reduce congestion (by expanding capacity), or reduce vehicle wear and fuel consumption, or reduce accidents, have the effect of lowering the price to the user and stimulating greater volumes, depending upon the elasticity of demand. If

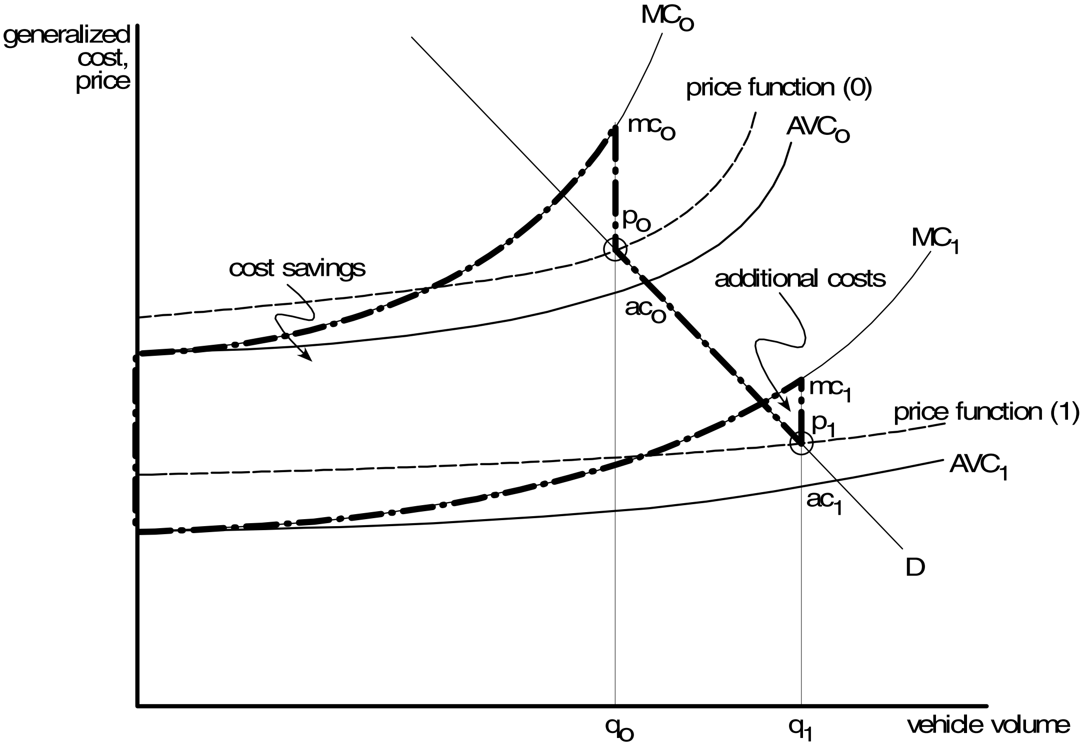

Figure D-3. **Net Operating Benefit (*NOB*) for a Project.**

the short-run price elasticity is non-zero, changes in the generalized price will cause changes in volume, within the same period, by movement along the demand curve.

To some extent, capacity expansions are self-limiting, in that induced traffic reintroduces congestion, which offsets some of the initial time savings from expansion. This supply-demand equilibrium may not result in as high a volume as would be the case if there were no congestion, but congestion will remain below the original congestion level before the capacity expansion. It is not possible for the same level of congestion to return after the expansion as before, because the short-run demand curve slopes downward to the right, and demand in the short run stays on the same demand curve. In subsequent demand periods, shifts in the demand curve might lead to higher congestion than in the current period, but such demand growth would be at least partly exogenous.[3]

Incremental Net Benefits

Benefits of the project are generally a combination of cost savings and additional travel. The net of such operating benefits is compared to the net or sum or fixed costs, with all values discounted or annualized as appropriate. Figure D-3 can be used to illustrate the

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[3] This effect of exogenous growth overtaking short-run improvements is observed in TRB Special Report 245 (1995).

net operating benefit (*NOB*) of the project. This diagram assumes price lies above *AVC*; the (minor) consequences of changing this assumption will be shown subsequently. The measurement of *NOB* can be defined in two ways, using different combinations of the variable cost and pricing functions and the demand curve.

NOB Based on Marginal Cost

Total variable costs for the base alternative are represented by the area under the *MC* curve up to the existing volume q_0. For the project alternative, the corresponding area is lower but extends out to q_1. The cost difference is an area of cost savings between the two curves up to q_0, and an area of additional costs under MC_1 from q_0 to q_1. The latter is offset by the (not necessarily equal) incremental benefits from the additional trips, represented by the area under the demand curve from q_0 to q_1. The resulting *NOB* is the area outlined by the dot-dash line. It can be described as the area between the two *MC* curves and under the demand curve.

Where *MC* crosses above the demand curve, the area—marked “additional costs”—is negative; these disbenefits are a consequence of underpricing the project alternative, relative to marginal cost pricing. *NOB* could be increased by this amount if the new project were efficiently priced, but this is not an option with exogenous pricing. Correspondingly, *NOB* would be smaller if it did not include the inefficiency from underpricing the base alternative.

NOB Based on *AVC*

Because areas under the marginal cost curve can also be represented by rectangles constructed from the *AVC* curve, using the relation,

$$\int_0^q MC = q \times AVC_q \qquad \textbf{[1]}$$

the area under MC_0 up to q_0 is equal to the rectangle whose length is q_0 and whose height is ac_0 (read from AVC_0), as shown in Figure D-4. Similarly, the area under MC_1 up to q_1 is equal to the rectangle q_1 by ac_1. The difference between these two rectangles is the shaded area labeled “delay and cost savings,” minus the additional costs from q_0 to q_1, plus the area under the demand curve from q_0 to q_1. This shaded area is exactly equal to the outlined area derived from the *MC* curves.

“Old” versus “New” Trips

In practice, a distinction is made between trips that are already being made in the base case (up to q_0), or “old” trips, on the one hand, and additional trips (from q_0 up to q_1) generated by the reduction in price (from p_0 to p_1), or “new” trips, on the other.[4] A reason for making this distinction is the nature of the benefits to the two groups: old users have “demonstrated” or “revealed” (even if the demand curve is estimated or forecast) their willingness to pay for their travel, and so the benefits to them are the cost savings

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[4] It is likely, though not necessary, that most previous users of the base facility remain on the new facility to become “old” users, since they obtain what they had previously but now at a lower generalized price. The old-new distinction, however, is heuristic, rather than defining a fixed set of vehicles.

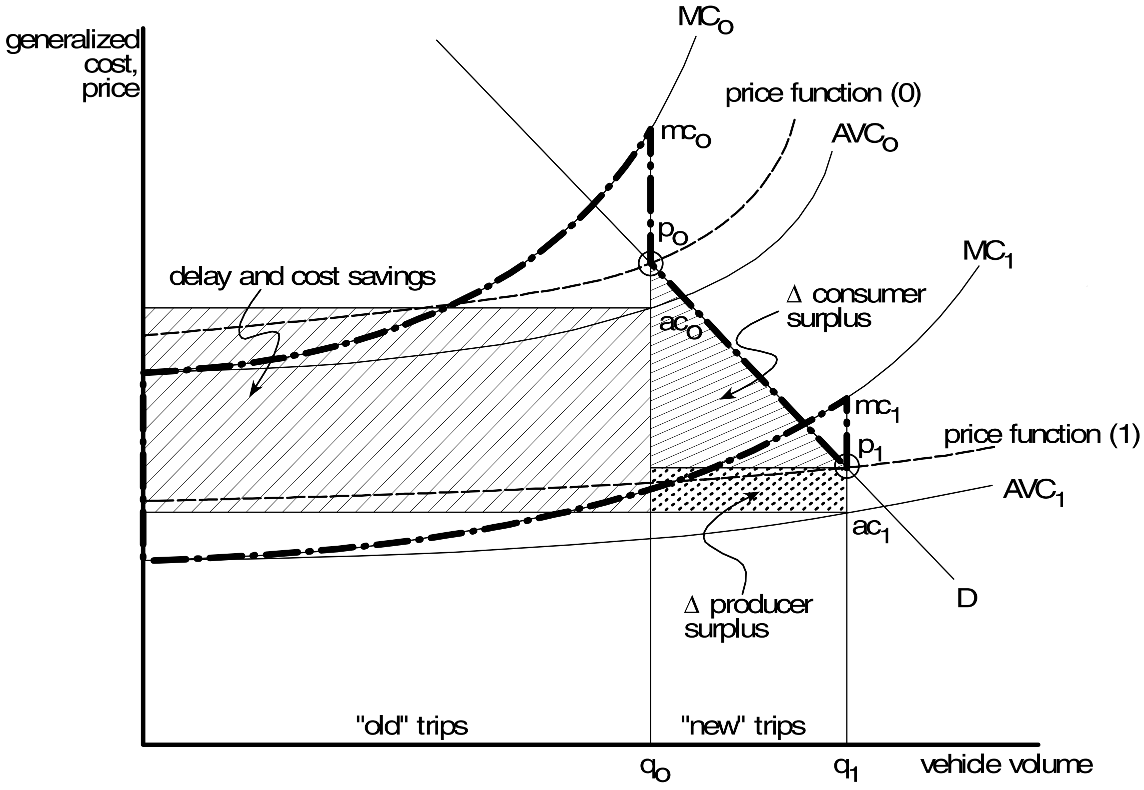

Figure D-4. ***NOB* Measured from *AVC*.**

over their previous generalized cost. New trip makers on this facility, in contrast, have not shown any willingness-to-pay, so their benefits must be estimated from the demand curve as consumer surplus over what they actually pay when using the new project.

Although the total *NOB* areas are the same whether defined by *MC* or *AVC*, the way they partition the benefits between old and new users is not. The area under MC_1 up to q_0 indicates the total average cost if volume on the new facility were held at the volume on the base facility, but that is not what will happen; the new volume will be q_1, and costs for "old" users will be higher than if volume were held to q_0. At a volume of q_0, ac_1 would occur where AVC_1 crosses the vertical at q_0, but none of the old users actually faces this hypothetical cost on the new facility; instead they all pay the actual ac_1 at q_1. The shaded area representation based on *AVC* provides a more useful interpretation with respect to old and new users, and also allows for direct empirical estimation of the benefit components.

NOB with Price Below *AVC*

With price above *AVC*, the *NOB* diagram looks similar in shape to the first best case. This is because with price being above *AVC* there is at least a partial "toll" even if it is below marginal cost. If it is assumed that $p < AVC$, the diagram is slightly different. Figure D-5 shows such a situation, in which price is below *AVC* for both the base and project alternatives.

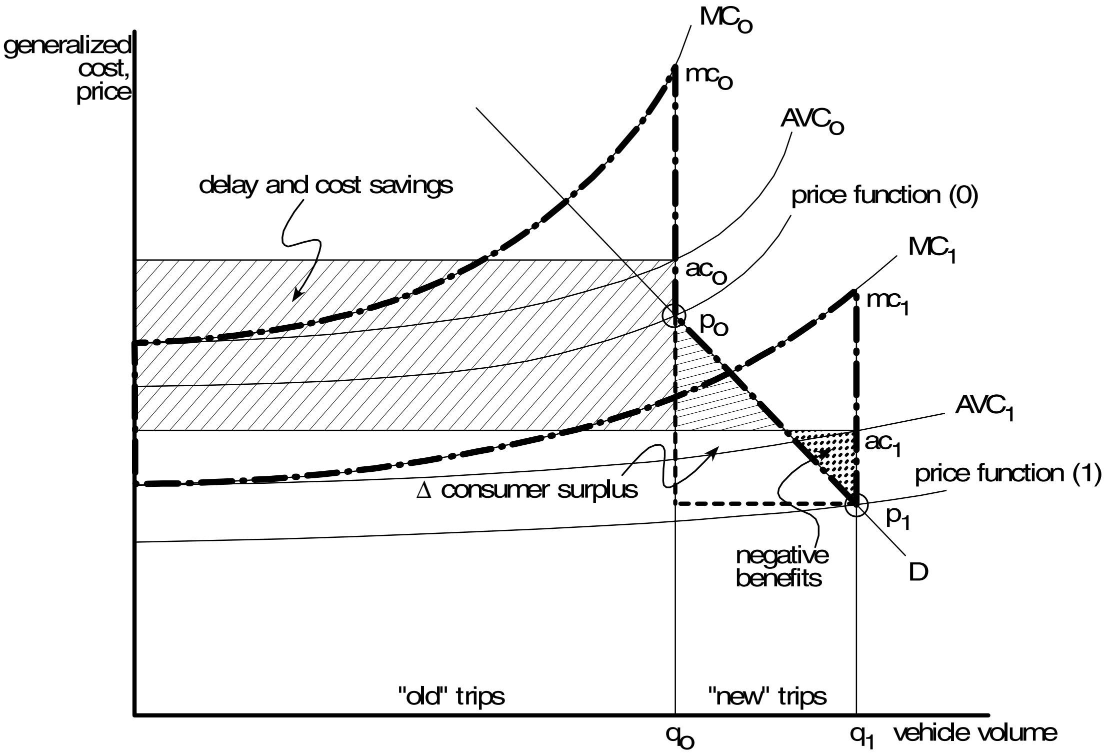

Figure D-5. ***NOB* with Price Below *AVC*.**

This diagram can be compared to Figure D-4. The outline of *NOB* based on *MC* is essentially the same, but the area defined by *AVC* curves has a somewhat different shape. Savings on old trips start above the current price, because the elimination of externalities in the base case is a benefit. Correspondingly, the benefits stop farther up, because some of the travel time and cost savings are offset by agency costs or externalities in the project alternative; cost savings would come down to p_1 were it not for the new externalities. Consumer surplus is the same in both diagrams, but a share of incremental consumer surplus in Figure D-5 is offset by additional agency costs or externalities from new trips, which might be thought of as negative producer surplus.

D.3 Components of Net Operating Benefit

Breaking *NOB* into components is useful for several reasons:

(1) Most of the components can be estimated directly, whereas the *NOB* defined by MC curves can only be estimated by estimating the functional form of total variable costs.

(2) Valuation can be done separately for each component, e.g., value of travel time, cost per accident.

Table D-1. **Price and Cost Components**

	Marginal Cost	Average Cost	Price	HERS
Travel Time				
Uncongested Time	y	y	y	y
Excess Delay	MT	AD	AD	AD
Operating Cost				
Fuel	y	y	y	y
Vehicle Maintenance	y	y	y	y
Vehicle Wear	y	y	y	y
Accidents (internal)	y	y	y	y
Parking (internal)				
Vehicle Ownership				
Infrastructure				
Pavement Wear	y	y		y
Maintenance and Operation	y	y		y
Fixed Capital				
Parking (unpriced)				
Externalities				
Air Pollution	y	y		y
Water Pollution	y	y		
Noise and Vibration	y	y		
User Charges				
Tolls			y	
Excise Taxes			y	
Other Variable Fees			y	

y = cost component is included in the total for the column category
MT = marginal time cost is included
AD = average delay cost is included

(3) The magnitudes of the components can be interpreted in meaningful terms and their relative magnitudes compared.

Most of the components can be disaggregated further than the major categories shown in Figures D-4 and D-5 and described below. A more detailed breakdown is provided in

Table D-1. The first three columns refer to the three functions of volume previously described. Travel time is divided into normal travel time and delay, which can be anything above free-flow speed or above a v/c of, say, 0.8 of capacity. Some operating and infrastructure costs (vehicle ownership and pavement) are divided into variable and fixed as well as internal (paid by the user) and external (paid or suffered by others). Parking cost is excluded for purposes of project evaluation of highway facilities, although it may be relevant to other purposes such as price elasticities.

The fourth column notes those components included in the HERS model. Travel time and operating cost components are included in both price and cost, while infrastructure costs (agency costs) and externalities are included in cost only. HERS does not include user fees such as fuel taxes or tolls. Neither HERS nor the general theory deal with fixed user fees, such as annual fees not based on miles traveled.

Most of the major components are shown again in Figure D-6, which is similar to (and a blend of) Figures D-4 and D-5 but with the *MC* outline of *NOB* and the *MC* lines themselves omitted.

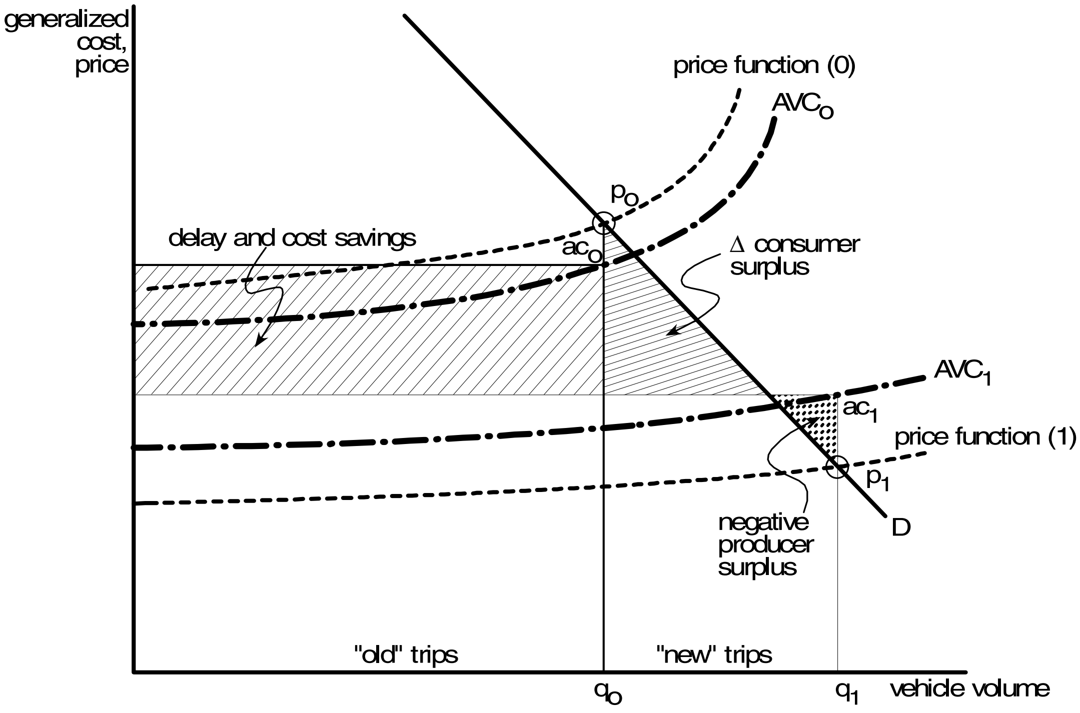

Figure D-6. **Components of Net Operating Benefit (*NOB*).**

Savings on Old Trips

Trips being taken on the base facility before the improvement and remaining on the new facility receive benefits in the form of reduced delay and operating costs. In Figure D-6, the average cost with no improvement is AVC_0 and yields an average cost of ac_0 for the base or “unimproved” volume q_0. With the improvement, ac_1 is the cost as read off the AVC_1 curve.

Savings on old trips, then, is the difference in average cost (a_0-a_1) times the unimproved volume q_0, indicated by the shaded rectangle. All costs listed in the “Average Cost” column of Table D-1 are included. For example, fuel savings, highway maintenance cost savings, and pollution reduction are included, but fuel tax savings are ignored.

Incremental Consumer Surplus

Consumer surplus is the amount users would be willing to pay above what they actually pay; it is measured as an area under the demand curve between the “with” and “without” volumes, and above the price. Because incremental consumer surplus applies to induced or “new” trips, the relevant volumes in Figure D-6 are q_0 (with no improvement) and q_1 (with improvement). Data required consist of two prices and the demand curve. This consumer surplus is a triangular area whose hypotenuse is the demand curve between p_0 and p_1, and whose legs are formed by q_0 and p_1 (only the top of this triangle is shown, because the bottom is offset by external costs). Both fuel costs and fuel taxes, for example, are included in the measurement.

Producer Surplus on New Trips

Producer surplus is an area under the demand curve that is below what users pay but above short-run variable cost. Normally, user fees are regarded as transfers and therefore ignored in estimating benefits, but here it is simply a part of the means for valuing induced travel. Like consumer surplus, it indicates a willingness to pay for new trips. A congestion toll generates producer surplus, but only the portion on new trips is counted as a benefit; the portion applying to old trips is already counted in the time and cost savings on old trips. The net of revenues above incremental agency costs and externalities is producer surplus.

Producer surplus can be negative if payments are less than average cost. Although not comprised of revenues, users create negative externalities that are omitted from the price, so these costs can be treated symmetrically to positive producer surplus. Negative producer surplus is shown in Figures D-5 and D-6, while Figure D-4 shows positive producer surplus. In Figure D-7, the surplus of revenues over short-run cost is the rectangle with a height of (p_0-ac_0) and a length of q_0; this area is excluded from *NOB* of the project because it occurs in the base case.

External Costs

Negative externalities shift the marginal and average social cost curves upward, but not the price function. External costs are included in the average variable cost (*AVC*) curves in Figure D-6. Thus the *MC* and *AVC* curves in the diagram include both externality as well as time costs.

A negative externality has the opposite effect as a user charge. If the user charge and the externality happened to be equal in value (at all volume levels), then there would be no externality. In outlining the incremental *NOB* area, external costs are rectangles taken from the average cost curves, and are negative in sign. In Figure D-7, for example, the

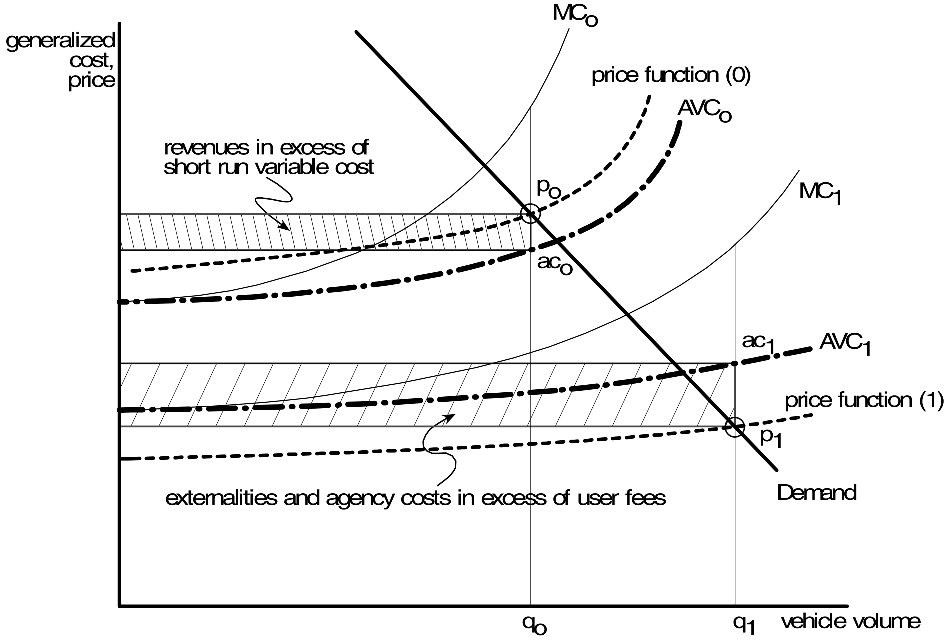

Figure D-7. **Positive and Negative Producer Surplus.**

net of external and agency costs over user payments in the project alternative has a height of (ac_1-p_1) and a length of q_1. Subtracting this area from consumer surplus (for new trips) and user cost savings (on old trips) leaves the small triangle above the demand curve at the outer end in Figure D-6 as a negative benefit (i.e., traffic induced by underpricing produces costs that exceed internal benefits).

Externalities in Related Markets

Externalities caused by induced trips diverted from other facilities may not be adding to the total emissions of pollutants, but this is irrelevant to the present project. The only way to incorporate changes in externalities in related markets (e.g, parallel facilities) is to measure the difference in the total inefficiency with and without the improvement project; it cannot be done one item (e.g., pollution or congestion) at a time.

It seems conceptually plausible to sum up the net change in air pollution caused by a project for a region, say, and count that as the project’s pollution benefit or disbenefit; then do the same for travel time, accidents, and running costs. While certainly a chore to detect the thousands of microscopic impacts occurring throughout the region, the task might be accomplished with regional simulation models.

The real problem, however, is that all of these calculations are meaningless without also calculating and summing all of the changes in consumer utility occurring at the same time, each of them the result of a shift in the demand curve in the relevant market. The likely error in such an estimate would greatly exceed the magnitude of the impact being estimated. Total air pollution in the region may be a performance measure of important policy concern, but the change in that index is not a basis for evaluating individual projects. The practical solution is to ignore what happens in related markets, except perhaps to trace out the efficiency changes for a few externalities in a few closely-related markets. The magnitude of such differences in related markets is generally small relative to benefits in the primary market.

D.4 Multi-Period Evaluation

The above steps describe a static equilibrium analysis conducted within a single short-run demand period. For each improvement alternative, the steps are repeated for each demand period over the lifetime of the improvement. Once the lifetime *NOB* is accumulated for each alternative and compared to costs, the investment choice can be made for that project.

Breaking the Project Life Into Discrete Demand Periods

The demand curve shifts over time in two primary patterns:

(1) Periodic Daily Peaks. Demand fluctuates with time of day, typically reaching peaks in the morning and afternoon, and lows in the small hours of the night.

(2) Secular Growth Trend. Average daily traffic may be growing, declining, or remaining stable over the course of years.

There are also periodic fluctuations over days of the week, and days or seasons of the year. Daily commuting peaks may be unimportant on some facilities. For evaluation, however, it is usually sufficient to recognize 1-3 daily demand period “types” and 1-4 demand periods over the investment lifetime, depending upon the rate of traffic growth.

The overall analysis period (e.g., twenty years) can be broken into shorter demand periods (e.g. 1-5 years), depending upon how rapidly exogenous demand factors are changing. Each demand period embodies a short run during which demand is assumed to be fixed, meaning that a single short-run demand curve applies for the duration of the period. This “single” demand can still be composed of several periodic demand curves, such as peak and off-peak, or it could be a daily average.

Once the overall analysis period is broken into demand periods, the secular or trend forecast becomes a series of discrete points representing the midpoints of demand periods. These points provide the origins or calibration points for the associated short-run demand curves.

Growth in Demand

Even in the short run, demand stimulated by reduction in the generalized price generates enough traffic to partly offset the gains from increased capacity. In the long run, this effect can be exaggerated, when general growth in demand and highway improvements reinforce each other to increase traffic volumes. A casual observer of this process can easily come to the conclusion that building more road capacity is self-defeating, because congestion is soon back to where it was. For those trying to carry out benefit-cost analysis, the benefits seem to disappear. The reality, however, is a bit different.

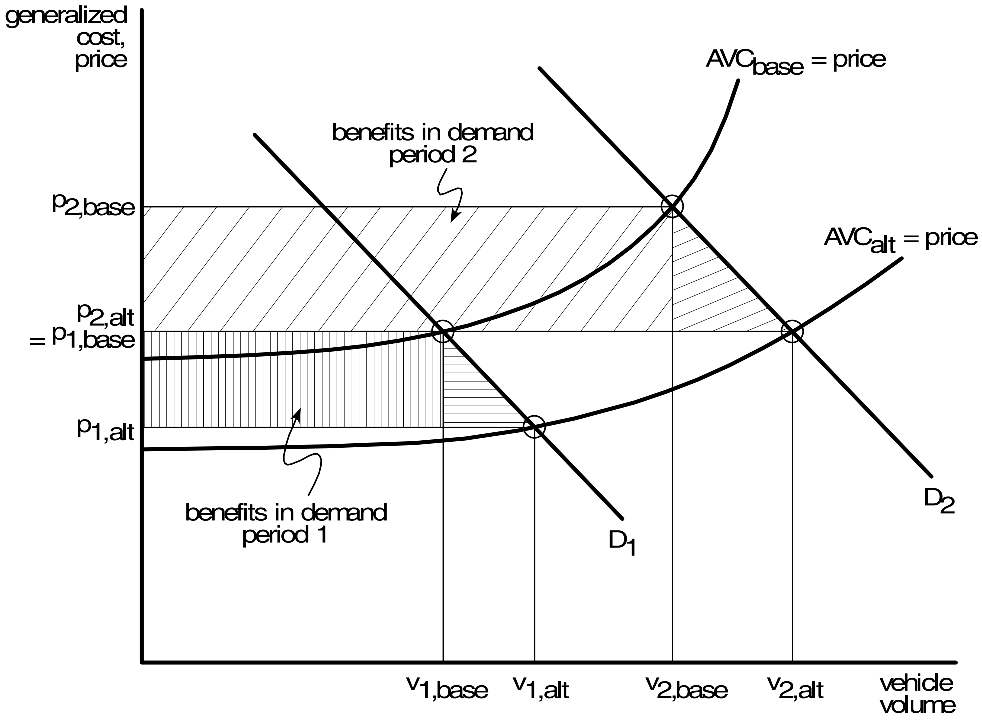

Figure D-8. Benefits From a Project in Two Demand Periods.

The simplest case is shown in Figure D-8, in which a base alternative and a project alternative are represented by their *AVC* curves, and these also give the price to the user under each alternative. Two demand curves are included, D_1 for the first period of time and D_2 for the next period. The curves are drawn such that, by coincidence, the cost to the user in the first demand period under the no-build alternative is the same as the price in the second period under the project alternative. In other words, users are individually no better off after the improvement than before.

This does not mean, however, that there are no benefits. First, there is more travel than was the case under the base alternative. Second, the relevant comparison is not to the price and volume in period one, but to the period two base case—i.e., the conditions that would have occurred in period two if the improvement had not been made. With an exogenous growth in demand, congestion would have been much worse without the improvement, and less travel would have been served. Hence, there is positive incremental *NOB* in the first period, and additional (and larger) *NOB* in the second demand period. Together (assuming only two periods) these account for project benefits, to be compared against incremental capital costs.

A more general case is illustrated in Figure D-9, in which user price does not follow the average cost curve. In this case, price is above average cost (compare this to Figure D-4, the single-period case with price above *AVC*). The MC curve is omitted because pricing inefficiency is ignored, i.e., a second-best investment comparison is assumed. Price is again arbitrarily set so as to equate base alternative price in the first period to the price with the improvement in the second period. Again, the areas of *NOB* are outlined and shaded, and together form the *NOB* for the project alternative. Because price is above AVC for the project alternative, *NOB* includes some producer surplus on new trips, in addition to consumers surplus.

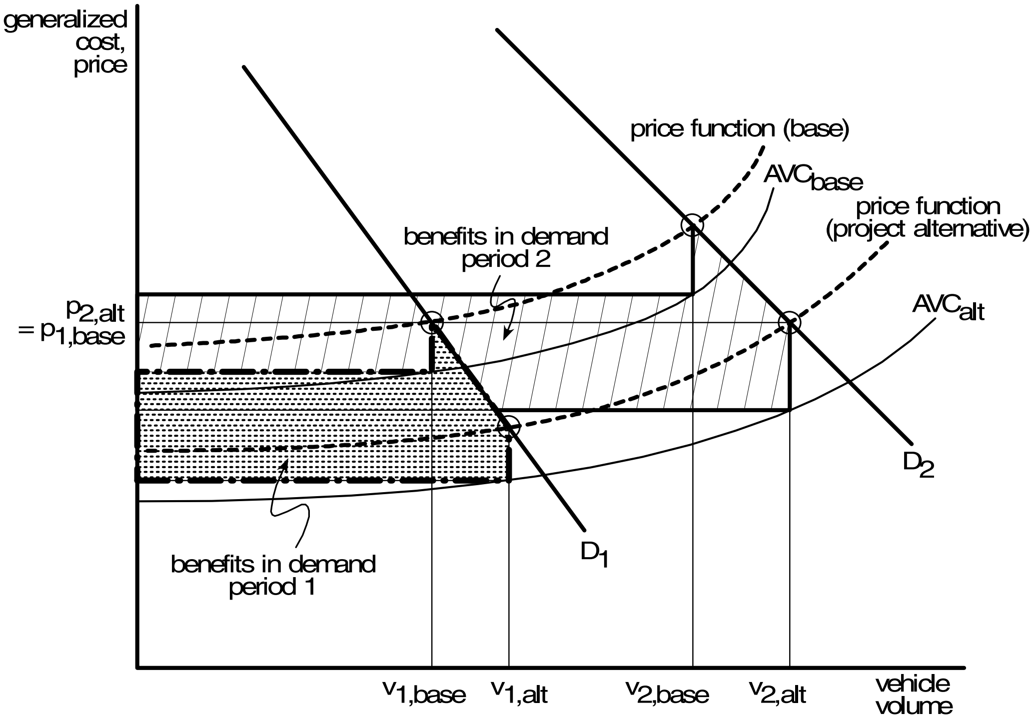

Figure D-9. ***NOB* For Two Demand Periods with Pricing Above *AVC*.**

A final configuration, shown in Figure D-10 illustrates the case when price is below social cost for both alternatives. The two demand periods are independent of each other. Each of these periods is similar to Figure D-5.

In summary, each demand period is handled as a single period, in which the short-run demand curve is fixed to a point based on the actual or forecast traffic at an associated price. Within the demand period, volume can move along the demand curve depending upon reductions in generalized price resulting from improvements being evaluated. Between demand periods, demand can shift and facilities wear out, resulting in a new set of cost and demand curves. The sum of the discounted benefits in each demand

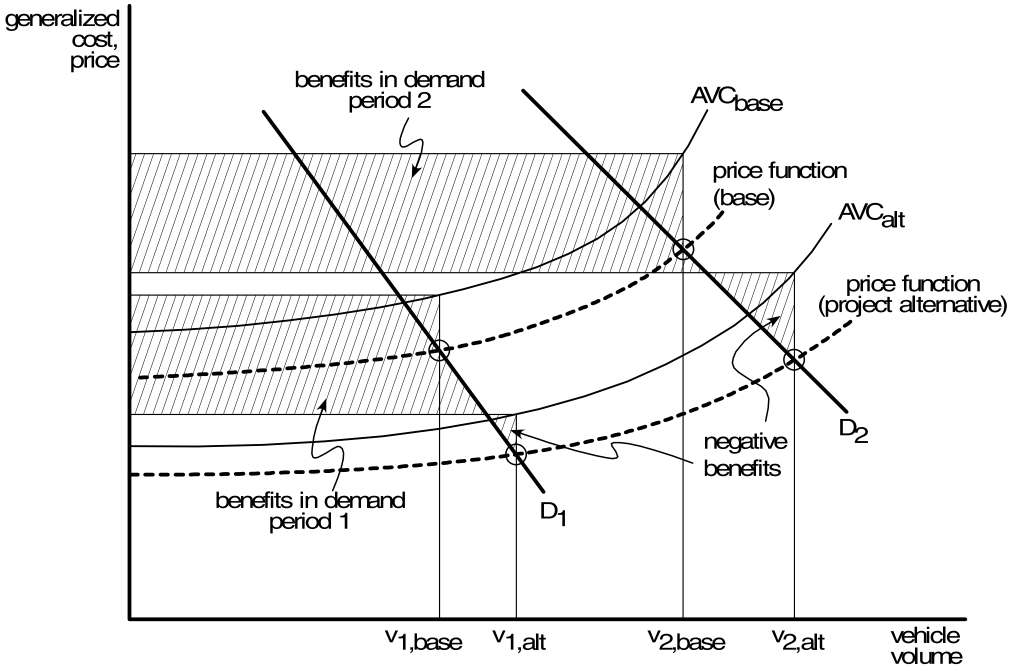

Figure D-10. ***NOB* for Two Demand Periods with Price Below *AVC*.**

period is the present value of project benefits. This is true whether pricing is efficient at $p = MC$, price follows AC, or pricing follows neither of the above.

The HERS model produces results like those shown in Figure D-10 because agency costs and air pollution (if the module is enabled) are included. If other negative externalities (e.g., noise, water pollution, external costs of accidents) were modeled in HERS, the gap between average variable cost and the price function would be wider. The model cannot produce results of the type shown in Figure D-9 because there is no price in the model that is separate from other user costs.

D.5 Summary

(1) Three functions (or selected points along them) are needed to define the base and project alternatives for evaluation: marginal cost, average cost, and price, as enumerated in Table D-1.

(2) For benefit-cost analysis, changes in costs determine incremental benefits, whereas changes in the generalized price lead to induced travel.

(3) Incremental net operating benefit (*NOB*) of a project alternative relative to the base alternative can be defined using marginal or average cost curves, but the latter is ultimately more practical.

(4) The primary components of *NOB* are delay and cost savings on old trips, consumer surplus on new trips, and producer surplus on new trips. The latter may be negative if agency costs and environmental externalities exceed user payments.

(5) Each demand period is a single evaluation of *NOB*. Demand periods can be periodic, such as peak and off-peak, as well as discrete intervals on a secular growth trend.

(6) Changes in user costs (time, running costs, accidents, user charges) cause changes in traffic volumes, referred to as induced traffic or induced demand. These effects should be incorporated into benefit-cost evaluation of improvement projects.

(7) Multiple demand periods (periodic and secular) are discounted and accumulated for comparison to fixed costs to assess the net benefits of an improvement project.

These concepts are readily made operational, and can be implemented in spreadsheet or other models.

D.6 A Numerical Example

Table D-2 shows some hypothetical data for a single demand period for one project alternative versus the base case. All of the data are converted from whatever natural units (e.g., minutes, crashes, grams) they might have been generated in to dollars per vehicle trip over the facility. All of the bolded numbers are required input data about costs and pricing that must be estimated for the specific conditions of the project, including the volumes that will occur at the relevant prices. Capacities of the existing and expanded facilities are also required.

Calculations are done on the basis of two contrasting assumptions:

(1) First-best pricing and investment, assuming that price can be set so as to maximize net benefits of both operation and investment. Numerical values for prices and volumes, and the outlines for *NOB*, are shown in Figure D-11.

(2) Second-best pricing, assuming that user fees are determined exogenously and cannot be changed. Prices and volumes are shown in Figure D-12, which is similar to Figure D-5.

Table D-2. Input Data for Example Project Evaluation

$ per trip	BASE	PROJECT	Marginal Cost	Price	Average Cost
RUNNING COSTS	**2.80**	**1.75**	1	1	1
Vehicle Wear	0.90	0.60			
Fuel	0.80	0.55			
Maintenance	0.50	0.30			
Insurance/Accidents	0.60	0.30			
Parking (internal)	0.00	0.00			
Other	0.00	0.00			
HIGHWAY COSTS	**0.50**	**0.40**	1	▨	1
Pavement Wear	0.30	0.30			
Administration	0.20	0.10			
Parking (unpriced)	0.00	0.00			
Other	0.00	0.00			
USER CHARGES	0.15	0.15	▨	1	▨
EXTERNALITIES	**1.10**	**1.10**	1	▨	1
Pollution	0.50	0.60			
Noise	0.40	0.40			
Accidents (external)	0.20	0.10			
Other	0.00	0.00			
TRAVEL TIME COST	6.80	3.40			
Free Flow	**1.80**	**1.40**	1	1	1
Excess Delay	**5.00**	**2.00**	▨	1	1
MARGINAL COST	6.20	4.65	<----		
PRICE	9.75	5.30		<----	
AVERAGE COST	11.20	6.65			<----
efficient price	12.19	7.31			
efficient toll	5.99	2.66			
efficient volume	4,000	6,000			
OTHER DATA AND PARAMETERS					
Capacity (veh/hr)	**4,000**	**6,000**			
Volume (act/est)	**5,000**	**6,826**			
elasticity	**-0.80**				

Total *NOB* as well as the major components under each of the two assumptions are shown in Table D-3. Areas in the diagrams correspond to components of *NOB* in the table. For example, savings on old trips in the first-best evaluation are measured by the rectangle

$$\begin{aligned} SOT &= (6.20 - 4.65) \times 4000 \\ &= 6{,}200 \end{aligned} \quad [2]$$

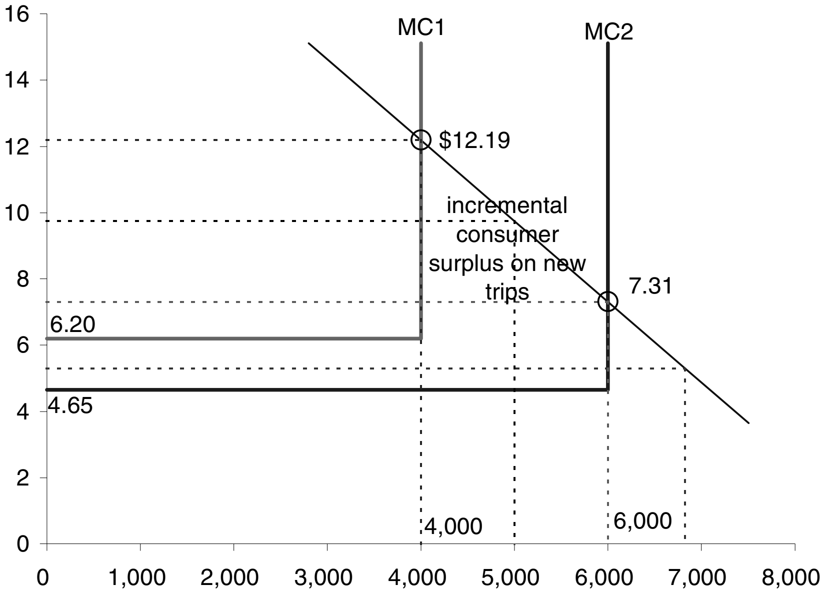

Figure D-11. First-best Net Operating Benefit (*NOB*).

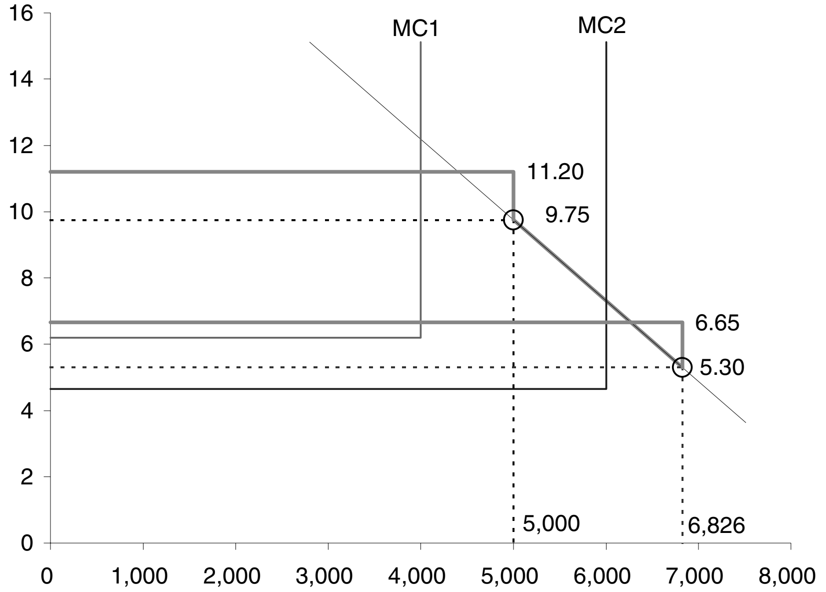

Figure D-12. Second-best Net Operating Benefit (*NOB*).

which is composed of normal running time savings = (1.80-1.40) *x* 4000 = 1,600, plus running cost savings = $(2.80 - 1.75) \times 4,000 = 4,200$, plus delay savings = zero with efficient pricing, plus highway operating cost savings $(0.50 - 0.40) \times 4,000 = 400$.

Numbers for the "Existing" facility show the net benefits of operating the facility efficiently (i.e., correctly priced) or inefficiently, and do not enter into the benefit-cost evaluation of the expansion project.

Table D-3. First-Best and Second-Best *NOB* for the Example Project

	Existing		Expansion	
NET OPERATING BENEFITS	efficient	inefficient	1stB	2ndB
normal running time savings on old trips			1,600	2,000
running cost savings on old trips			4,200	5,250
delay savings on old trips				15,000
externality cost savings on old trips			0	0
highway operating cost savings on old trips			400	500
incremental consumer surplus on new trips	19,500	30,469	4,875	4,062
producer surplus on new trips	23,950	750	5,325	274
externality costs on new trips		(5,500)		(2,008)
highway operating costs on new trips		(2,500)		(730)
Total NOB	43,450	23,219	16,400	24,347

D.7 References

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Appendix E: Operating Cost Equations

This appendix contains 22 exhibits which fall into three groups:

- Exhibits E-1 through E-8 contain equations for calculating Constant-Speed Operating Costs
- Exhibits E-9 through E-15 contain equations for calculating Excess Operating Costs Due to Speed Variability
- Exhibits E-16 through E-22 contain equations for calculating Excess Operating Costs Due to Curvature (AES >=55)

Each group contains one exhibit for each of the seven vehicle types recognized by HERS. The Constant-Speed group also contains an exhibit of the pavement-condition adjustment factor equations. On the line after each equation are the conditions under which the equation will be selected for use. (For example, if average effective speed is greater than 55 mph.) The list below summarizes the terms used in the equations:

AES = average effective speed
GR = grade (in percent)
CSMAX = maximum speed during speed change cycle
DCA = degrees of curvature
CSFC = constant-speed fuel consumption (gallons / 1000 miles)
CSOC = constant-speed oil consumption (quarts / 1000 miles)
CSTW = constant-speed tire wear (% worn / 1000 miles)
CSMR = constant-speed maintenance and repair (% avg. cost / 1000 miles)
CSVD = constant-speed depreciation (% new price / 1000 miles)
PLAFOC = pavement condition adjustment factor for oil consumption
PCAFTW = pavement condition adjustment factor for tire wear
PCAFMR = pavement condition adjustment factor for maintenance and repair
PCAFVD = pavement condition adjustment factor for depreciation expenses
SCCFC = excess fuel consumption for speed change cycles (gallons / 1000 cycles)
SCCOC = excess oil consumption for speed change cycles (quarts / 1000 cycles)
SCCTW = excess tire wear for speed change cycles (% worn / 1000 cycles)
SCCMR = excess maintenance and repair for speed change cycles (% average cost / 1000 cycles)
SCCD = excess depreciation for speed change cycles (% new price / 1000 cycles)
CFC = excess fuel consumption due to curves (gallons / 1000 vehicle miles)
CTW = excess tire wear due to curves (% worn / 1000 vehicle miles)
CMR = excess maintenance and repair due to curves (% average cost / 1000 vehicle miles)

Exhibit E-1. Constant-Speed Operating Costs: Small Automobiles

FUEL CONSUMPTION:

$CSFC=118.3+0.0001132*AES^3-27.3*ln(AES)+2.431*GR$
GR >= 0

$CSFC=66.0+0.774*GR^2+10.0*GR$
GR < 0 And AES <= 10

$CSFC=exp(7.56-1.422*ln(AES)-0.228*ln(-GR))$
GR < 0 And 10<AES <= 20

$CSFC=exp(-6.86+0.001872*AES^2-0.285*AES+4.97*ln(AES) +0.0739*GR)$
GR < 0 And 20 < AES <= 80

$CSFC=118.3+0.0001132*AES^3-27.3*ln(AES)+2.431*GR$
GR < 0 And AES > 80

OIL CONSUMPTION:

$CSOC=exp(3.20+0.01252*AES-0.854*ln(AES)+0.208*GR-0.0016*AES*GR)$
GR > 0 And AES < 55

$CSOC=-170.4+34.02*ln(AES)+1939/AES+0.4747*GR-0.003296*AES*GR$
GR >= 0 And 55 <= AES < 70

$CSOC=-170.4+34.02*ln(AES)+1939/AES+0.27*GR$
GR >= 0 And AES >= 70

$CSOC=9.09+0.0000368*AES^3-0.00573*AES^2+0.379*AES-4.36*ln(AES)$
min(-2.5,-AES/7.0) <= GR <= 0 And AES < 55

$CSOC=exp(1.492-0.000325*AES^2-0.813*ln(AES) -0.0275*GR^2-0.579*GR)$
GR < min(-2.5,-AES/7.0) And AES < 55

$CSOC=-170.4+34.02*ln(AES)+1939/AES$
otherwise

TIRE WEAR:

$CSTW=exp(-2.55+0.0001621*AES^2+0.01441*AES+1.473*ln(GR)-0.001638*AES*GR)$
GR >= 2.5 And AES < 55

$CSTW=1.314+0.000733*AES^2-0.05758*AES+0.01514*GR^2+0.003997*AES*GR$

GR >= 2.5 And AES >= 55

$CSTW=0.1959+2.51*10^{-6}*AES^{3}-0.0352*\ln(AES)+0.01754*GR^{2}+0.00348*AES*GR$
0 < GR < 2.5 And AES < 15 , or
-AES / 20 < GR < 2.5 And AES >= 15

$CSTW=0.0604+2.92*10^{-8}*AES^{4}+0.0000796*AES^{2}+0.0274*GR^{2}+0.074*GR+$
$0.0000568*AES^{2}*GR$
-1.5 < GR <= 0 And AES < 15
-AES / 10 < GR <= -AES / 20 And AES >= 15

$CSTW=\exp(-5.39-0.000895*AES^{2}+0.0962*GR+2.83*\ln(-GR)-0.00397*AES*GR)$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=48.3+0.00865*AES^{2}+0.0516*AES*GR$
GR >= 0

$CSMR=45.1+0.00582*AES^{2}+0.23*AES+0.0502*AES*GR$
-1.5 <= GR < 0 And AES <= 25 , or
GR < 0 And 25 < AES < 55 And AES >= -12.2*GR+4

$CSMR = -5.83-0.01932*AES^{2}-23.4*GR$
GR < -1.5 And AES <= 25
GR < 0 And 25 < AES < 55 And AES < -12.2*GR+4

$CSMR=73.35+0.01397*AES^{2}-0.7398*AES+0.04994*AES*GR$
-0.14*AES+3.6 < GR < 0 And AES >= 55

$CSMR=4.27-0.0208*AES^{2}-23.63*GR$
otherwise

DEPRECIATION:

$CSVD = 2.2+0.001596*AES-0.38*\ln(AES)$

Exhibit E-2. Constant-Speed Operating Costs: Medium/Large Automobiles

FUEL CONSUMPTION:

$CSFC=71.7+0.0001347*AES^3-10.71*\ln(AES)+5.1*GR$
$GR >= 0$

$CSFC=\exp(3.88-0.00375*GR^2-0.0791*GR-0.1299*\ln(-GR))$
$GR < 0$ And $AES <= 10$

$CSFC=\exp(4.85-0.0746*AES-0.0324*GR-0.1352*\ln(-GR))$
$GR < 0$ And $10 < AES <= 20$

$CSFC=\exp(9.03+0.0733*AES-2.32*\ln(AES)+0.001933*AES*GR)$
$GR < 0$ And $20 < AES <= 75$

$CSFC=71.7+0.0001347*AES^3-10.71*\ln(AES)+5.1*GR$
$4.3-0.08*AES <= GR < 0$ And $AES > 75$

$CSFC=\exp(9.03+0.0733*AES-2.32*\ln(AES)+0.001933*AES*GR)$
$GR<(4.3-0.08*AES)$ And $AES >75$

OIL CONSUMPTION:

$CSOC=\exp(3.18+0.01218*AES-0.842*\ln(AES)+0.208*GR-0.001565*AES*GR)$
$GR > 0$ And $AES < 55$

$CSOC=-173.3+34.6*\ln(AES)+1973 / AES+0.4907*GR-0.003317*AES*GR$
$GR >= 0$ And $55 <= AES < 70$

$CSOC=-173.3+34.6*\ln(AES)+1973 / AES+0.29*GR$
$GR >= 0$ And $AES >= 70$

$CSOC=9.10+0.0000369*AES^3-0.00574*AES^2+0.378*AES-4.37*\ln(AES)$
$\min(-2.5,-AES / 7.0) < GR <=0$ And $AES < 55$

$CSOC=\exp(1.44-0.000318*AES^2-0.795*\ln(AES) -0.028*GR^2-0.586*GR)$
$GR <= \min(-2.5,-AES / 7.0)$ And $AES < 55$

$CSOC=-173.3+34.6*\ln(AES)+1973 / AES$
otherwise

TIRE WEAR:

$CSTW=\exp(-2.39+0.0001564*AES^2+0.01367*AES+1.475*\ln(GR)-0.001586*AES*GR)$

GR >= 2.5 And AES<55

$CSTW=0.229+2.65*10^{-6}*AES^{3}-0.0403*\ln(AES)+0.0214*GR^{2}+0.00392*AES*GR$
0 < GR < 2.5 And AES < 15 , or
-AES/20 <= GR <2.5 And 15 <= AES <55

$CSTW=0.08+3.0*10^{-6}*AES^{3}+0.029*GR^{2}+0.0828*GR+0.000056*AES^{2}*GR$
-1.5 < GR <= 0 And AES < 15 , or
-AES/10 < GR < -AES/20 And 15 <= AES <55

$CSTW=\exp(-5.22-0.000771*AES^{2}+0.0843*GR+2.81*\ln(-GR)-0.00323*AES*GR)$
GR <= -1.5 And AES < 15 , or
GR <= -AES/10 And 15 <= AES <55

$CSTW=1.318+0.000743*AES^{2}-0.05661*AES+0.01941*GR^{2}+0.00417*AES*GR$
GR>=0.5 And AES >= 55

$CSTW=-0.2022+0.000237*AES^{2}+0.0213*GR^{2}-1.0322*GR+0.3099*\ln(AES)*GR$
-AES/10+1 < GR < 0.5 And AES >= 55 , or
GR < 0.5 And AES >= 80

$CSTW=-0.2613+0.000164*AES^{2}+0.02065*GR^{2}+0.005452*AES*GR-0.03975*\ln(AES)*GR$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=48.4+0.00867*AES^{2}+0.0577*AES*GR$
GR>=0

$CSMR=45.19+0.00584*AES^{2}+0.229*AES+0.0562*AES*GR$
-1.5 <= GR < 0 And AES <= 25 , or
GR < 0 And -12.2*GR+4 <= AES And 25 < AES < 55

$CSMR=-6.67-0.018*AES^{2}-23.4*GR$
GR < -1.5 And AES <= 25 , or
GR < 0 And -12.2*GR+4 > AES And 25 < AES < 55

$CSMR=72.46+0.01373*AES^{2}-0.7081*AES+0.05597*AES*GR$
-0.14*AES+3.6 < GR < 0 And AES >= 55

$CSMR=-5.415-0.01912*AES^{2}-23.51*GR$
otherwise

DEPRECIATION:

$CSVD=1.725+0.001892*AES-0.311*\ln(AES)$

Exhibit E-3. Constant-Speed Operating Costs: Four-Tire Trucks

FUEL CONSUMPTION:

$CSFC=110.4+0.000249*AES^3-18.93*ln(AES)+8.06*GR$
GR >= 0 And AES < 55

$CSFC=exp(4.31+0.00474*GR^2+0.0402*GR)$
GR < 0 And AES <= 10

$CSFC=exp(5.07-0.0743*AES-0.0461*GR-0.1361*ln(-GR))$
GR < 0 And 10 < AES <= 20

$CSFC=exp(7.67+0.0557*AES-1.692*ln(AES)+0.001432*AES*GR)$
GR < 0 And 20 < AES < 55

$CSFC=110.4+0.000249*AES^3-18.93*ln(AES)+8.06*GR$
GR >= 1.5 And AES >= 55

$CSFC=exp(3.801+0.000138*AES^2+0.2229*GR)$
-2.5 <= GR < 1.5 And AES >=55

$CSFC=exp(2.784+0.02014*AES+0.06881*GR)$
otherwise

OIL CONSUMPTION:

$CSOC=exp(2.47-0.604*ln(AES)-0.00994*GR^2+0.277*GR-0.001248*AES*GR)$
GR > 0 And AES < 50

$CSOC=16.41+0.004424*AES^2-0.5255*AES+1.296*GR-0.2664*ln(AES)*GR$
GR > 0 And 50 <= AES <= 70

$CSOC=16.41+0.004424*AES^2-0.5255*AES+0.19*GR$
GR > 0 And AES > 70

$CSOC=8.45+0.0000352*AES^3-0.00567*AES^2+0.370*AES-4.12*ln(AES)$
min(-3.5, -AES / 6.0) < GR<= 0 And AES < 50

$CSOC=exp(0.92-0.000295*AES^2-0.751*ln(AES) -0.0269*GR^2-0.584*GR)$
GR < min(-3.5, -AES / 6.0) And AES < 50

$CSOC=16.41+0.004424*AES^2-0.5255*AES$
otherwise

TIRE WEAR:

$CSTW=exp(-2.08+0.0001517*AES^{2}+0.012*AES+1.367*ln(GR)-0.001389*AES*GR)$
GR >= 2.5 And AES < 55

$CSTW=0.297+2.90*10^{-6}*AES^{3}-0.0421*ln(AES)+0.0234*GR^{2}+0.00429*AES*GR$
0 < GR < 2.5 And AES < 15 , or
-AES/20 < GR < 2.5 And 15 <= AES < 55

$CSTW=0.1294+3.64*10^{-6}*AES^{3}+0.0324*GR^{2}+0.1085*GR+0.0000631*AES^{2}*GR$
-2.5 < GR <= 0 And AES < 15 , or
-AES/10 < GR <= -AES/20 And 15 <= AES < 55

$CSTW=exp(-5.45-4.13*10^{-6}*AES^{3}-0.01377*AES+2.79*ln(-GR))$
GR <= -2.5 And AES < 15 , or
GR <= -AES/10 And 15 <= AES < 55

$CSTW=1.365+0.000736*AES^{2}-0.05471*AES+0.0197*GR^{2}+0.004395*AES*GR$
GR >= 0.5 And AES >=55

$CSTW=-0.1554+0.000258*AES^{2}+0.0205*GR^{2}-0.05138*GR+0.005058*AES*GR$
-AES/10+1 < GR < 0.5 And AES >=55 , or
GR < 0.5 And AES >= 80

$CSTW=max(0.01,-0.2177+0.000208*AES^{2}+0.02376*GR^{2}+0.005895*AES*GR-0.03288*ln(AES)*GR)$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=49.2+0.00881*AES^{2}+0.0545*AES*GR$
GR >= 0

$CSMR=46.0+0.00595*AES^{2}+0.231*AES+0.0531*AES*GR$
-1.5 <= GR < 0 And AES <= 20 , or
GR < 0 And 20 < AES < 55 And AES>=-10*GR+6

$CSMR=-12.43-0.019*AES^{2}-23.5*GR$
GR < -1.5 And AES <= 20 , or
GR < 0 And 20 < AES < 55 And AES < -10*GR+6

$CSMR=72.36+0.01373*AES^{2}-0.6841*AES+0.0532*AES*GR$
GR <0 And AES >= 55 And GR > -0.1*AES+0.75 , or
GR < 0 And AES>70

$CSMR=-13.83-0.0197*AES^{2}-24.01*GR$
otherwise

DEPRECIATION:

$$CSVD = 0.742+0.000589*AES-0.1307*\ln(AES)$$

Exhibit E-4. Constant-Speed Operating Costs: Six-Tire Trucks

FUEL CONSUMPTION:

$CSFC=262.0+0.0752*AES^2-6.41*AES+23.0*GR-0.258*AES*GR$
$GR >= 0$ And $AES < 55$

$CSFC=103.8+0.0854*AES^2-7.66*AES+41.4*\ln(AES)+0.1378*AES*GR$
$GR < 0$ And $AES < 55$

$CSFC=1194+0.04852*AES^2-296.3*\ln(AES)+5.964*GR$
$GR >= 1.5$ And $AES >= 55$

$CSFC=101.5+0.000186*AES^3+1.102*GR^2+18.22*GR$
$GR < 1.5$ And $AES >= 55$

OIL CONSUMPTION:

$CSOC=\exp(2.87+0.00066*AES^2-0.0694*AES+0.227*GR-0.001486*AES*GR)$
$GR>0$ And $AES<55$

$CSOC=51.76+0.002513*AES^2-14.29*\ln(AES)+0.7485*GR$
$GR>0$ And $AES >= 55$

$CSOC=13.98+0.0000603*AES^3-0.00857*AES^2+0.523*AES-6.17*\ln(AES)$
$-1.5 < GR <= 0$ And $AES < 55$, or
$-AES/10 <= GR <= 0$ And $AES < 55$

$CSOC=\exp(1.41+0.000519*AES^2-0.0845*AES-0.0344*GR^2-0.649*GR)$
$GR < -AES/10$ And $AES<70$

$CSOC=51.76+0.002513*AES^2-14.29*\ln(AES)$
otherwise

TIRE WEAR:

$CSTW=\exp(-1.572+0.0000943*AES^2+0.01509*AES+1.65*\ln(GR)-0.001535*AES*GR)$
$GR>=2.5$ And $AES<55$

$CSTW=2.206+0.001267*AES^2-0.09683*AES+0.07733*GR^2+0.01096*AES*GR$
$GR>=2.5$ And $AES >= 55$

$CSTW=0.353+4.5*10^{-6}*AES^3-0.0556*\ln(AES)+0.0855*GR^2+0.01012*AES*GR$
$0 < GR < 2.5$ And $AES<15$, or
$-AES/25 < GR <2.5$ And $AES>=15$

$CSTW=0.104+5.37*10^{-8}*AES^4+0.0001578*AES^2+0.1282*GR^2+$
$0.222*GR+0.000168*AES^2*GR$
$-1.5 < GR <= 0$ And $AES < 15$, or
$-AES/14 < GR < -AES/25$ And $AES >= 15$

$CSTW=exp(-3.16-3.35*10^{-6}*AES^3-0.0308*AES+2.28*ln(-GR)-0.00377*AES*GR)$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=44.2+0.01147*AES^2+0.1462*AES*GR$
$GR>=0$

$CSMR=36.3+0.00649*AES^2+0.439*AES+0.1463*AES*GR$
$GR < 0$ And $AES <= 25$ And $AES >= -15*GR$, or
$GR < 0$ And $AES > 25$ And $AES >= -13.4*GR+15$

$CSMR = -0.722-0.00697*AES^2-15.9*GR$
otherwise

DEPRECIATION:

$CSVD=1.126+0.0028*AES-0.247*ln(AES)$
$AES < 55$

$CSVD=0.2006+4.936/AES$
$AES >= 55$

Exhibit E-5. Constant-Speed Operating Costs: 3+ Axle Single-Unit Trucks

FUEL CONSUMPTION:

$CSFC=exp(5.37-0.01105*GR^2+0.304*GR-0.0075*AES*GR)$
GR >= 0 And AES<=20

$CSFC=exp(5.54-0.00271*AES^2+0.1089*GR-0.212*ln(-GR)+0.00403*AES*GR)$
GR < 0 And AES <=20

$CSFC=172.0-4.53*GR^2+53.5*GR+0.1552*AES*GR$
GR >= -0.5 And 20 < AES < 45

$CSFC=exp(94.3-0.001703*AES^2+8.18*ln(AES)2-53.9*ln(AES)-0.955*ln(-GR))$
GR < -0.5 And 20 < AES < 45

$CSFC=172.0-4.53*GR^2+53.5*GR+0.1552*AES*GR$
GR > 0.5 And AES >= 45 , or
GR >- 0.5 And 45 <= AES < 55

$CSFC=349.03+1.421*AES-67.84*ln(AES)$
GR > -0.5 And AES >= 55

$CSFC=52.39-822.1/AES-2.048*GR^2-40.88*GR-106.7*ln(-GR)$
otherwise

OIL CONSUMPTION:

$CSOC=exp(4.36+0.00711*AES-0.869*ln(AES)-0.01712*GR^2+0.338*GR)$
GR > 0 And AES<55

$CSOC=20.2+0.0000724*AES^3-0.0103*AES^2+0.662*AES-8.52*ln(AES)$
min(-1.5,-AES/12.5) < GR <= 0 And AES<55

$CSOC=exp(1.77+0.00055*AES^2-0.0769*AES-0.0343*GR^2-0.646*GR)$
GR <= min(-1.5,-AES/12.5) And AES < 55

$CSOC=22.85+0.006514*AES^2-0.7188*AES+1.615*GR$
GR > 0 And AES >= 55

$CSOC=22.85+0.006514*AES^2-0.7188*AES$
-AES/12.5 <= GR <= 0 And AES >=55 , or
GR <=0 And AES >= 90

$CSOC=exp(1.77+0.00055*AES^2-0.0769*AES-0.0343*GR^2-0.646*GR)$
otherwise

TIRE WEAR:

$CSTW=exp(-1.71+0.0000511*AES^{2}+0.01134*AES+1.575*ln(GR)-0.001038*AES*GR)$
GR>=2.5 And AES<55

$CSTW=1.085+0.000405*AES^{2}-0.03274*AES+0.05955*GR^{2}+0.00577*AES*GR$
GR>=2.5 And AES >= 55

$CSTW=0.0896+0.0001308*AES^{2}+0.0552*GR^{2}+0.1181*GR+0.00402*AES*GR$
-0.5 < GR < 2.5 And AES<15
-AES / 30 < GR <2.5 And AES>=15

$CSTW=0.0345+0.000387*AES^{2}+0.257*GR^{2}+0.01988*AES*GR$
-AES / 20 < GR <= -AES / 30 And AES>=15

$CSTW=exp(-3.30-0.0275*AES+0.1868*GR+2.92*ln(-GR)-0.00275*AES*GR)$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=46.0+0.008*AES^{2}+0.146*AES*GR$
GR >= 0

$CSMR=49.7+0.01004*AES^{2}-0.184*AES+0.1478*AES*GR$
GR < 0 And AES<=35 And AES>=-20*GR , or
GR < 0 And AES > 35 And AES>=-16.6*GR+21

$CSMR=0.871-0.00335*AES^{2}-14.7*GR$
otherwise

DEPRECIATION EXPENSES:

$CSVD=1.126+0.00279*AES-0.247*ln(AES)$
AES<55

$CSVD=0.2006+4.936/AES$
otherwise

Exhibit E-6. Constant-Speed Operating Costs: 3-4 Axle Combinations

FUEL CONSUMPTION:

$CSFC=670.4-4.650*AES+0.02839*GR^4-266.2/GR-0.6943*GR*AES$
GR > 1.5 And AES < 50

$CSFC=-22.09+4.261*AES+0.4149*GR^3-5.981*GR^2+0.5563*GR*AES$
GR > 1.5 And AES >= 50

$CSFC=\max(0,766.0+4.42*AES-210.0*\ln(AES)+116.0*GR-1.03*AES*GR)$
$-0.0017*AES^2+0.13*AES-4.33 < GR <= 1.5$ And AES < 55

$CSFC=\exp(4.033+0.01849*AES-0.04914*GR^2+0.3505*GR)$
$-0.0017*AES^2+0.13*AES-4.33 < GR <= 1.5$ And AES >= 55

$CSFC=0$
otherwise

OIL CONSUMPTION:

$CSOC=\exp(3.92-0.661*\ln(AES)-0.01718*GR^2+0.361*GR-0.000640*AES*GR)$
GR > 0 And AES < 45

$CSOC=78.59+0.003813*AES^2-21.76*\ln(AES)+2.1254*GR-0.0109*AES*GR$
GR > 0 And 45 <= AES <= 70

$CSOC=78.59+0.003813*AES^2-21.76*\ln(AES)+1.41*GR$
GR > 0 And AES > 70

$CSOC=20.2+0.0000724*AES^3-0.01034*AES^2+0.662*AES-8.52*\ln(AES)$
min(-1.5,-AES / 12.5) < GR <= 0 , or
GR <= 0 And AES >= 70

$CSOC=\exp(1.85+0.000458*AES^2-0.0746*AES-0.0336*GR^2-0.638*GR)$
otherwise

TIRE WEAR:

$CSTW=\exp(-1.89+0.0000962*AES^2+0.00878*AES+1.589*\ln(GR)-0.001091*AES*GR)$
GR>=2.5 And AES<55

$CSTW=0.113+1.694*10^{-6}*AES^3+0.0469*GR^2+0.0732*GR+0.00393*AES*GR$
-0.5 < GR < 2.5 And AES<15 , or
-AES / 30 < GR < 2.5 And 15 <= GR < 55

$CSTW=-1.742+2.07*10^{-8}*AES^{4}+0.00268*AES-1.768*GR-2.02*\ln(-GR)-0.00318*AES*GR^{2}$
$-AES/20 <= GR <= -AES/30$ And $15 <= AES < 55$

$CSTW=\exp(-3.32-2.39*10^{-6}*AES^{3}-0.0204*AES+2.15*\ln(-GR)-0.0026*AES*GR)$
$GR < -0.5$ And $AES<15$
$GR < -AES/20$ And $15 <= AES < 55$

$CSTW=1.058+0.000493*AES^{2}-0.03958*AES+0.04812*GR^{2}+0.005241*AES*GR$
$GR >= 0.5$ And $AES >= 55$

$CSTW=4.401+0.04413*AES-1.605*\ln(AES) +0.05145*GR^{2}+0.005251*AES*GR$
$-AES/10+3.5 <= GR < 0.5$ And $AES >= 55$

$CSTW=-0.3949+0.00948*AES+0.04849*GR^{2}+0.005991*AES*GR-0.04346*\ln(AES)*GR$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=43.6+0.01002*AES^{2}+0.1606*AES*GR$
$GR>=0$

$CSMR=-257.0+0.0428*AES^{2}2-5.96*AES+131.6*\ln(AES) +0.1617*AES*GR$
$GR < 0$ And $AES<=40$ And $AES>=-25*GR$
$GR < 0$ And $AES>40$ And $AES>=-15*GR+25$

$CSMR=0.696-0.00456*AES^{2}-15.8*GR$
otherwise

DEPRECIATION EXPENSES:

$CSVD=0.354+0.000974*AES-0.0806*\ln(AES)$
$AES<55$

$CSVD=0.05657+1.598/AES$
otherwise

Exhibit E-7. Constant-Speed Operating Costs: 5+ Axle Combinations

FUEL CONSUMPTION:

$CSFC=exp(6.03+0.000218*AES^2-0.0239*AES-0.01560*GR^2+0.204*GR)$
GR>=0 And AES<55

$CSFC=81.9+1.513*AES+84.1*GR$
-AES/30 <= GR < 0 And AES<55

$CSFC=0$
GR < -AES/30 And AES<55

$CSFC=exp(3.556+0.4293*ln(AES)+0.00392*GR^3-0.06277*GR^2+0.348*GR)$
GR >= -0.5 And AES >= 55

$CSFC=0.667*exp(3.556+0.4293*ln(AES)+0.00392*GR^3-0.06277*GR^2+0.348*GR)$
-1.5 <= GR < -0.5 And AES >= 55

$CSFC=max(0,81.9+1.513*AES+84.1*GR)$
-AES/30 <= GR < -1.5 And AES >= 55

$CSFC=0$
otherwise

OIL CONSUMPTION:

$CSOC=exp(4.60-0.668*ln(AES)-0.01879*GR^2+0.394*GR-0.000873*AES*GR)$
GR > 0 And AES < 55

$CSOC=9.383+0.003478*AES-0.271*AES+3.040*GR$
GR > 0 And AES >= 55

$CSOC=42.6+0.000189*AES^3-0.0273*AES^2+1.633*AES-18.96*ln(AES)$
min(-1.5,-AES/15.0) < GR <= 0 And AES < 55

$CSOC=9.383+0.003478*AES^2-0.271*AES$
min(-1.5,-AES/15.0) < GR <= 0 And AES >= 55

$CSOC=exp(2.52+0.000397*AES^2-0.0675*AES-0.0353*GR^2-0.652*GR)$
GR <= min(-1.5,-AES/15.0) And AES < 55

$CSOC=115.8+0.5094*AES-37.27*ln(AES)-3.064*GR$
GR <= min(-1.5,-AES/15.0) And AES >= 55

TIRE WEAR:

$CSTW=\exp(-1.6+0.0000684*AES^{2}+0.00608*AES+1.567*\ln(GR)-0.000762*AES*GR)$
$GR>=2.5$ And $AES < 55$

$CSTW=1.122+0.000357*AES^{2}-0.03264*AES+0.06295*GR^{2}+0.005081*AES*GR$
$GR>=2.5$ And $AES >= 55$

$CSTW=0.1432+1.248*10^{-6}*AES^{3}+0.0639*GR^{2}+0.1167*GR+0.00332*AES*GR$
$-0.5 < GR < 2.5$ And $AES<15$
$-AES/35 < GR < 2.5$ And $AES >= 15$

$CSTW=-0.1283+1.442*10^{-6}*AES^{3}+0.01044*AES+0.208*GR^{2}+0.01337*AES*GR$
$GR < -AES/35$ And $AES >= \max(15.,-25*GR)$

$CSTW=\exp(-3.05-1.5*10^{-6}*AES^{3}-0.01358*AES+2.13*\ln(-GR)-0.001779*AES*GR)$
otherwise

MAINTENANCE AND REPAIR:

$CSMR=44.9+0.01148*AES^{2}+0.254*AES*GR$
$GR >= 0$

$CSMR = 78.7+1.545*AES-20.6*\ln(AES)+0.254*AES*GR$
$GR < 0$ And $AES > 25$ And $AES >= -40*GR-15$

$CSMR=0.996-0.00149*AES^{2}-15.8*GR$
otherwise

DEPRECIATION:

$CSVD = 0.395+0.001215*AES-0.0941*\ln(AES)$
$AES < 55$

$CSVD = 0.05657+1.598/AES$
otherwise

Exhibit E-8. Constant-Speed Operating Costs – Pavement Condition Adjustment Factors

OIL CONSUMPTION:

Four-Tire Vehicles:
$PCAFOC = 2.64+0.0729*PSR^2-0.722*PSR$

Trucks:
$PCAFOC = 1.176-0.1348*\ln(PSR)$

TIRE WEAR:

Four-Tire Vehicles:
$PCAFTW = 2.40-1.111*\ln(PSR)$

Trucks:
$PCAFTW = 1.668+0.001372*PSR^3-0.581*\ln(PSR)$

MAINTENANCE AND REPAIR:

Four-Tire Vehicles:
$PCAFMR = 3.19+0.0967*PSR^2-0.961*PSR$

Single-Unit Trucks:
$PCAFMR = 1.724+0.00830*PSR^2-0.661*\ln(PSR)$

Combinations:
$PCAFMR = 2.075+0.273*PSR-1.622*\ln(PSR)$

DEPRECIATION:

Four-Tire Vehicles:
$PCAFVD = 1.136-0.106*\ln(PSR)$

Single-Unit Trucks:
$PCAFVD = 1.332-0.262*\ln(PSR)$

Combinations:
$PCAFVD = 1.32-0.254*\ln(PSR)$

Exhibit E-9. Excess Operating Costs Due to Speed Variability: Small Automobiles

FUEL CONSUMPTION:

$SCCFC=0.00424*CSMAX^3$
$CSMAX < 5$

$SCCFC=0.04547+0.08559*CSMAX+3677*10^{-8}*CSMAX^3$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.00004*CSMAX^3$
$CSMAX < 5$

$SCCOC=0.000879+0.000934*CSMAX-1612*10^{-8}*CSMAX^2+193*10^{-9}*CSMAX^3$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0008*CSMAX^2$
$CSMAX < 5$

$SCCTW=exp(-7.112+1.999*ln(CSMAX)- 8384*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0016*CSMAX^2$
$CSMAX < 5$

$SCCMR=exp(-6.284+0.006889*CSMAX+1.881*ln(CSMAX)- 7388*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

DEPRECIATION EXPENSES:

$SCCD=0.0004*CSMAX$
$CSMAX < 60$

$SCCD=exp(-4.327+0.000168*CSMAX^2)$
$CSMAX >= 60$

Exhibit E-10. Excess Operating Costs Due to Speed Variability: Medium/Large Automobiles

FUEL CONSUMPTION:

$SCCFC=0.008*CSMAX^3$
$CSMAX < 5$

$SCCFC=0.03401+0.1902*CSMAX+4491*10^{-8}*CSMAX^3$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.00004*CSMAX^3$
$CSMAX < 5$

$SCCOC=0.000801+0.000869*CSMAX-1617*10^{-8}*CSMAX^2+197*10^{-8}*CSMAX^3$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCTW=\exp(-6.64+1.947*\ln(CSMAX)-9909*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0016*CSMAX^2$
$CSMAX < 5$

$SCCMR=\exp(-6.277+0.007347*CSMAX+1.876*\ln(CSMAX)-7275*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

DEPRECIATION EXPENSES

$SCCD=0.0004*CSMAX$
$CSMAX < 5$

$SCCD=0.001+0.0002*CSMAX$
$5 <= CSMAX < 50$

$SCCD=\exp(-4.973+0.000228*CSMAX^2)$
$CSMAX >= 50$

Exhibit E-11. Excess Operating Costs Due to Speed Variability: Four-Tire Trucks

FUEL CONSUMPTION:

$SCCFC=0.00904*CSMAX^3$
$CSMAX < 5$

$SCCFC=0.8137+0.1576*CSMAX+7327*10^{-8}*CSMAX^3$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.0002*CSMAX^2$
$CSMAX < 5$

$SCCOC=\exp(-6.242+0.5935*\ln(CSMAX)+0.000131*CSMAX^2)$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCTW=\exp(-6.568+1.906*\ln(CSMAX)- 7502*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0016*CSMAX^2$
$CSMAX < 5$

$SCCMR=\exp(-6.39+1.958*\ln(CSMAX)- 1781*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

DEPRECIATION EXPENSES:

$SCCD=0.0002*CSMAX$
$CSMAX < 60$

$SCCD=\exp(-5.0007+0.000162*CSMAX^2)$
$CSMAX >= 60$

Exhibit E-12. Excess Operating Costs Due to Speed Variability: Six-Tire Trucks

FUEL CONSUMPTION:

$SCCFC=0.1184*CSMAX^2$
$CSMAX < 5$

$SCCFC=3.09+0.02843*CSMAX^2$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.00068*CSMAX^2$
$CSMAX < 5$

$SCCOC=exp(-5.069+0.6392*ln(CSMAX)+0.000169*CSMAX^2)$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0016*CSMAX^2$
$CSMAX < 5$

$SCCTW=exp(-6.387+1.984*ln(CSMAX)-988*10^{-7}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0012*CSMAX^2$
$CSMAX <= 5$

$SCCMR=exp(-6.427+0.01826*CSMAX+1.758*ln(CSMAX)-0.000103*CSMAX^2)$
$CSMAX > 5$

DEPRECIATION EXPENSES:

$SCCD=0.0004*CSMAX$
$CSMAX < 5$

$SCCD=0.001429+0.000221*CSMAX$
$5 <= CSMAX < 40$

$SCCD=exp(-4.957+0.000294*CSMAX^2)$
$CSMAX >= 40$

Exhibit E-13. Excess Operating Costs Due to Speed Variability: 3+ Axle Single-Unit Trucks

FUEL CONSUMPTION:

$SCCFC=0.174*CSMAX^2$
$CSMAX < 5$

$SCCFC=4.477+0.03862*CSMAX^2$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.00136*CSMAX^2$
$CSMAX < 5$

$SCCOC=\exp(-4.408+0.6632*\ln(CSMAX)+0.000148*CSMAX^2)$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCTW=\exp(-6.595+1.918*\ln(CSMAX)-6855*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0008*CSMAX^2$
$CSMAX < 5$

$SCCMR=\exp(-7.446-0.005514*CSMAX+2.212*\ln(CSMAX)+ 5075*10^{-8}*CSMAX^2)$
$CSMAX >= 5$

DEPRECIATION EXPENSES:

$SCCD=0.0006*CSMAX$
$CSMAX < 5$

$SCCD=0.001+0.0004*CSMAX$
$5 <= CSMAX < 55$

$SCCD=\exp(-4.439+0.000231*CSMAX^2)$
$CSMAX >= 55$

Exhibit E-14. Excess Operating Costs Due to Speed Variability: 3-4 Axle Combinations

FUEL CONSUMPTION:

$SCCFC=0.324*CSMAX^2$
$CSMAX < 5$

$SCCFC=6.342+0.5855*CSMAX+0.03191*CSMAX^2$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.00136*CSMAX^2$
$CSMAX < 5$

$SCCOC=exp(-4.408+0.6632*ln(CSMAX)+0.000148*CSMAX^2)$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0008*CSMAX^2$
$CSMAX < 5$

$SCCTW=exp(-7.111+2.0276*ln(CSMAX)-0.000102*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCMR=exp(-6.639+0.006003*CSMAX+1.912*ln(CSMAX))$
$CSMAX >= 5$

DEPRECIATION EXPENSES:

$SCCD=0.0002*CSMAX$
$CSMAX < 60$

$SCCD=exp(-5.007+0.000162*CSMAX^2)$
$CSMAX >= 60$

Exhibit E-15. Excess Operating Costs Due to Speed Variability: 5+ Axle Combinations

FUEL CONSUMPTION:

$SCCFC=0.3584*CSMAX^2$
$CSMAX < 5$

$SCCFC=2.052+1.167*CSMAX+0.03292*CSMAX^2$
$CSMAX >= 5$

OIL CONSUMPTION:

$SCCOC=0.0028*CSMAX^2$
$CSMAX < 5$

$SCCOC=\exp(-3.735+0.6849*\ln(CSMAX)+0.000112*CSMAX^2)$
$CSMAX >= 5$

TIRE WEAR:

$SCCTW=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCTW=\exp(-6.643+1.947*\ln(CSMAX)-721*10^{-7}*CSMAX^2)$
$CSMAX >= 5$

MAINTENANCE AND REPAIR:

$SCCMR=0.0012*CSMAX^2$
$CSMAX < 5$

$SCCMR=\exp(-6.705+0.008136*CSMAX+1.94*\ln(CSMAX))$
$CSMAX >= 5$

DEPRECIATION EXPENSES:

$SCCD=0.0002*CSMAX$
$CSMAX < 60$

$SCCD=\exp(-5.007+0.000162*CSMAX^2)$
$CSMAX >= 60$

Exhibit E-16. Excess Operating Costs Due to Curvature (AES >=55): Small Automobiles

FUEL CONSUMPTION:

$CFC=0.5*DCA*exp(-7.262+0.08857*AES)$
$DCA<=2$

$CFC=exp(-9.014+0.08857*AES-0.05682*DCA^{2}+1.492*DCA-1.45*ln(DCA))$
$DCA > 2$

TIRE WEAR:

$CTW=0.5*DCA*exp(-25.262+6.518*ln(AES))$
$DCA<=2$

$CTW=exp(-26.78+6.518*ln(AES)-0.0494*DCA^{2}+1.357*DCA-1.44*ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*exp(-36.874+8.434*ln(AES))$
$DCA<=2$

$CMR=exp(-38.35+8.434*ln(AES)-0.01168*DCA^{2}+0.5472*DCA+0.6178*ln(DCA))$
$DCA > 2$

Exhibit E-17. Excess Operating Costs Due to Curvature (AES >=55): Medium/ Large Automobiles

FUEL CONSUMPTION:

$CFC=0.5*DCA*exp(-10.256+0.1429*AES)$
$DCA<=2$

$CFC=exp(-12.02+0.1429*AES-0.05306*DCA^{2}+1.426*DCA-1.264*ln(DCA))$
$DCA < 2$

TIRE WEAR:

$CTW=0.5*DCA*exp(-25.093+6.510*ln(AES))$
$DCA<=2$

$CTW=exp(-26.63+6.510*ln(AES)-0.04985*DCA^{2}+1.366*DCA-1.437*ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*exp(-36.735+8.437*ln(AES))$
$DCA<=2$

$CMR=exp(-38.19+8.437*ln(AES)-0.008751*DCA^{2}+0.4629*DCA+0.8137*ln(DCA))$
$DCA > 2$

Exhibit E-18. Excess Operating Costs Due to Curvature (AES >=55): Four-Tire Trucks

FUEL CONSUMPTION:

$CFC=0.5*DCA*\exp(-10.08+0.1503*AES)$
$DCA<=2$

$CFC=\exp(-12.4+0.1503*AES-0.09975*DCA^2+2.224*DCA-2.494*\ln(DCA))$
$DCA > 2$

TIRE WEAR:

$CTW=0.5*DCA*\exp(-24.659+6.399*\ln(AES))$
$DCA<=2$

$CTW=\exp(-26.39+6.399*\ln(AES)-0.06917*DCA^2+1.66*DCA-1.893*\ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*\exp(-37.399+8.582*\ln(AES))$
$DCA<=2$

$CMR=\exp(-38.85+8.582*\ln(AES)-0.01271*DCA^2+0.5934*DCA+0.4549*\ln(DCA))$
$DCA > 2$

Exhibit E-19. Excess Operating Costs Due to Curvature (AES >=55): Six-Tire Trucks

FUEL CONSUMPTION:

$CFC=0.5*DCA*\exp(-7.616+0.1071*AES)$
$DCA<=2$

$CFC=\exp(-9.937+0.1071*AES-0.09918*DCA^2+2.255*DCA-2.585*\ln(DCA))$
$DCA < 2$

TIRE WEAR:

$CTW=0.5*DCA*\exp(-26.308+6.793*\ln(AES))$
$DCA<=2$

$CTW=\exp(-28.34+6.793*\ln(AES)-0.08519*DCA^2+1.983*DCA-2.299*\ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*\exp(-40.336+9.506*\ln(AES))$
$DCA<=2$

$CMR=\exp(-41.9+9.506*\ln(AES)-0.01908*DCA^2+0.8204*DCA)$
$DCA > 2$

Exhibit E-20. Excess Operating Costs Due to Curvature (AES >=55): 3+ Axle Single-Unit Trucks

FUEL CONSUMPTION:

$CFC=0.5*DCA*exp(-30.74+7.715*ln(AES))$
$DCA<=2$

$CFC=exp(-33.06+7.715*ln(AES)-0.1007*DCA^2+2.254*DCA-2.576*ln(DCA))$
$DCA > 2$

TIRE WEAR:

$CTW=0.5*DCA*exp(-26.605+6.779*ln(AES))$
$DCA<=2$

$CTW=exp(-28.66+6.779*ln(AES)-0.08644*DCA^2+2.003*DCA-2.316*ln(DCA))$
$DCA > 2$

MAINTNENANCE AND REPAIR:

$CMR=0.5*DCA*exp(-39.515+9.314*ln(AES))$
$DCA<=2$

$CMR=exp(-41.07+9.314*ln(AES)-0.01939*DCA^2+0.8161*DCA)$
$DCA > 2$

Exhibit E-21. Excess Operating Costs Due to Curvature (AES >=55): 3-4 Axle Combination

FUEL CONSUMPTION:

$CFC=0.5*DCA*\exp(-10.903+0.187*AES)$
$DCA<=2$

$CFC=\exp(-9.272+0.1308*AES-0.05*DCA^2-2.065*\ln(DCA)+0.0283*DCA*AES)$
$DCA > 2$

TIRE WEAR:

$CTW=0.5*DCA*\exp(-26.453+6.722*\ln(AES))$
$DCA<=2$

$CTW=\exp(-28.43+6.722*\ln(AES)-0.0824*DCA^2+1.927*DCA-2.233*\ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*\exp(-37.363+8.819*\ln(AES))$
$DCA<=2$

$CMR=\exp(-38.94+8.819*\ln(AES)-0.02202*DCA^2+0.8326*DCA)$
$DCA > 2$

Exhibit E-22. Excess Operating Costs Due to Curvature (AES >=55): 5+ Axle Combination

FUEL CONSUMPTION:

$CFC=0.5*DCA*exp(-4.27+0.000385*AES^2+0.055*AES)$
$DCA<=2$

$CFC=exp(-2.676+0.000385*AES^2-0.04632*DCA^2-2.033*ln(DCA)+0.02737*DCA*AES)$
$DCA > 2$

TIRE WEAR:

$CTW=0.5*DCA*exp(-26.569+6.792*ln(AES))$
$DCA<=2$

$CTW=exp(-28.60+6.792*ln(AES)-0.08529*DCA^2+1.982*DCA-2.297*ln(DCA))$
$DCA > 2$

MAINTENANCE AND REPAIR:

$CMR=0.5*DCA*exp(-39.517+9.45*ln(AES))$
$DCA<=2$

$CMR=exp(-41.05+9.45*ln(AES)-0.01822*DCA^2+0.8027*DCA)$
$DCA > 2$

Appendix F: Detailed Description of Procedures for Incorporating Air Pollution Costs in HERS

F.1 Overview

HERS calculates the monetary value of damages from air pollution generated by motor vehicles using a sample section under "baseline" conditions during each funding period, and with each candidate improvement to that sample section. Air pollution costs under baseline or improved travel conditions on a section depend upon three factors: (1) HERS' estimates of average daily traffic volume on the section during each funding period; (2) the mix of vehicle classes that typically use facilities of the type represented by the sample section; and (3) HERS' estimates of the average effective speed (AES) of travel on the section during each future funding period. Figure F-1 illustrates the process used to calculate air pollution costs for a sample section under each set of travel conditions.[1]

Differences in air pollution costs between baseline or unimproved travel conditions -- including daily traffic volume and average effective speed -- and conditions with an improvement in place are included in HERS' calculation of the net benefits from implementing that improvement. Reductions in air pollution costs *increase* the net benefits from an improvement, while an increase in the air pollution costs generated by the travel volume and speed estimated to result from an improvement *reduce* its net benefits. Changes in air pollution costs resulting from an improvement's effect on travel conditions on a sample section increase or reduce the benefits from making that improvement during all funding periods comprising its lifetime.

F.1.1 How Improvements Affect Air Pollution Costs

Differences between baseline travel conditions and conditions with an improvement in place can cause total air pollutant emissions from vehicles traveling on a section to change for two reasons. First, the per-mile *rates* at which motor vehicles emit some pollutants vary with travel speed, and can rise or decline in response to the increase in average speed on a sample section that results from an improvement. Second, average daily traffic and thus total vehicle-miles of travel on a section increases from its baseline level under improved conditions due to the response of travel demand to the increase in average travel speed on the section.

By increasing the volume of travel on a section, a candidate improvement increases air pollutant emissions and their resulting costs, since these costs are assumed to depend directly on total emissions. At the same time, the increase in average travel speed on the segment can reduce emissions per *vehicle-mile* of some pollutants, thus offsetting some or all of the effect of higher travel volumes on total air pollution costs. However, particularly large speed increases can actually cause per-mile emission rates of some pollutants to rise, thereby "magnifying" the

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[1] The broad outline for these procedures was developed by Apogee Research under contract to the Federal Highway Administration, and is documented in the report *Procedures for Incorporating Air Pollution Effects in the HERS Model for National Highway Investment Analysis*, September 1996.

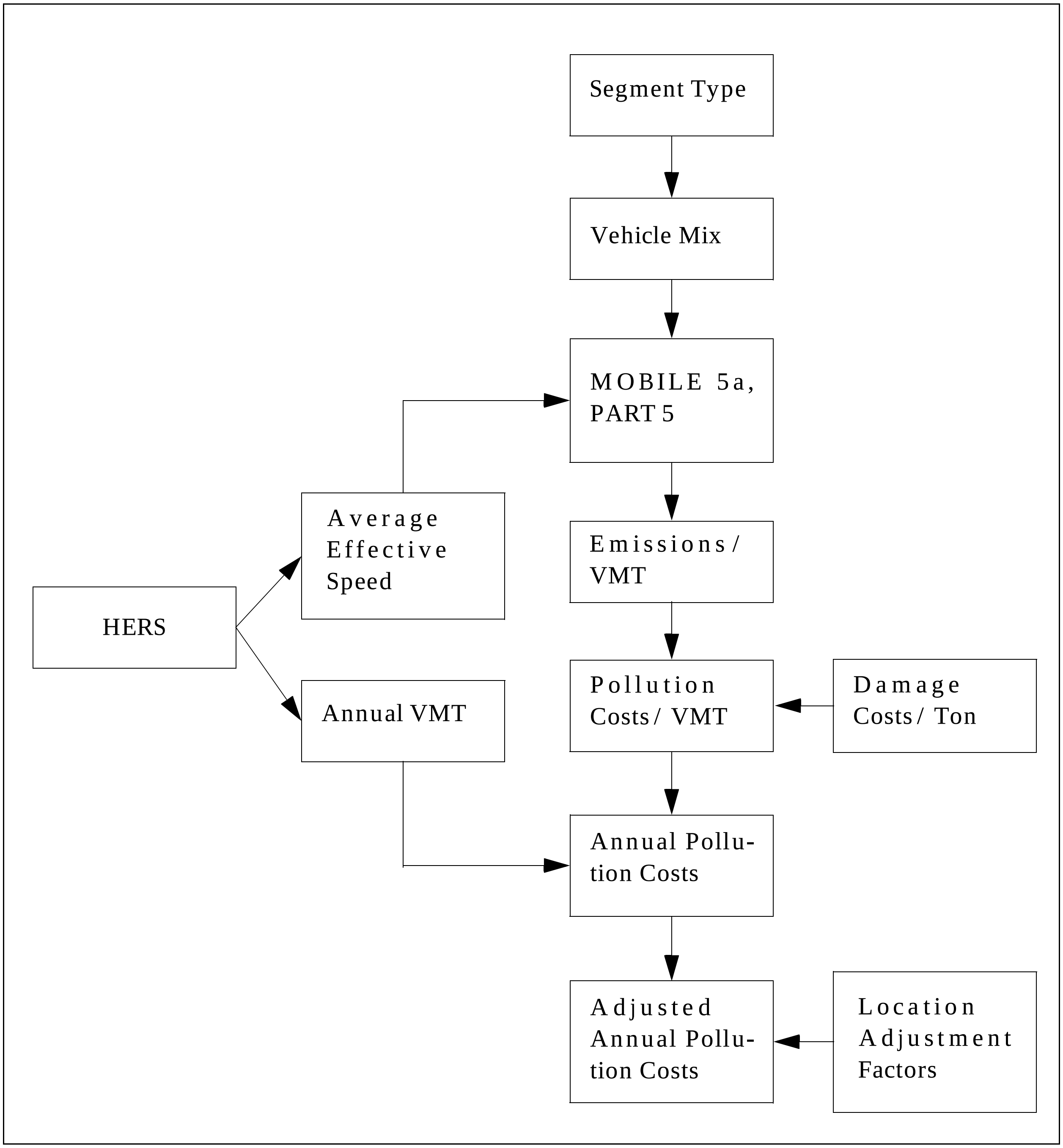

Figure F-1. Overview of HERS Procedure for Estimating Air Pollution Costs

increase in air pollution costs from higher travel volumes. Thus total air pollution costs resulting from travel on a HERS sample section can either rise or fall as the result of an improvement.

F.1.2 Critical Assumptions

Differences in air pollutant emissions generated by changes between baseline and improved travel conditions are assumed to contribute directly to changes in atmospheric concentrations of those pollutants. In turn, the total costs of damages to human health and property from air pollution are assumed to vary in response to changes in these atmospheric concentrations. Thus potential improvements to a HERS sample section are assumed to alter total air pollution damage costs in exact proportion to any change in pollutant emissions generated by vehicles traveling on the section that results from an improvement. HERS uses widely-accepted estimates of the dollar value of health and property damages caused per ton of each major pollutant to calculate air pollution costs from travel on sample sections under baseline and improved conditions.

Because the air pollution cost estimates used by HERS represent nationwide averages for dollar damages to human health and property caused by individual pollutants, they reflect the exposure of residents and property to air pollution that occurs at typical U.S. population and development densities. For pollutants that tend to remain concentrated near their original source, HERS scales these average per-ton damage costs upward to reflect the greater population and property exposure to emissions of those pollutants from vehicles using sample sections located in urban areas. Conversely, HERS scales these nationwide average damage costs downward to reflect the lower population and development densities that typically surround sample sections located outside urban areas. For pollutants that tend to disperse widely, HERS applies nationwide average damage costs per ton of emissions generated by travel on both urban and non-urban sample sections.

HERS estimates the changes in costs from air pollution damages that would result from all candidate improvements to a sample section during the current and each future funding period. Because the per-mile rates at which motor vehicles emit most air pollutants are expected to decline throughout the time horizon considered by HERS, air pollution costs on most sample sections are expected to fall throughout the foreseeable future under both baseline and improved travel conditions. As a result, differences in air pollution costs between baseline and improved conditions – and thus the *changes* in air pollution costs that HERS includes among the benefits or disbenefits resulting from candidate improvements -- are expected to decline during each successive future funding period considered by the model.

F.2 Estimating Air Pollutant Emissions

F.2.1 Specific Pollutants Considered

Motor vehicles' contribution to air pollution consists partly of tailpipe emissions of four commonplace pollutants that can accumulate in unhealthful concentrations in the earth's atmosphere: carbon monoxide (usually abbreviated CO), sulfur oxides (SOx), nitrogen oxides (NOx), and small particulate matter (PM). Under certain conditions, nitrogen oxides also combine in the atmosphere with other chemical compounds emitted by motor vehicles (among other sources) to form ground-level ozone.[2] Atmospheric levels of airborne dust, another pollutant that can be harmful to human health and property when it reaches certain concentrations, are also increased as moving vehicles' tires contact road pavement surfaces.

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[2] These "volatile organic compounds" (VOC) are emitted from the tailpipes of gasoline-powered vehicles, as well as from the evaporation of gasoline during their fueling, storage, and operation.

F.2.2 Composite Emission Rates for HERS Section Types

Different types of motor vehicles emit each of these six pollutants at varying rates per mile of travel. Vehicles' emission rates depend on the type of fuel used (gasoline or diesel), engine size, and vehicle weight, as well as on operating conditions such as ambient temperature, road grade, and altitude. Emission rates for some pollutants also vary with vehicles' operating speeds, while others are approximately constant regardless of speed. As an illustration, Figure F-2 shows the relationship of per-mile emission rates of the three speed-sensitive pollutants to travel speed for gasoline-powered automobiles, the largest class of motor vehicles. Variation in other vehicle classes' emission rates for these three pollutants with operating speeds exhibits similar patterns, while emission rates for the three remaining pollutants (sulfur oxides, particulate matter, and road dust) are approximately constant regardless of speed for all vehicle classes.

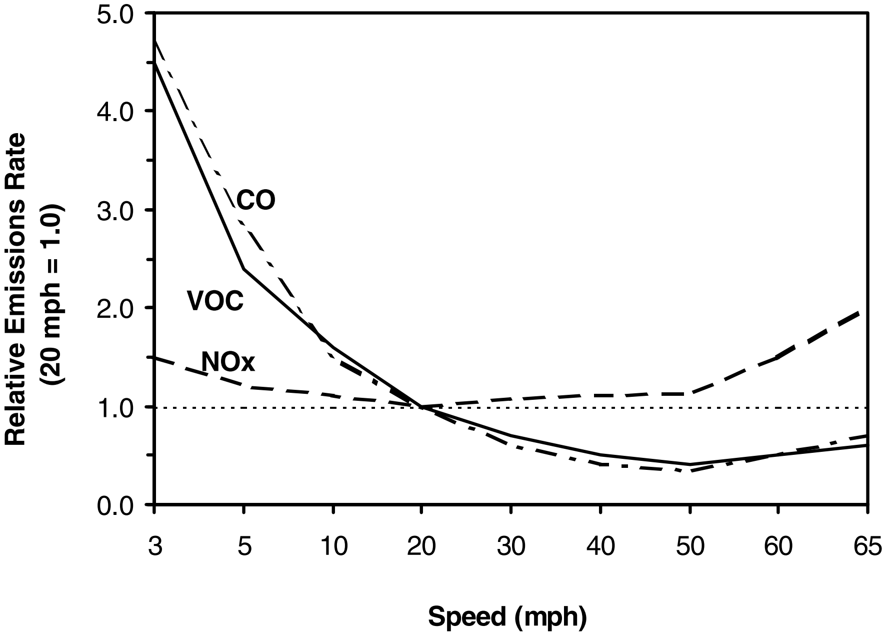

Figure F-2. Relationship of Emissions Rates to Average Speed (Gasoline Automobiles)

Each of the nine section types utilized by HERS, which are differentiated by location (urban vs. rural) and functional class (expressway, arterial, collector) tends to be used by a characteristic mix of vehicle types. Differing vehicle mixes reflect the varying combinations of travel purposes served by different road and highway facilities, together with the common use of specific types of vehicles to provide different types of transportation services. Because information on the use of different types of highway facilities by individual vehicle classes is limited in its detail, some of the nine section types used by HERS are assumed to have identical vehicle mixes. Table F-1 groups the nine HERS section types into five consolidated groups for which detailed information on the typical mix of travel among different vehicle classes is available. Table F-2 reports the proportions of travel on each of these five consolidated section groups that are assumed to be accounted for by eight different vehicle classes during each of the five year funding periods used by HERS.

Table F-1. Grouping of HERS Section Types for Estimating Air Pollution Costs[a]

HERS Section Type	Consolidated Section Group
Rural Interstate	Rural Interstate
Rural Other Principal Arterials Rural Minor Arterials	Rural Arterial
Rural Major Collectors	Rural Collector
Urban Interstate Urban Other Freeway / Expressway	Urban Interstate
Urban Other Principal Arterials Urban Minor Arterials Urban Collectors	Urban Other

a. Source: Apogee Research (1996), Technical Note D.

The typical mix of vehicle classes using each section type is used as an input to models developed by the U.S. Environmental Protection Agency (EPA) to predict average emissions per vehicle-mile of travel for each of the six air pollutants whose damage costs are considered by HERS. The MOBILE5a motor vehicle emission factor model developed by EPA was used to estimate average emissions per vehicle-mile of travel for carbon monoxide (CO), volatile organic compounds (VOCs), and oxides of nitrogen (NOx) as functions of average travel speed.[3] The EPA's vehicle emission factor model PART5 is used to estimate average emissions per vehicle-mile of sulfur oxides (SOx), small particulate matter (PM-10), and road dust generated by the typical mix of vehicle classes using each HERS section type.[4] (The PART5 model assumes that these emissions do not vary significantly with changes in vehicle operating speeds.) Both models' "default" assumptions regarding the age distribution of the U.S. vehicle fleet and operating conditions such as typical fuel composition, ambient temperatures, and altitude were employed in developing these estimates.

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[3] For a brief description of the structure of the MOBILE model, see *The MOBILE Model and Transportation Planning, Report FHWA-PD-96-005*, Federal Highway Administration, September 1995.

[4] The PART5 model is described in *An Overview of PM-10 Base Year Emission Inventories, Report FHWA-PD-98-002*, Federal Highway Administration, November 1997.

Table F-2. Vehicle Class Mix by Consolidated Section Group (1996-2000)[a]

Consolidated Section Group		Percent of Travel by Vehicle Class:							
		LDGV[b]	LDDV[c]	MC[d]	LDGT1[e]	LDGT2[f]	LDDT[g]	HDGV[h]	HDDV[i]
1996 - 2000	Rural Interstate	0.5612	0.0025	0.0096	0.1625	0.0752	0.0013	0.0364	0.1513
	Rural Arterial	0.5782	0.0026	0.0075	0.1940	0.0898	0.0015	0.0395	0.0869
	Rural Collector	0.5352	0.0024	0.0065	0.2256	0.1044	0.0017	0.0475	0.0767
	Urban Interstate	0.6689	0.0030	0.0069	0.1564	0.0724	0.0012	0.0254	0.0658
	Urban Other	0.6711	0.0030	0.0063	0.1751	0.0810	0.0013	0.0233	0.0389
2001 - 2005	Rural Interstate	0.5451	0.0012	0.0086	0.1706	0.0765	0.0012	0.0366	0.1602
	Rural Arterial	0.5627	0.0013	0.0067	0.2040	0.0915	0.0014	0.0398	0.0926
	Rural Collector	0.5196	0.0012	0.0058	0.2367	0.1061	0.0016	0.0477	0.0813
	Urban Interstate	0.6551	0.0015	0.0062	0.1655	0.0742	0.0011	0.0257	0.0707
	Urban Other	0.6575	0.0015	0.0057	0.1854	0.0831	0.0013	0.0236	0.0419
2006 - 2010	Rural Interstate	0.5285	0.0015	0.0077	0.1740	0.0768	0.0018	0.0365	0.1732
	Rural Arterial	0.5486	0.0016	0.0060	0.2093	0.0923	0.0021	0.0399	0.1002
	Rural Collector	0.5062	0.0014	0.0052	0.2426	0.1070	0.0025	0.0478	0.0873
	Urban Interstate	0.6420	0.0018	0.0056	0.1707	0.0753	0.0017	0.0259	0.0770
	Urban Other	0.6457	0.0018	0.0052	0.1916	0.0845	0.0019	0.0238	0.0455
2011 - 2016	Rural Interstate	0.5168	0.0016	0.0070	0.1765	0.0773	0.0025	0.0372	0.1811
	Rural Arterial	0.5381	0.0016	0.0055	0.2130	0.0933	0.0030	0.0408	0.1047
	Rural Collector	0.4960	0.0015	0.0048	0.2466	0.1080	0.0034	0.0488	0.0909
	Urban Interstate	0.6322	0.0019	0.0051	0.1744	0.0764	0.0024	0.0266	0.0810
	Urban Other	0.6366	0.0019	0.0047	0.1960	0.0858	0.0027	0.0245	0.0478

a. Source: Apogee Research (1996), technical Note D.
b. Gasoline automobiles (Light Duty Gasoline Vehicle).
c. Diesel automobiles (Light Duty Diesel Vehicle).
d. Motorcycles.
e. Gasoline trucks of 6,000 pounds or less gross vehicle weight (GVW) (Light Duty Gasoline Truck).
f. Gasoline trucks 6,001 - 8,500 pounds GVW (Light Duty Gasoline Truck).
g. Diesel trucks 6,001 - 8,500 pounds GVW (Light Duty Diesel Truck).
h. Gasoline trucks over 8,500 pounds GVW (Heavy Duty Gasoline Vehicle).
i. Diesel trucks over 8,500 pounds GVW (Heavy Duty Diesel Vehicle).

The measure used by the MOBILE5a emissions factor model to adjust individual vehicle classes' emission rates for speed variation represents the average operating speeds for several different "driving cycles" that combine different phases of vehicle operation (acceleration, cruising, braking, and idling) in varying proportions.[5] The specific driving cycles used to test variation in different vehicle classes' emission rates are intended to represent typical trips that specific types of vehicles are commonly used to make, and that result in different overall average speeds. This measure of travel speed is broadly consistent with the average effective speed (AES) measure employed by HERS, which is intended to represent the average speed of travel on a section associated with its predicted daily travel volume, assuming a characteristic mix of vehicle classes and distribution of travel between peak and off-peak periods for that section type.

F.2.3 Future Trends in Emission Rates

In response to the progressive tightening of federal regulations on new motor vehicles' emission rates, the vehicles added to the U.S. fleet each year are significantly less polluting than those they replace.[6] The downward trend in average emission rates resulting from such "turnover" of the vehicle fleet is reflected in the estimates of future emission rates for both individual vehicle classes and the vehicle fleet as a whole that are obtained from the MOBILE5a and PART5 models.[7] Emission rates predicted by MOBILE5a and PART5 for individual vehicle classes during the middle year of each five-year funding period considered by HERS (for example, 1998 for the 1996-2000 funding period) are used to represent average emissions for that class of vehicles over the entire funding period. Because average emission rates for vehicle classes are predicted to change very slowly over the future, this approximation results in only minimal error in estimating emissions for the first and last two years of each funding period, while enormously reducing computation requirements.

The average emissions rates for each pollutant and section type calculated by HERS thus reflect the projected downward trend in future emission rates. As a consequence, estimated air pollution costs under baseline and improved travel conditions on each sample section are predicted to decline over successive future funding periods. HERS' estimates of *differences* in air pollution costs between baseline and improved travel conditions on each section -- which the model includes in its estimates of the benefits from potential improvements to the section -- are also expected to narrow during each successive future funding period considered by HERS. Thus the effect of considering air pollution costs on the likelihood that HERS will select candidate improvements to a sample section diminishes during each successive future funding period.

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[5] Emissions for a sample of vehicles are measured on each of these driving cycles, and expressed relative to those measured for the test cycle used to certify their compliance with prevailing federal emission standards. The resulting "speed correction factors" are used to estimate vehicles' emissions when driven at speeds other than the approximately 20 mph average of the certification test cycle.

[6] The effect on average emissions of adding new, cleaner vehicles to the fleet has been partly offset by the tendency for aging vehicles – most of which met less stringent emission standards when new -- to be kept in service for longer periods and to be used more intensively than has historically been the case. Shifts toward heavier vehicles that are subject to less stringent emission standard, particularly the increasing substitution of light trucks (pickups, vans, and sport/utility vehicles) for automobiles as passenger vehicles, have also offset some of the effect of new vehicles' progressively lower emission rates. On balance, however, individual vehicle classes' and fleet-wide average emission rates for most pollutants have declined significantly in recent years, and are expected to decline significantly over the foreseeable future.

[7] Both models also assume continued increases in the number of light- duty trucks used as passenger vehicles and in the average weight of heavy-duty trucks over the future, which slightly slow the decline in fleet-wide average emissions rates resulting from a progressively "cleaner" fleet.

F.2.4 Final Emission Rates

The products of this process are average emissions rates -- measured as mass per vehicle-mile of travel -- for each of the six air pollutants and the five consolidated section types considered by HERS; thus the model calculates thirty such rates. Average emissions rates for each pollutant differ among the five section types because of differences in the typical mixes of vehicle classes using each section type. Average emissions rates on each section type for three of the six pollutants -- carbon monoxide, volatile organic compounds, and nitrogen oxides -- vary in response to changes in the average effective speed of travel; thus the emission rates calculated by HERS for these three pollutants will differ between baseline conditions and those with each candidate in place. In contrast, average emission rates for the three remaining pollutants -- sulfur oxides, particulate matter, and road dust -- do not vary significantly with travel speed, and will thus be identical under baseline and improved conditions within a funding period. Finally, average emission rates for all six pollutants generated by travel on all section types will decline across the entire range of travel speeds during each successive future funding period considered by HERS.

Figures F-3 through F-7 illustrate variation in average emissions rates of the three speed-sensitive pollutants (CO, VOC, and NOx) produced by the specific mix of vehicle classes using each of the five consolidated section groups shown previously in Table F-1. These figures show emission rates for the first five-year funding period considered by HERS (1996-2000); the corresponding relationships for future funding periods would reveal progressively lower emissions per mile of each pollutant for all values of average effective speed. Tables F-3 through F-5 report

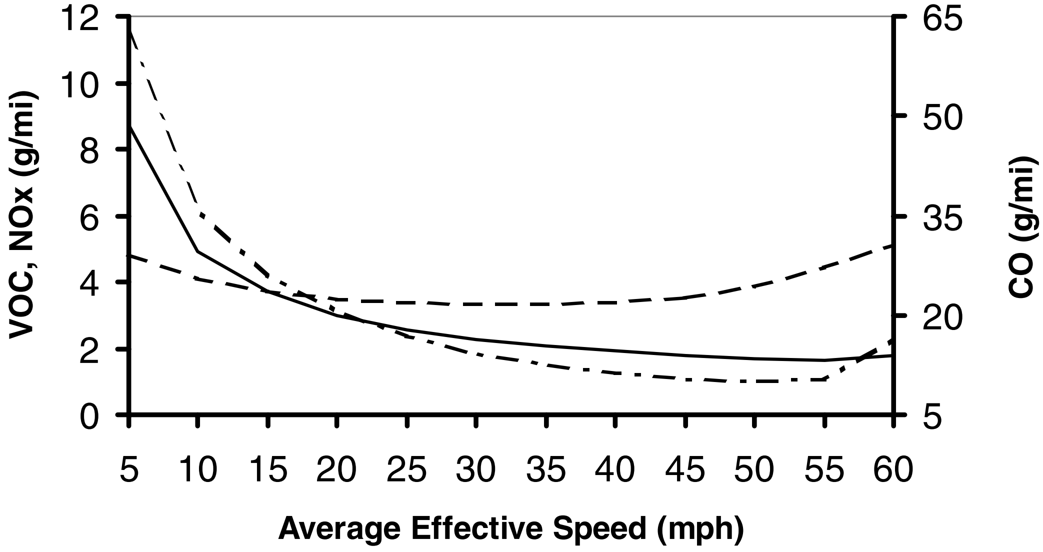

Figure F-3. Average Emission Rates for Rural Interstate Sections

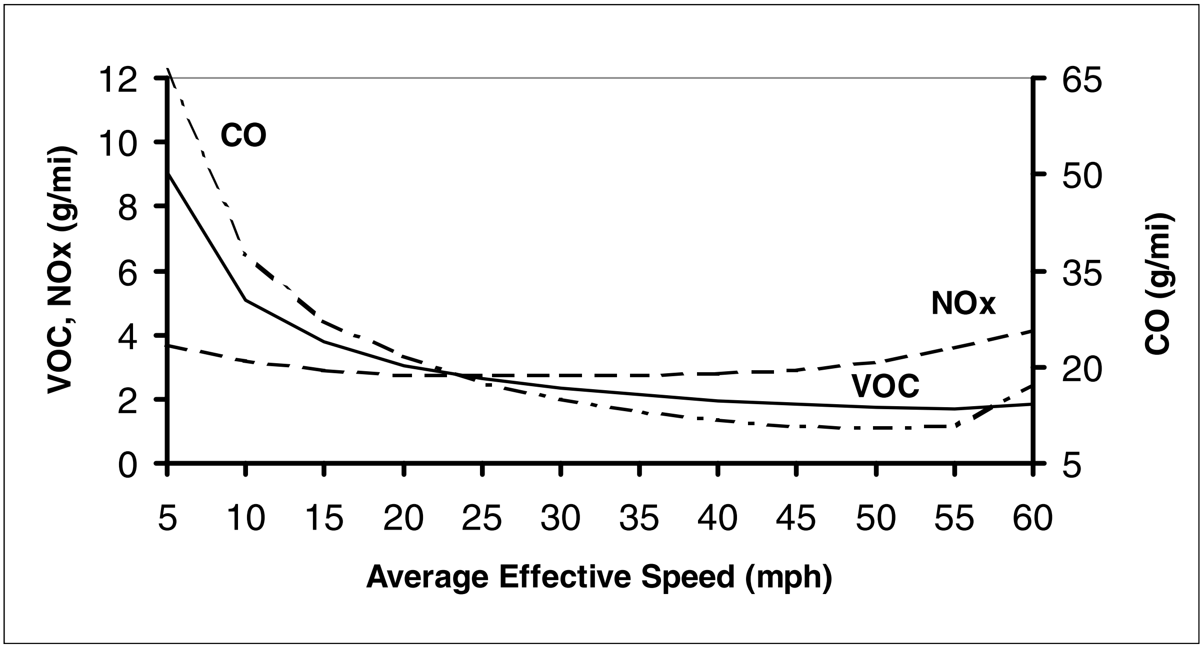

Figure F-4. Average Emission Rates for Rural Arterial Sections

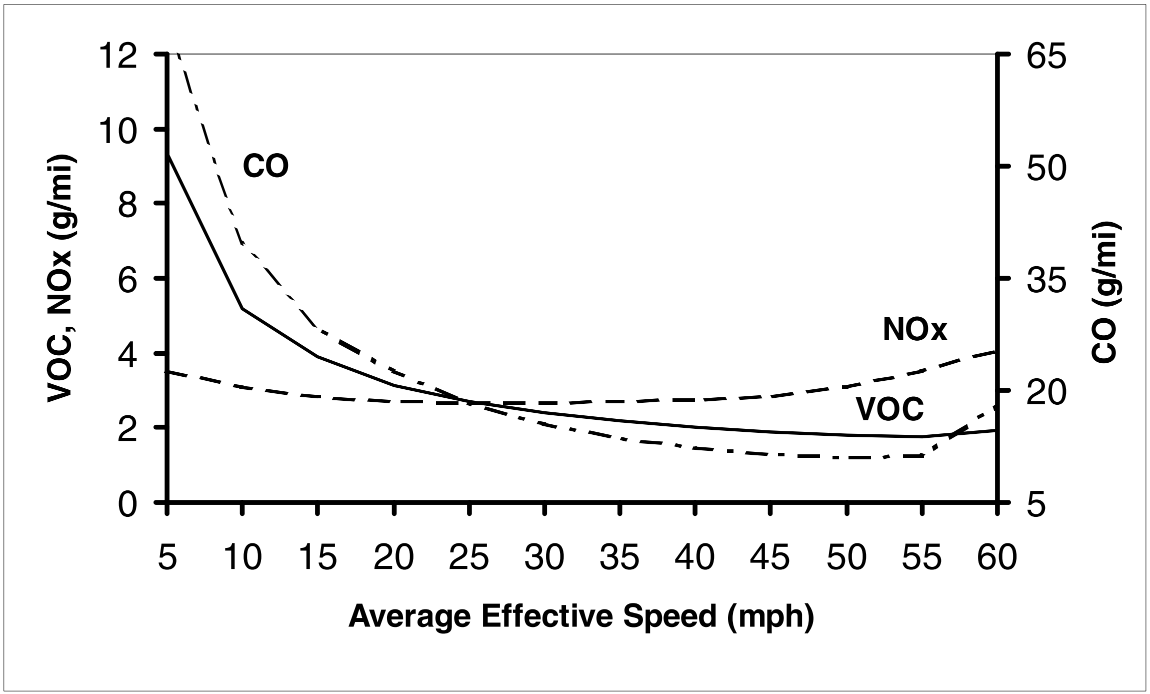

Figure F-5. Average Emission Rates for Rural Other Sections

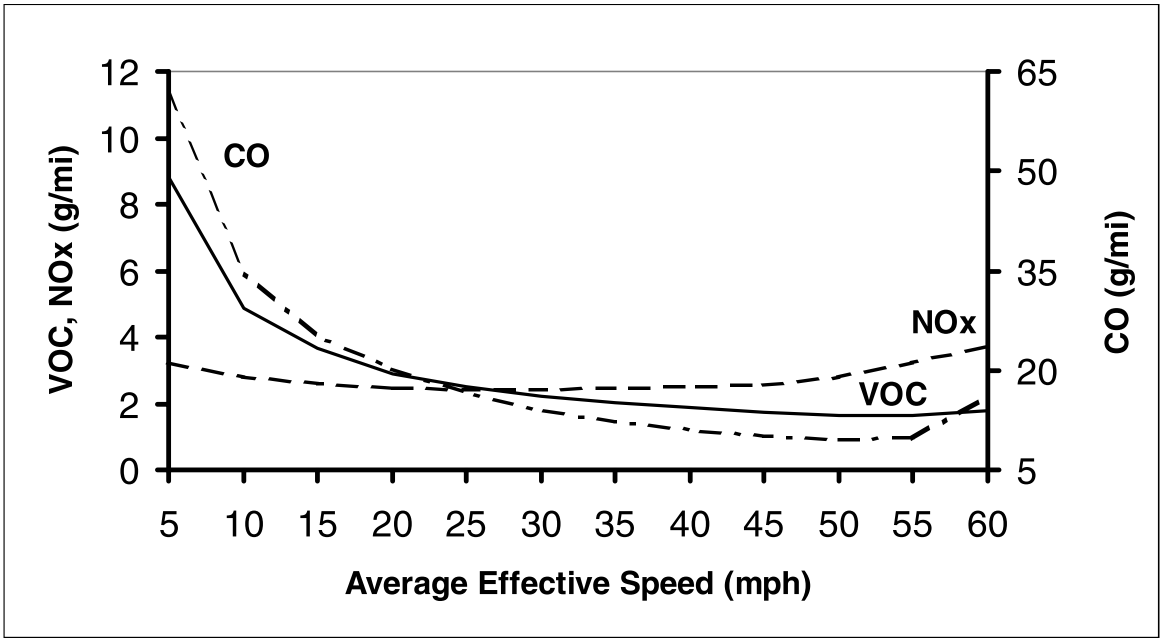

Figure F-6. Average Emission Rates for Urban Interstate Sections

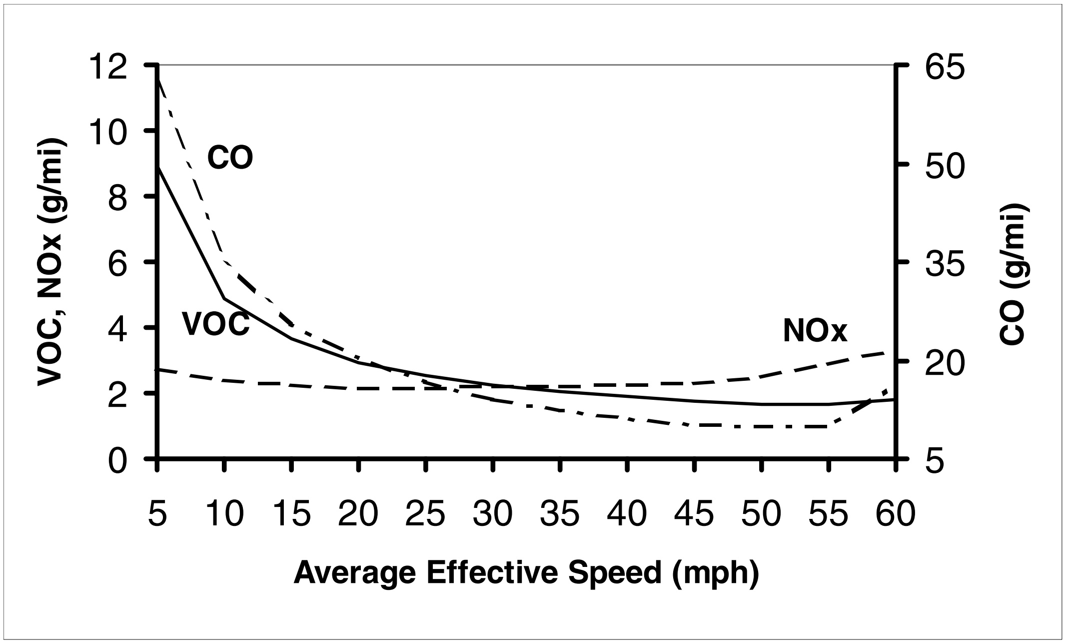

Figure F-7. Average Emission Rates for Other Urban Sections

average emission rates by consolidated section group and funding period for the three pollutants whose emissions are assumed to be independent of travel speed (SOx, PM, and road dust). As these tables show, average emission rates for these pollutants vary among section types in

Table F-3. Average Sulphur Dioxide (SO_2) Emission Rates[a]

Consolidated Section Group	Average Emissions (g / mi.) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.149	0.147	0.148	0.148
Rural Arterial	0.124	0.122	0.122	0.123
Rural Collector	0.121	0.118	0.119	0.119
Urban Interstate	0.114	0.112	0.112	0.113
Urban Other	0.103	0.101	0.102	0.102

a. Source: Apogee Research (1996), Technical Note B, Table B19.

Table F-4. Average Particulate Matter (PM) Emission Rates[a]

Consolidated Section Group	Average Emissions (g / mi.) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.238	0.176	0.141	0.126
Rural Arterial	0.160	0.125	0.105	0.097
Rural Collector	0.147	0.115	0.098	0.091
Urban Interstate	0.137	0.109	0.094	0.088
Urban Other	0.105	0.088	0.079	0.076

a. Source: Apogee Research (1996), Technical Note B, Table B17.

Table F-5. Average Road Dust Generation Rates[a]

Consolidated Section Group	Average Generation (g / mi.) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	1.901	1.901	1.901	1.901
Rural Arterial	2.879	2.879	2.879	2.879
Rural Collector	4.505	4.505	4.505	4.505
Urban Interstate	1.405	1.405	1.405	1.405
Urban Other	3.142	3.142	3.142	3.142

a. Source: Apogee Research (1996), Technical Note B, Table B16.

response to differences in their characteristic mixes of vehicles, and (with the exception of those for road dust) are also expected to change slightly during each future funding period considered by HERS.[8]

F.3 Air Pollution Damage Costs

F.3.1 Calculating Pollution Costs Under Baseline and Improved Conditions

In effect, HERS calculates the economic costs of air pollution generated by annual travel on a sample section by multiplying total annual emissions of each of the six pollutants by an estimate of its dollar cost per ton emitted, and summing the results.[9] As described previously, total annual emissions of each pollutant on a sample section are the product of annual vehicle-miles of travel on the section and the its characteristic emission rate per vehicle-mile of travel for that pollutant (for some pollutants this emission rate depends on HERS' estimate of average effective speed on the section). This calculation is performed for each pollutant, and the results are summed to yield total annual air pollution damage costs generated by travel on each sample section during a funding period. By repeating this procedure under baseline travel conditions and under improved conditions, HERS calculates the *change* in total air pollution costs generated by travel on the section that would result from implementing each improvement.

F.3.2 Damage Costs for Individual Air Pollutants

The estimated costs of human health and property damage per ton of each pollutant that are used by HERS to perform these calculations are derived from a widely cited recent study.[10] These values are derived by dividing the study's estimate of total annual costs from health and property damages caused by highway vehicles' contribution to atmospheric levels of each individual pollutant by the total number of tons of that pollutant emitted annually by highway vehicles. Thus they represent estimates of nationwide average damage costs per ton of each pollutant, given the typical atmospheric levels of those pollutants that prevailed at the time the study was conducted (1995). These values are assumed to represent acceptable estimates of the *changes* in total health and property damage costs that would result if emissions of each pollutant changed by one ton. HERS provides the option of using either the midpoint or the upper limit of the range for costs per ton of each pollutant implied by the study's reported range of estimates for total annual economic costs attributable to each pollutant. These dollar-denominated dam-

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[8] The slight increases in SO_2 emission rates during the 2011-2016 funding period shown in Table F-3 reflect the PART5 model's assumptions about the increasing weights of some types of heavy trucks.

[9] For computational simplicity the exact calculation procedures used by HERS differ slightly from this description; they are described in detail in the following section.

[10] D. McCubbin and M. Delucchi, *Health Effects of Motor Vehicle Air Pollution,* Institute for Transportation Studies, University of California, Davis, 1996.

age costs per ton of each pollutant are assumed to remain constant over all future funding periods considered by HERS.

F.3.3 Adjustments to Damage Costs

The cost per ton estimates derived from this study represent average damage costs from exposure to prevailing air pollution levels that occurs at typical U.S. population and development densities. For pollutants that remain concentrated near their original sources, these average costs should be scaled up or down to reflect local variation in damage costs resulting from differences in population and property exposure to air pollution caused by higher or lower population and development density surrounding those sources. HERS uses the functional class of each sample section (that is, whether a rural or urban section) to adjust the nationwide average costs per ton of each individual pollutant generated by vehicles traveling on it.

Specifically, HERS scales costs for the three pollutants that tend to remain localized (carbon monoxide, particulate matter, and road dust) downward from their national average values for rural sections to reflect the lower density of rural populations located adjacent to highways and thus exposed to these pollutants. Damage costs per ton of these three pollutants emitted by vehicles using urban sample sections are assumed to equal their nationwide average values. In contrast, average damage costs for the three more widely dispersed pollutants -- ozone, nitrogen oxides, and sulfur oxides -- are scaled *upward* from their national averages for urban sample sections in order to reflect the larger populations exposed to them. The exact scaling factors used in this process were developed by examining county-level population and population density data for the 100 largest U.S. metropolitan areas and comparing them to corresponding figures for all non-urbanized counties in the nation. Table F-6 summarizes the moderate and high estimates of per-ton damage costs for each pollutant derived from the McCubbin-Delucchi study, as well as the factors used by HERS to make these locational adjustments.

Table F-6. Air Pollutant Damage Costs and HERS Adjustment Factors (1996 Dollars)[a]

Pollutant	Damage Costs ($/ton)		Adjustment Factor:	
	Moderate	High	Urban	Rural
Carbon Monoxide	$20	$100	1.0	0.5
Volatile Organic Compounds	$1,054	$2,754	1.5	1.0
Nitrogen Oxides	$1,525	$3,625	1.5	1.0
Sulfur Dioxide	$1,601	$8,401	1.5	1.0
Particulate Matter	$2,422	$4,822	1.0	0.5
Road Dust	$2,422	$4,822	1.0	0.5

a. Source: Apogee Research (1996), p. 25 and Technical Appendix G.

F.4 Specific Computation Procedures Used by HERS

In order to streamline the repeated computations of air pollution costs under baseline and improved travel conditions on the large number of sample sections it analyzes, HERS employs a set of equations developed using the following procedures. First, variation in emission rates with the average effective speed of travel on a section for the three speed-sensitive pollutants is captured by fitting polynomial equations to the relationships between emission rates and average effective speed shown previously in Figures F-3 through F-7. Each of these equations predicts average emissions in grams per vehicle-mile of one of the three pollutants on a specific type of section as a function of the average effective speed of travel.

Because there are three pollutants whose emission rates vary with speed as well as in response to differences in the mix of vehicle classes operating on the five different section types, fifteen such equations are required. In addition, the parameters of these equations change during each future funding period covered by HERS, since as discussed previously each curve shown in Figures F-3 through F-7 shifts downward (and changes shape slightly) during successive future funding periods. Tables F-7, F-8, and F-9 report the coefficients of the polynomial equations used to predict CO, VOC, and NOx emission rates for each HERS section type and funding period.

Next, the dollar damage cost per gram of each speed-sensitive pollutant is derived by dividing its damage cost per ton (reported previously in Table F-6) by the number of grams equivalent to one ton. As described previously, damage costs per gram of each pollutant are adjusted upward for sections in urban locations, and downward for those in non-urbanized locations. The resulting adjusted damage cost per gram of each speed-sensitive pollutant is then multiplied by each coefficient in the equations used to predict its emissions in grams per mile for the five different section types. The result is a set of fifteen equations (three equations for each of five section types) predicting air pollution damage *costs* per vehicle-mile caused by emissions of each speed-sensitive pollutant from the typical mix of vehicles using a specific section type during a funding period.

Each of these equations calculates average air pollution costs per vehicle-mile of travel on one type of sample sections as a function of the average effective speed of travel. Tables F-10, F-11, and F-12 report the coefficient values appearing in the equations for CO, VOC, and NOx damage costs per vehicle-mile for each section type and funding period. (For each table, the “a” version contains the moderate damage cost estimate, and the “b” version the high damage cost estimate.) The coefficients on each corresponding term of the polynomial equations for damage costs caused by emissions of these three pollutants are then summed to yield an equation for their combined damage cost per vehicle-mile of travel on each of the five section types during each funding period considered by HERS. This summation reduces the number of damage cost equations to a single one for each of the five section types during each funding period.

Finally, the estimated damage cost per ton of each pollutant that is *unaffected* by speed (SOx, PM, and road dust) is converted to a cost per gram and multiplied by the average emission rates in grams per mile for that pollutant on each of the five section types. As with the unit damage costs for speed-sensitive pollutants, the per-ton damage costs used in these calculations are first adjusted upward for urban section types or downward for rural sections, depending on the

Table F-7. Carbon Monoxide (CO) Emission Rate Equations[a]

Consolidated Section Group		Coefficient on Variable in Equation for Carbon Monoxide Emission Rate (g / mi.):						
		Constant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	143.04595	-21.448136	1.6887607	-0.0716740	0.0016504	-0.0000194	0.0000001
	Rural Arterial	143.04595	-21.448136	1.6887607	-0.0716740	0.0016504	-0.0000194	0.0000001
	Rural Collector	147.92270	-22.093088	1.7354190	-0.0736310	0.0016976	-0.0000200	0.0000001
	Urban Interstate	138.88591	-21.150156	1.6801357	-0.0715243	0.0016459	-0.0000193	0.0000001
	Urban Other	142.13337	-21.806509	1.7390971	-0.0742039	0.0017111	-0.0000201	0.0000001
2001 - 2005	Rural Interstate	123.11248	-18.228589	1.4663821	-0.0632393	0.0014612	-0.0000171	0.0000001
	Rural Arterial	125.94324	-18.594355	1.4939536	-0.0644528	0.0014917	-0.0000175	0.0000001
	Rural Collector	125.94324	-18.594355	1.4939536	-0.0644528	0.0014917	-0.0000175	0.0000001
	Urban Interstate	121.94038	-18.301320	1.4830561	-0.0640894	0.0014790	-0.0000173	0.0000001
	Urban Other	124.80506	-18.855721	1.5340722	-0.0664473	0.0015361	-0.0000180	0.0000001
2006 - 2010	Rural Interstate	114.17363	-16.827916	1.3701258	-0.0596681	0.0013845	-0.0000162	0.0000001
	Rural Arterial	114.17363	-16.827916	1.3701258	-0.0596681	0.0013845	-0.0000162	0.0000001
	Rural Collector	116.30324	-17.104592	1.3922637	-0.0606909	0.0014110	-0.0000166	0.0000001
	Urban Interstate	114.17298	-17.043957	1.3963221	-0.0608872	0.0014105	-0.0000165	0.0000001
	Urban Other	117.04281	-17.584568	1.4466227	-0.0632336	0.0014675	-0.0000171	0.0000001
2011 - 2016	Rural Interstate	111.76610	-16.485495	1.3504753	-0.0591227	0.0013766	-0.0000161	0.0000001
	Rural Arterial	111.76610	-16.485495	1.3504753	-0.0591227	0.0013766	-0.0000161	0.0000001
	Rural Collector	113.74774	-16.749829	1.3724203	-0.0601578	0.0014036	-0.0000165	0.0000001
	Urban Interstate	112.14462	-16.746249	1.3795722	-0.0604532	0.0014050	-0.0000164	0.0000001
	Urban Other	115.13169	-17.304034	1.4316551	-0.0628916	0.0014643	-0.0000171	0.0000001

a. Source: Apogee Research (1996), Technical Note B, Tables B1-B5.

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dispersion characteristics of the individual pollutants. The resulting dollar figures, which are reported in Tables F-13, F-14, and F-15, represent estimates of the damage cost per vehicle-mile traveled on sections of each type caused by emissions of SOx, PM, and road dust, and are independent of travel speed. This estimated cost is then added to the intercept or constant term appearing in the appropriate equation for combined damage costs per vehicle-mile from emissions of the three speed-dependent pollutants on that same section type.

Table F-8. Volatile Organic Compound (VOC) Emission Rate Equations[a]

Consolidated Section Group		Coefficient on Variable in Equation for VOC Emission Rate (g / mi.):						
		Constant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	11.470260	-1.4296556	0.0977159	-0.0037311	0.0000797	-0.0000009	4.052E-09
	Rural Arterial	12.046060	-1.5429255	0.1067980	-0.0041046	0.0000881	-0.0000010	4.493E-09
	Rural Collector	12.434908	-1.5900442	0.1097000	-0.0042046	0.0000900	-0.0000010	4.585E-09
	Urban Interstate	11.672387	-1.5271727	0.1072718	-0.0041627	0.0000899	-0.0000010	4.616E-09
	Urban Other	11.908979	-1.5806696	0.1118507	-0.0043583	0.0000943	-0.0000011	4.859E-09
2001 - 2005	Rural Interstate	9.7168336	-1.1277938	0.0730478	-0.0026773	0.0000554	-0.0000006	2.684E-09
	Rural Arterial	10.192291	-1.2234297	0.0807030	-0.0029901	0.0000623	-0.0000007	3.043E-09
	Rural Collector	10.447068	-1.2472411	0.0815731	-0.0029983	0.0000620	-0.0000007	3.006E-09
	Urban Interstate	10.014635	-1.2418181	0.0842256	-0.0031882	0.0000675	-0.0000007	3.362E-09
	Urban Other	10.232036	-1.2911777	0.0884630	-0.0033694	0.0000716	-0.0000008	3.585E-09
2006 - 2010	Rural Interstate	9.8994526	-1.3735297	0.1048065	-0.0043525	0.0000985	-0.0000011	5.298E-09
	Rural Arterial	10.392135	-1.4852650	0.1144876	-0.004771	0.0001081	-0.0000013	5.820E-09
	Rural Collector	10.684134	-1.5302442	0.1178403	-0.004905	0.0001111	-0.0000013	5.971E-09
	Urban Interstate	10.154998	-1.4733830	0.1145351	-0.0047948	0.0001089	-0.0000013	5.880E-09
	Urban Other	10.371455	-1.5248514	0.1190820	-0.0049931	0.0001135	-0.0000013	6.130E-09
2011 - 2016	Rural Interstate	9.5859661	-1.3208984	0.1006140	-0.0041756	0.0000944	-0.0000011	5.068E-09
	Rural Arterial	10.069602	-1.4324983	0.1103430	-0.0045976	0.0001041	-0.0000012	5.595E-09
	Rural Collector	10.335011	-1.4773689	0.1137320	-0.0047343	0.0001072	-0.0000012	5.751E-09
	Urban Interstate	9.8415541	-1.4214115	0.1104162	-0.0046213	0.0001049	-0.0000012	5.654E-09
	Urban Other	10.058255	-1.4735247	0.1150439	-0.0048237	0.0001096	-0.0000013	5.909E-09

a. Source: Apogee Research (1996), Technical Note B, Tables B11-B15.

This procedure yields a single equation for *total* damage costs per vehicle-mile from air pollution generated by travel on each of the five section types during the current funding period. The general form of these equations was shown previously as Equation 7.19, which appears in paragraph 7.3 (page 7-34) of the *HERS Technical Report*. Each equation shows how total damage costs per vehicle-mile traveled caused by all six air pollutants vary with the average effective speed of travel on sections of that type during a specific funding period. Repeating this process generates a set of such equations for each future funding period. The procedure is repeated as well to develop a corresponding set of equations using the high per-ton damage cost estimates for each pollutant shown in Table F-6.

Table F-9. Nitrogen Oxide (NOx) Emission Rate Equations[a]

Consolidated Section Group		Coefficient on Variable in Equation for Nitrogen Oxide Emission Rate (g / mi.):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	5.5330384	-0.1733633	-0.0005301	0.0004434	-0.0000173	0.0000003	-1.460E-09
	Rural Arterial	4.1797100	-0.1014986	-0.0037785	0.0005585	-0.0000201	0.0000003	-1.651E-09
	Rural Collector	3.9948042	-0.0888996	-0.0043894	0.0005825	-0.0000207	0.0000003	-1.694E-09
	Urban Interstate	3.6710817	-0.0797430	-0.0047073	0.0005879	-0.0000207	0.0000003	-1.694E-09
	Urban Other	3.0967102	-0.0495682	-0.0061283	0.0006407	-0.0000221	0.0000003	-1.786E-09
2001 - 2005	Rural Interstate	4.6569497	-0.1532212	0.0006322	0.0003137	-0.0000129	0.0000002	-1.124E-09
	Rural Arterial	3.6168951	-0.0974691	-0.0019035	0.0004056	-0.0000152	0.0000002	-1.284E-09
	Rural Collector	3.4768676	-0.0873869	-0.0024015	0.0004259	-0.0000158	0.0000002	-1.324E-09
	Urban Interstate	3.2089837	-0.0805473	-0.0026159	0.0004280	-0.0000157	0.0000002	-1.315E-09
	Urban Other	2.7624333	-0.0569369	-0.0037378	0.0004707	-0.0000168	0.0000003	-1.393E-09
2006 - 2010	Rural Interstate	4.2386051	-0.1450051	0.0013180	0.0002465	-0.0000108	0.0000002	-9.558E-10
	Rural Arterial	3.3532036	-0.0972051	-0.0008692	0.0003278	-0.0000128	0.0000002	-1.103E-09
	Rural Collector	3.2310079	-0.0881977	-0.0013176	0.0003464	-0.0000133	0.0000002	-1.142E-09
	Urban Interstate	3.0017081	-0.0829004	-0.0014691	0.0003469	-0.0000133	0.0000002	-1.130E-09
	Urban Other	2.6178499	-0.0624976	-0.0024455	0.0003851	-0.0000143	0.0000002	-1.203E-09
2011 - 2016	Rural Interstate	4.0842899	-0.1408217	0.0013903	0.0002330	-0.0000103	0.0000002	-9.223E-10
	Rural Arterial	3.2517527	-0.0954250	-0.0007099	0.0003121	-0.0000123	0.0000002	-1.068E-09
	Rural Collector	3.1330198	-0.0868261	-0.0011238	0.0003289	-0.0000128	0.0000002	-1.102E-09
	Urban Interstate	2.9219077	-0.0815919	-0.0013321	0.0003338	-0.0000128	0.0000002	-1.101E-09
	Urban Other	2.5586167	-0.0621062	-0.0022731	0.0003710	-0.0000138	0.0000002	-1.172E-09

a. Source: Apogee Research (1996), Technical Note B, Tables B6-B10.

Table F-16 reports the coefficients of these equations for the moderate per-ton damage costs for each pollutant shown previously in Table F-6; Table F-16 shows that these equations have the same polynomial form as those used to calculate per-mile emissions rates and damage costs for the three individual speed-sensitive pollutants. The coefficients reported in Table F-16 are the numerical values of the emission factors EF_1, EF_2,…,EF_6 appearing in Equation 7.19; as the table shows, 25 such equations are required for the five consolidated section groups and five funding periods. Table F-17 shows the coefficient values for the corresponding set of damage cost equations developed using the high per-ton damage costs for each pollutant.[11] Figure F-8

Table F-10a. Carbon Monoxide (CO) Damage Cost Equations: Moderate Damage Costs[a]

	Consolidated Section Group	Coefficient on Variable in Equation for Carbon Monoxide Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.00158	(0.00024)	0.00002	(7.894E-07)	1.818E-08	(2.140E-10)	1.012E-12
	Rural Arterial	0.00158	(0.00024)	0.00002	(7.894E-07)	1.818E-08	(2.140E-10)	1.012E-12
	Rural Collector	0.00163	(0.00024)	0.00002	(8.109E-07)	1.870E-08	(2.207E-10)	1.046E-12
	Urban Interstate	0.00306	(0.00047)	0.00004	(1.575E-06)	3.625E-08	(4.258E-10)	2.006E-12
	Urban Other	0.00313	(0.00048)	0.00004	(1.634E-06)	3.769E-08	(4.433E-10)	2.092E-12
2001 - 2005	Rural Interstate	0.00136	(0.00020)	0.00002	(6.965E-07)	1.609E-08	(1.883E-10)	8.793E-13
	Rural Arterial	0.00139	(0.00020)	0.00002	(7.098E-07)	1.643E-08	(1.927E-10)	9.023E-13
	Rural Collector	0.00139	(0.00020)	0.00002	(7.098E-07)	1.643E-08	(1.927E-10)	9.023E-13
	Urban Interstate	0.00269	(0.00040)	0.00003	(1.412E-06)	3.258E-08	(3.801E-10)	1.767E-12
	Urban Other	0.00275	(0.00042)	0.00003	(1.464E-06)	3.383E-08	(3.954E-10)	1.842E-12
2006 - 2010	Rural Interstate	0.00126	(0.00019)	0.00002	(6.571E-07)	1.525E-08	(1.784E-10)	8.303E-13
	Rural Arterial	0.00126	(0.00019)	0.00002	(6.571E-07)	1.525E-08	(1.784E-10)	8.303E-13
	Rural Collector	0.00128	(0.00019)	0.00002	(6.684E-07)	1.554E-08	(1.823E-10)	8.507E-13
	Urban Interstate	0.00251	(0.00038)	0.00003	(1.341E-06)	3.107E-08	(3.623E-10)	1.679E-12
	Urban Other	0.00258	(0.00039)	0.00003	(1.393E-06)	3.232E-08	(3.776E-10)	1.753E-12
2011 - 2016	Rural Interstate	0.00123	(0.00018)	0.00001	(6.511E-07)	1.516E-08	(1.777E-10)	8.278E-13
	Rural Arterial	0.00123	(0.00018)	0.00001	(6.511E-07)	1.516E-08	(1.777E-10)	8.278E-13
	Rural Collector	0.00125	(0.00018)	0.00002	(6.625E-07)	1.546E-08	(1.817E-10)	8.486E-13
	Urban Interstate	0.00247	(0.00037)	0.00003	(1.332E-06)	3.095E-08	(3.617E-10)	1.678E-12
	Urban Other	0.00254	(0.00038)	0.00003	(1.385E-06)	3.225E-08	(3.775E-10)	1.754E-12

a. Source: Derived from Tables F-6 and F-7 using procedure described in paragraph F.4, page F-14.

displays the relationships between speed and damage costs described by the equations shown in Table F-17; it shows the relationships between average effective speed and combined air pol-

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[11] The values presented in Tables F-16 and F-17 (and their predecessor tables) have limited precision due to the size of the tables. The actual values used by HERS are presented in Appendix G, ”Factors For Emissions Equations,” to the full sixteen decimal places utilized by the model.

Table F-10b. Carbon Monoxide (CO) Damage Cost Equations: High Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for Carbon Monoxide Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.00788	(0.00118)	0.00009	(3.947E-06)	9.088E-08	(1.070E-09)	5.061E-12
	Rural Arterial	0.00788	(0.00118)	0.00009	(3.947E-06)	9.088E-08	(1.070E-09)	5.061E-12
	Rural Collector	0.00815	(0.00122)	0.00010	(4.055E-06)	9.348E-08	(1.103E-09)	5.230E-12
	Urban Interstate	0.01530	(0.00233)	0.00019	(7.877E-06)	1.813E-07	(2.129E-09)	1.003E-11
	Urban Other	0.01565	(0.00240)	0.00019	(8.172E-06)	1.884E-07	(2.216E-09)	1.046E-11
2001 - 2005	Rural Interstate	0.00678	(0.00100)	0.00008	(3.482E-06)	8.046E-08	(9.416E-10)	4.396E-12
	Rural Arterial	0.00694	(0.00102)	0.00008	(3.549E-06)	8.214E-08	(9.636E-10)	4.512E-12
	Rural Collector	0.00694	(0.00102)	0.00008	(3.549E-06)	8.214E-08	(9.636E-10)	4.512E-12
	Urban Interstate	0.01343	(0.00202)	0.00016	(7.058E-06)	1.629E-07	(1.900E-09)	8.837E-12
	Urban Other	0.01375	(0.00208)	0.00017	(7.318E-06)	1.692E-07	(1.977E-09)	9.208E-12
2006 - 2010	Rural Interstate	0.00629	(0.00093)	0.00008	(3.286E-06)	7.624E-08	(8.921E-10)	4.151E-12
	Rural Arterial	0.00629	(0.00093)	0.00008	(3.286E-06)	7.624E-08	(8.921E-10)	4.151E-12
	Rural Collector	0.00640	(0.00094)	0.00008	(3.342E-06)	7.770E-08	(9.115E-10)	4.254E-12
	Urban Interstate	0.01257	(0.00188)	0.00015	(6.706E-06)	1.553E-07	(1.812E-09)	8.397E-12
	Urban Other	0.01289	(0.00194)	0.00016	(6.964E-06)	1.616E-07	(1.888E-09)	8.764E-12
2011 - 2016	Rural Interstate	0.00615	(0.00091)	0.00007	(3.256E-06)	7.580E-08	(8.887E-10)	4.139E-12
	Rural Arterial	0.00615	(0.00091)	0.00007	(3.256E-06)	7.580E-08	(8.887E-10)	4.139E-12
	Rural Collector	0.00626	(0.00092)	0.00008	(3.313E-06)	7.729E-08	(9.085E-10)	4.243E-12
	Urban Interstate	0.01235	(0.00184)	0.00015	(6.658E-06)	1.547E-07	(1.808E-09)	8.388E-12
	Urban Other	0.01268	(0.00191)	0.00016	(6.926E-06)	1.613E-07	(1.888E-09)	8.769E-12

a. Source: Derived from Tables F-6 and F-7 using procedure described in paragraph F.4, page F-14.

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lution damage costs per vehicle-mile for each of the five groups of sample sections during the current funding period, using the high per-ton damage cost assumptions shown in Table F-6.

HERS uses its calculated value of average effective speed on each sample section under baseline conditions to solve the appropriate equation from Table F-16 or F-17 (depending on whether the moderate or high damage cost assumption is being employed) for an estimate of air pollution costs per vehicle-mile. This value is multiplied by HERS' estimate of annual vehicle-

Table F-11a. Volatile Organic Compound (VOC) Damage Cost Equations: Moderate Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for VOC Damage Costs (1996 Dollars per Vehicle Mile):						
		Constant	Speed	$Speed^2$	$Speed^3$	$Speed^4$	$Speed^5$	$Speed^6$
1996 - 2000	Rural Interstate	0.01331	(0.00166)	0.00011	(4.331E-06)	9.255E-08	(1.034E-09)	4.704E-12
	Rural Arterial	0.01398	(0.00179)	0.00012	(4.765E-06)	1.022E-07	(1.145E-09)	5.216E-12
	Rural Collector	0.01443	(0.00185)	0.00013	(4.881E-06)	1.045E-07	(1.169E-09)	5.322E-12
	Urban Interstate	0.02032	(0.00266)	0.00019	(7.248E-06)	1.565E-07	(1.759E-09)	8.037E-12
	Urban Other	0.02074	(0.00275)	0.00019	(7.589E-06)	1.642E-07	(1.850E-09)	8.461E-12
2001 - 2005	Rural Interstate	0.01128	(0.00131)	0.00008	(3.108E-06)	6.427E-08	(6.991E-10)	3.115E-12
	Rural Arterial	0.01183	(0.00142)	0.00009	(3.471E-06)	7.228E-08	(7.902E-10)	3.532E-12
	Rural Collector	0.01213	(0.00145)	0.00009	(3.480E-06)	7.202E-08	(7.834E-10)	3.490E-12
	Urban Interstate	0.01744	(0.00216)	0.00015	(5.551E-06)	1.175E-07	(1.299E-09)	5.854E-12
	Urban Other	0.01782	(0.00225)	0.00015	(5.867E-06)	1.247E-07	(1.382E-09)	6.241E-12
2006 - 2010	Rural Interstate	0.01149	(0.00159)	0.00012	(5.052E-06)	1.143E-07	(1.325E-09)	6.150E-12
	Rural Arterial	0.01206	(0.00172)	0.00013	(5.538E-06)	1.255E-07	(1.455E-09)	6.755E-12
	Rural Collector	0.01240	(0.00178)	0.00014	(5.694E-06)	1.289E-07	(1.493E-09)	6.931E-12
	Urban Interstate	0.01768	(0.00257)	0.00020	(8.349E-06)	1.897E-07	(2.202E-09)	1.024E-11
	Urban Other	0.01806	(0.00266)	0.00021	(8.694E-06)	1.977E-07	(2.296E-09)	1.067E-11
2011 - 2016	Rural Interstate	0.01113	(0.00153)	0.00012	(4.847E-06)	1.096E-07	(1.269E-09)	5.883E-12
	Rural Arterial	0.01169	(0.00166)	0.00013	(5.337E-06)	1.209E-07	(1.400E-09)	6.495E-12
	Rural Collector	0.01200	(0.00171)	0.00013	(5.495E-06)	1.244E-07	(1.440E-09)	6.676E-12
	Urban Interstate	0.01714	(0.00247)	0.00019	(8.047E-06)	1.827E-07	(2.120E-09)	9.845E-12
	Urban Other	0.01751	(0.00257)	0.00020	(8.399E-06)	1.909E-07	(2.215E-09)	1.029E-11

a. Source: Derived from Tables F-6 and F-8 using procedure described in paragraph F.4, page F-14.

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miles of travel on the section under baseline or unimproved travel conditions to determine total annual costs from air pollution damages under those conditions during the current funding period. HERS then repeats this procedure to estimate total annual air pollution costs caused by travel on that sample section under the speed and traffic conditions predicted to result from each candidate improvement under consideration.

Table F-11b. Volatile Organic Compound (VOC) Damage Cost Equations: High Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for VOC Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	$Speed^2$	$Speed^3$	$Speed^4$	$Speed^5$	$Speed^6$
1996 - 2000	Rural Interstate	0.01331	(0.00166)	0.00011	(4.331E-06)	9.255E-08	(1.034E-09)	4.704E-12
	Rural Arterial	0.01398	(0.00179)	0.00012	(4.765E-06)	1.022E-07	(1.145E-09)	5.216E-12
	Rural Collector	0.01443	(0.00185)	0.00013	(4.881E-06)	1.045E-07	(1.169E-09)	5.322E-12
	Urban Interstate	0.02032	(0.00266)	0.00019	(7.248E-06)	1.565E-07	(1.759E-09)	8.037E-12
	Urban Other	0.02074	(0.00275)	0.00019	(7.589E-06)	1.642E-07	(1.850E-09)	8.461E-12
2001 - 2005	Rural Interstate	0.01128	(0.00131)	0.00008	(3.108E-06)	6.427E-08	(6.991E-10)	3.115E-12
	Rural Arterial	0.01183	(0.00142)	0.00009	(3.471E-06)	7.228E-08	(7.902E-10)	3.532E-12
	Rural Collector	0.01213	(0.00145)	0.00009	(3.480E-06)	7.202E-08	(7.834E-10)	3.490E-12
	Urban Interstate	0.01744	(0.00216)	0.00015	(5.551E-06)	1.175E-07	(1.299E-09)	5.854E-12
	Urban Other	0.01782	(0.00225)	0.00015	(5.867E-06)	1.247E-07	(1.382E-09)	6.241E-12
2006 - 2010	Rural Interstate	0.01149	(0.00159)	0.00012	(5.052E-06)	1.143E-07	(1.325E-09)	6.150E-12
	Rural Arterial	0.01206	(0.00172)	0.00013	(5.538E-06)	1.255E-07	(1.455E-09)	6.755E-12
	Rural Collector	0.01240	(0.00178)	0.00014	(5.694E-06)	1.289E-07	(1.493E-09)	6.931E-12
	Urban Interstate	0.01768	(0.00257)	0.00020	(8.349E-06)	1.897E-07	(2.202E-09)	1.024E-11
	Urban Other	0.01806	(0.00266)	0.00021	(8.694E-06)	1.977E-07	(2.296E-09)	1.067E-11
2011 - 2016	Rural Interstate	0.01113	(0.00153)	0.00012	(4.847E-06)	1.096E-07	(1.269E-09)	5.883E-12
	Rural Arterial	0.01169	(0.00166)	0.00013	(5.337E-06)	1.209E-07	(1.400E-09)	6.495E-12
	Rural Collector	0.01200	(0.00171)	0.00013	(5.495E-06)	1.244E-07	(1.440E-09)	6.676E-12
	Urban Interstate	0.01714	(0.00247)	0.00019	(8.047E-06)	1.827E-07	(2.120E-09)	9.845E-12
	Urban Other	0.01751	(0.00257)	0.00020	(8.399E-06)	1.909E-07	(2.215E-09)	1.029E-11

a. Source: Derived from Tables F-6 and F-8 using procedure described in paragraph F.4, page F-14.

The *difference* in total air pollution costs between baseline and improved conditions increases or reduces net benefits from the improvement under consideration, depending on whether the changes in average effective speed and annual vehicle travel resulting from that improvement cause air pollution costs to rise or decline. This process is repeated to evaluate the effect on net benefits from the candidate improvement from including air pollution costs during each future funding period making up the expected lifetime of that improvement. HERS then applies the usual process of discounting the stream of future net benefits from each candidate

Table F-12a. Nitrogen Oxide (NOx) Damage Cost Equations: Moderate Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for Carbon Monoxide Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.00929	(0.00029)	(8.903E-07)	7.447E-07	(2.900E-08)	4.491E-10	(2.452E-12)
	Rural Arterial	0.00702	(0.00017)	(6.346E-06)	9.380E-07	(3.371E-08)	5.101E-10	(2.773E-12)
	Rural Collector	0.00671	(0.00015)	(7.372E-06)	9.783E-07	(3.475E-08)	5.239E-10	(2.846E-12)
	Urban Interstate	0.00925	(0.00020)	(1.186E-05)	1.481E-06	(5.224E-08)	7.860E-10	(4.269E-12)
	Urban Other	0.00780	(0.00012)	(1.544E-05)	1.614E-06	(5.557E-08)	8.298E-10	(4.500E-12)
2001 - 2005	Rural Interstate	0.00782	(0.00026)	1.062E-06	5.268E-07	(2.174E-08)	3.431E-10	(1.888E-12)
	Rural Arterial	0.00607	(0.00016)	(3.197E-06)	6.813E-07	(2.558E-08)	3.937E-10	(2.156E-12)
	Rural Collector	0.00584	(0.00015)	(4.033E-06)	7.153E-07	(2.649E-08)	4.061E-10	(2.223E-12)
	Urban Interstate	0.00808	(0.00020)	(6.590E-06)	1.078E-06	(3.963E-08)	6.058E-10	(3.313E-12)
	Urban Other	0.00696	(0.00014)	(9.416E-06)	1.186E-06	(4.239E-08)	6.427E-10	(3.509E-12)
2006 - 2010	Rural Interstate	0.00712	(0.00024)	2.214E-06	4.140E-07	(1.807E-08)	2.900E-10	(1.605E-12)
	Rural Arterial	0.00563	(0.00016)	(1.460E-06)	5.506E-07	(2.155E-08)	3.364E-10	(1.853E-12)
	Rural Collector	0.00543	(0.00015)	(2.213E-06)	5.819E-07	(2.240E-08)	3.483E-10	(1.918E-12)
	Urban Interstate	0.00756	(0.00021)	(3.701E-06)	8.740E-07	(3.341E-08)	5.179E-10	(2.848E-12)
	Urban Other	0.00660	(0.00016)	(6.161E-06)	9.702E-07	(3.593E-08)	5.520E-10	(3.031E-12)
2011 - 2016	Rural Interstate	0.00686	(0.00024)	2.335E-06	3.913E-07	(1.730E-08)	2.790E-10	(1.549E-12)
	Rural Arterial	0.00546	(0.00016)	(1.192E-06)	5.242E-07	(2.071E-08)	3.246E-10	(1.793E-12)
	Rural Collector	0.00526	(0.00015)	(1.887E-06)	5.524E-07	(2.148E-08)	3.354E-10	(1.852E-12)
	Urban Interstate	0.00736	(0.00021)	(3.356E-06)	8.409E-07	(3.236E-08)	5.032E-10	(2.773E-12)
	Urban Other	0.00645	(0.00016)	(5.727E-06)	9.346E-07	(3.483E-08)	5.367E-10	(2.953E-12)

a. Source: Derived from Tables F-6 and F-9 using procedure described in paragraph F.4, page F-14.

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improvement -- including its effect on air pollution costs -- to its present value in order to evaluate the desirability of selecting that improvement during the current funding period.

Table F-12b. Nitrogen Oxide (NOx) Damage Cost Equations: High Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for Carbon Monoxide Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.02209	(0.00069)	(2.116E-06)	1.770E-06	(6.894E-08)	1.068E-09	(5.827E-12)
	Rural Arterial	0.01669	(0.00041)	(1.508E-05)	2.230E-06	(8.013E-08)	1.212E-09	(6.591E-12)
	Rural Collector	0.01595	(0.00035)	(1.752E-05)	2.325E-06	(8.260E-08)	1.245E-09	(6.764E-12)
	Urban Interstate	0.02198	(0.00048)	(2.819E-05)	3.520E-06	(1.242E-07)	1.868E-09	(1.015E-11)
	Urban Other	0.01854	(0.00030)	(3.670E-05)	3.837E-06	(1.321E-07)	1.972E-09	(1.070E-11)
2001 - 2005	Rural Interstate	0.01859	(0.00061)	2.524E-06	1.252E-06	(5.167E-08)	8.155E-10	(4.487E-12)
	Rural Arterial	0.01444	(0.00039)	(7.599E-06)	1.619E-06	(6.081E-08)	9.357E-10	(5.125E-12)
	Rural Collector	0.01388	(0.00035)	(9.587E-06)	1.700E-06	(6.297E-08)	9.653E-10	(5.284E-12)
	Urban Interstate	0.01922	(0.00048)	(1.567E-05)	2.563E-06	(9.420E-08)	1.440E-09	(7.875E-12)
	Urban Other	0.01654	(0.00034)	(2.238E-05)	2.819E-06	(1.008E-07)	1.528E-09	(8.342E-12)
2006 - 2010	Rural Interstate	0.01692	(0.00058)	5.262E-06	9.841E-07	(4.295E-08)	6.893E-10	(3.816E-12)
	Rural Arterial	0.01339	(0.00039)	(3.470E-06)	1.309E-06	(5.122E-08)	7.996E-10	(4.405E-12)
	Rural Collector	0.01290	(0.00035)	(5.260E-06)	1.383E-06	(5.325E-08)	8.279E-10	(4.558E-12)
	Urban Interstate	0.01798	(0.00050)	(8.798E-06)	2.078E-06	(7.942E-08)	1.231E-09	(6.769E-12)
	Urban Other	0.01568	(0.00037)	(1.464E-05)	2.306E-06	(8.542E-08)	1.312E-09	(7.204E-12)
2011 - 2016	Rural Interstate	0.01631	(0.00056)	5.551E-06	9.302E-07	(4.112E-08)	6.631E-10	(3.682E-12)
	Rural Arterial	0.01298	(0.00038)	(2.834E-06)	1.246E-06	(4.923E-08)	7.717E-10	(4.262E-12)
	Rural Collector	0.01251	(0.00035)	(4.487E-06)	1.313E-06	(5.105E-08)	7.971E-10	(4.401E-12)
	Urban Interstate	0.01750	(0.00049)	(7.977E-06)	1.999E-06	(7.692E-08)	1.196E-09	(6.592E-12)
	Urban Other	0.01532	(0.00037)	(1.361E-05)	2.222E-06	(8.280E-08)	1.276E-09	(7.020E-12)

a. Source: Derived from Tables F-6 and F-9 using procedure described in paragraph F.4, page F-14.

F.5 Likely Effects of Including Air Pollution Costs

It is difficult to anticipate the exact effects that implementing these procedures for incorporating air pollution costs will have on HERS' selection of improvement projects. As indicated previously, proposed improvements to a sample section tend to *increase* air pollution costs by making travel on it less costly and thus raising the level of travel on the section. Thus if air pol-

Table F-13. Sulfur Dioxide (SO2) Damage Costs[a]

Consolidated Section Group	Moderate Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0002627	0.0002592	0.0002610	0.0002610
Rural Arterial	0.0002186	0.0002151	0.0002151	0.0002169
Rural Collector	0.0002133	0.0002081	0.0002098	0.0002098
Urban Interstate	0.0003015	0.0002962	0.0002962	0.0002989
Urban Other	0.0002724	0.0002671	0.0002698	0.0002698

Consolidated Section Group	High Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0013786	0.0013601	0.0013693	0.0013693
Rural Arterial	0.0011473	0.0011288	0.0011288	0.0011380
Rural Collector	0.0011195	0.0010918	0.0011010	0.0011010
Urban Interstate	0.0015821	0.0015544	0.0015544	0.0015682
Urban Other	0.0014295	0.0014017	0.0014156	0.0014156

a. Source: Derived from Tables F-3 andF-6 using procedure described in paragraph F.4, page F-14.

lutant emissions per vehicle-mile were unaffected by the changes in travel conditions that occur when sample sections are improved, air pollution costs would normally rise, thereby reducing the net benefits from typical improvements.

As Figures F-3 through F-7 showed previously, however, increases in the average effective speed of travel that result from an improvement can reduce average emissions per vehicle-mile for certain pollutants. By doing so, an improvement can thus reduce average air pollution costs per vehicle-mile traveled on the section, thereby offsetting some or all of the effect of higher travel volumes on total air pollution costs. As Figure F-8 showed, per-mile air pollution costs on most facility types fall significantly as speeds increase up to about 45 mph, so benefits from improvements that increase speeds over this range are likely to be reduced only modestly -- and may actually be increased in some cases -- by including air pollution costs.

Table F-14. Particulate Matter (PM) Damage Costs[a]

Consolidated Section Group	Moderate Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0003174	0.0002347	0.0001881	0.0001680
Rural Arterial	0.0002134	0.0001667	0.0001400	0.0001294
Rural Collector	0.0001961	0.0001534	0.0001307	0.0001214
Urban Interstate	0.0003654	0.0002907	0.0002507	0.0002347
Urban Other	0.0002801	0.0002347	0.0002107	0.0002027
Consolidated Section Group	**High Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:**			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0006320	0.0004673	0.0003744	0.0003346
Rural Arterial	0.0004248	0.0003319	0.0002788	0.0002576
Rural Collector	0.0003903	0.0003054	0.0002602	0.0002416
Urban Interstate	0.0007275	0.0005789	0.0004992	0.0004673
Urban Other	0.0005576	0.0004673	0.0004195	0.0004036

a. Source: Derived from Tables F-4 and F-6 using procedure described in paragraph F.4, page F-14.

Because per-mile emission rates and thus air pollution costs rise at higher speeds, however -- Figure F-8 showed that per-mile air pollution costs begin to rise gradually above about 45 mph -- large speed increases resulting from an improvement can accentuate the increase in air pollution costs caused by higher travel volumes.[12] Thus where travel speeds on sample sections

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[12] This increase is more pronounced for sections located in urbanized areas, because MOBILE5a estimates that NOx emissions – which are assumed to have higher per-ton damage costs in urban areas – increase sharply at higher speeds. However, both the sharp increase in NOx emission rates at high speeds predicted by MOBILE5a and the high per-ton damage cost for urban NOx emissions are controversial. Some recent evidence suggests that the increase in NOx emission rates above 50 mph for gasoline-powered automobiles is much less pronounced than predicted by MOBILE5a. McCubbin and DeLucchi's estimate of damages from urban NOx emissions assume that in most major urban areas, changes in ozone concentrations respond proportionally to changes in NOx emissions rather than to changes in emissions of volatile organic compounds, the other major constituent of ground-level ozone.

Table F-15. Road Dust Damage Costs[a]

Consolidated Section Group	Moderate Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0025354	0.0025354	0.0025354	0.0025354
Rural Arterial	0.0038397	0.0038397	0.0038397	0.0038397
Rural Collector	0.0060083	0.0060083	0.0060083	0.0060083
Urban Interstate	0.0037464	0.0037464	0.0037464	0.0037464
Urban Other	0.0083801	0.0083801	0.0083801	0.0083801

Consolidated Section Group	High Damage Costs (1996 Dollars per Vehicle Mile) for Funding Period:			
	1996-2000	2001-2005	2006-2010	2011-2016
Rural Interstate	0.0050477	0.0050477	0.0050477	0.0050477
Rural Arterial	0.0076446	0.0076446	0.0076446	0.0076446
Rural Collector	0.0119621	0.0119621	0.0119621	0.0119621
Urban Interstate	0.0074587	0.0074587	0.0074587	0.0074587
Urban Other	0.0166840	0.0166840	0.0166840	0.0166840

a. Source: Derived from Tables F-5 and F-6 using procedure described in paragraph F.4, page F-14.

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under baseline or unimproved conditions are *already* above about 45 mph, the increase in air pollution costs resulting from the higher travel volumes produced by most improvements will be *reinforced* by an increase in per-mile air pollution costs. (This same effect may also occur where baseline travel speeds are below the 45 mph threshold, but where candidate improvements to a sample section produce very large increases in travel speeds.) In these cases, including air pollution costs may significantly reduce the net benefits from many potential improvements considered by HERS, making them less likely to be selected.

As Figure F-8 also illustrates, air pollution damage costs per vehicle-mile differ considerably among the various section types considered by HERS across the entire range of travel speeds. Air pollution costs imposed by travel on facilities located in urban areas are significantly higher than those for identical facility types in rural areas because of the increased exposure to air pollution experienced by residents and properties surrounding sample sections located in

Table F-16. Total Damage Cost Equations: Moderate Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for Total Damage Costs (1996 Dollars per Vehicle Mile):						
		Con-stant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.02730	(0.00219)	0.00013	(4.376E-06)	8.172E-08	(7.988E-10)	3.265E-12
	Rural Arterial	0.02685	(0.00220)	0.00014	(4.616E-06)	8.668E-08	(8.486E-10)	3.455E-12
	Rural Collector	0.02919	(0.00224)	0.00014	(4.713E-06)	8.845E-08	(8.655E-10)	3.522E-12
	Urban Interstate	0.03704	(0.00333)	0.00021	(7.342E-06)	1.405E-07	(1.399E-09)	5.774E-12
	Urban Other	0.04060	(0.00336)	0.00022	(7.609E-06)	1.464E-07	(1.463E-09)	6.053E-12
2001 - 2005	Rural Interstate	0.02349	(0.00177)	0.00010	(3.277E-06)	5.862E-08	(5.444E-10)	2.107E-12
	Rural Arterial	0.02351	(0.00179)	0.00011	(3.499E-06)	6.313E-08	(5.892E-10)	2.279E-12
	Rural Collector	0.02572	(0.00180)	0.00011	(3.475E-06)	6.195E-08	(5.700E-10)	2.169E-12
	Urban Interstate	0.03254	(0.00277)	0.00017	(5.885E-06)	1.104E-07	(1.073E-09)	4.308E-12
	Urban Other	0.03641	(0.00281)	0.00018	(6.145E-06)	1.161E-07	(1.135E-09)	4.574E-12
2006 - 2010	Rural Interstate	0.02285	(0.00202)	0.00014	(5.295E-06)	1.115E-07	(1.213E-09)	5.375E-12
	Rural Arterial	0.02315	(0.00207)	0.00015	(5.645E-06)	1.192E-07	(1.297E-09)	5.733E-12
	Rural Collector	0.02546	(0.00211)	0.00015	(5.780E-06)	1.220E-07	(1.327E-09)	5.864E-12
	Urban Interstate	0.03205	(0.00315)	0.00023	(8.816E-06)	1.873E-07	(2.047E-09)	9.071E-12
	Urban Other	0.03609	(0.00320)	0.00023	(9.116E-06)	1.940E-07	(2.121E-09)	9.395E-12
2011 - 2016	Rural Interstate	0.02218	(0.00195)	0.00013	(5.107E-06)	1.075E-07	(1.167E-09)	5.162E-12
	Rural Arterial	0.02257	(0.00200)	0.00014	(5.464E-06)	1.153E-07	(1.253E-09)	5.530E-12
	Rural Collector	0.02485	(0.00205)	0.00015	(5.606E-06)	1.184E-07	(1.286E-09)	5.673E-12
	Urban Interstate	0.03125	(0.00305)	0.00022	(8.537E-06)	1.813E-07	(1.978E-09)	8.749E-12
	Urban Other	0.03535	(0.00310)	0.00023	(8.850E-06)	1.883E-07	(2.056E-09)	9.090E-12

[a] Source: Derived from Tables F-10a, F-11a, F-12a, F-13, F-14, and F-15 using procedure described in paragraph F.4, page F-14.

urbanized areas. Average costs per vehicle-mile are also higher for facilities that carry larger shares of heavy vehicle travel (Interstate highways and other major arterials), since the per-mile rates at which trucks and other heavy vehicles emit some pollutants are much higher than those for light-duty vehicles. Thus considering air pollution costs is more likely to result in significant reductions in net benefits from candidate improvements to higher-order facilities (Interstate highways and other major arterials) and sample sections in urbanized locations.

On balance, the increase in air pollution costs from higher travel volumes seems likely to outweigh the effect of any decline in per-mile pollution costs for most proposed improvements.

Table F-17. Total Damage Cost Equations: High Damage Costs[a]

Consolidated Section Group		Coefficient on Variable in Equation for Total Damage Costs (1996 Dollars per Vehicle Mile):						
		Constant	Speed	Speed^2	Speed^3	Speed^4	Speed^5	Speed^6
1996 - 2000	Rural Interstate	0.05034	(0.00353)	0.00020	(6.508E-06)	1.145E-07	(1.037E-09)	3.937E-12
	Rural Arterial	0.04776	(0.00338)	0.00020	(6.482E-06)	1.130E-07	(1.002E-09)	3.686E-12
	Rural Collector	0.05200	(0.00342)	0.00021	(6.610E-06)	1.154E-07	(1.027E-09)	3.788E-12
	Urban Interstate	0.06737	(0.00547)	0.00034	(1.160E-05)	2.135E-07	(2.020E-09)	7.921E-12
	Urban Other	0.07360	(0.00545)	0.00035	(1.192E-05)	2.206E-07	(2.094E-09)	8.224E-12
2001 - 2005	Rural Interstate	0.04353	(0.00292)	0.00017	(5.338E-06)	9.306E-08	(8.253E-10)	3.025E-12
	Rural Arterial	0.04231	(0.00283)	0.00017	(5.401E-06)	9.361E-08	(8.180E-10)	2.919E-12
	Rural Collector	0.04630	(0.00282)	0.00017	(5.329E-06)	9.118E-08	(7.816E-10)	2.718E-12
	Urban Interstate	0.05968	(0.00466)	0.00029	(1.005E-05)	1.861E-07	(1.759E-09)	6.816E-12
	Urban Other	0.06666	(0.00467)	0.00030	(1.037E-05)	1.931E-07	(1.832E-09)	7.107E-12
2006 - 2010	Rural Interstate	0.04149	(0.00310)	0.00020	(7.354E-06)	1.476E-07	(1.527E-09)	6.486E-12
	Rural Arterial	0.04079	(0.00304)	0.00020	(7.515E-06)	1.505E-07	(1.547E-09)	6.502E-12
	Rural Collector	0.04503	(0.00307)	0.00021	(7.653E-06)	1.534E-07	(1.577E-09)	6.626E-12
	Urban Interstate	0.05774	(0.00494)	0.00034	(1.298E-05)	2.656E-07	(2.783E-09)	1.187E-11
	Urban Other	0.06514	(0.00497)	0.00035	(1.335E-05)	2.738E-07	(2.871E-09)	1.223E-11
2011 - 2016	Rural Interstate	0.04034	(0.00300)	0.00020	(7.172E-06)	1.443E-07	(1.494E-09)	6.340E-12
	Rural Arterial	0.03987	(0.00295)	0.00020	(7.346E-06)	1.475E-07	(1.517E-09)	6.372E-12
	Rural Collector	0.04407	(0.00298)	0.00020	(7.495E-06)	1.506E-07	(1.551E-09)	6.518E-12
	Urban Interstate	0.05648	(0.00481)	0.00034	(1.271E-05)	2.605E-07	(2.732E-09)	1.164E-11
	Urban Other	0.06402	(0.00484)	0.00034	(1.310E-05)	2.693E-07	(2.827E-09)	1.204E-11

a. Source: Derived from Tables F-10b, F-11b, F-12b, F-13, F-14, and F-15 using procedure described in paragraph F.4, page F-14.

Thus considering air pollution costs will make most improvements less likely to meet the benefit-cost criterion used by HERS to select improvements for adoption. At an aggregate level, the result seems likely to be a reduction in the number and value of improvement projects that are selected by HERS when the economic efficiency criterion is employed. Where projects are selected on a different basis, including air pollution costs is likely to reduce the net benefits generated by any selected set of improvements.

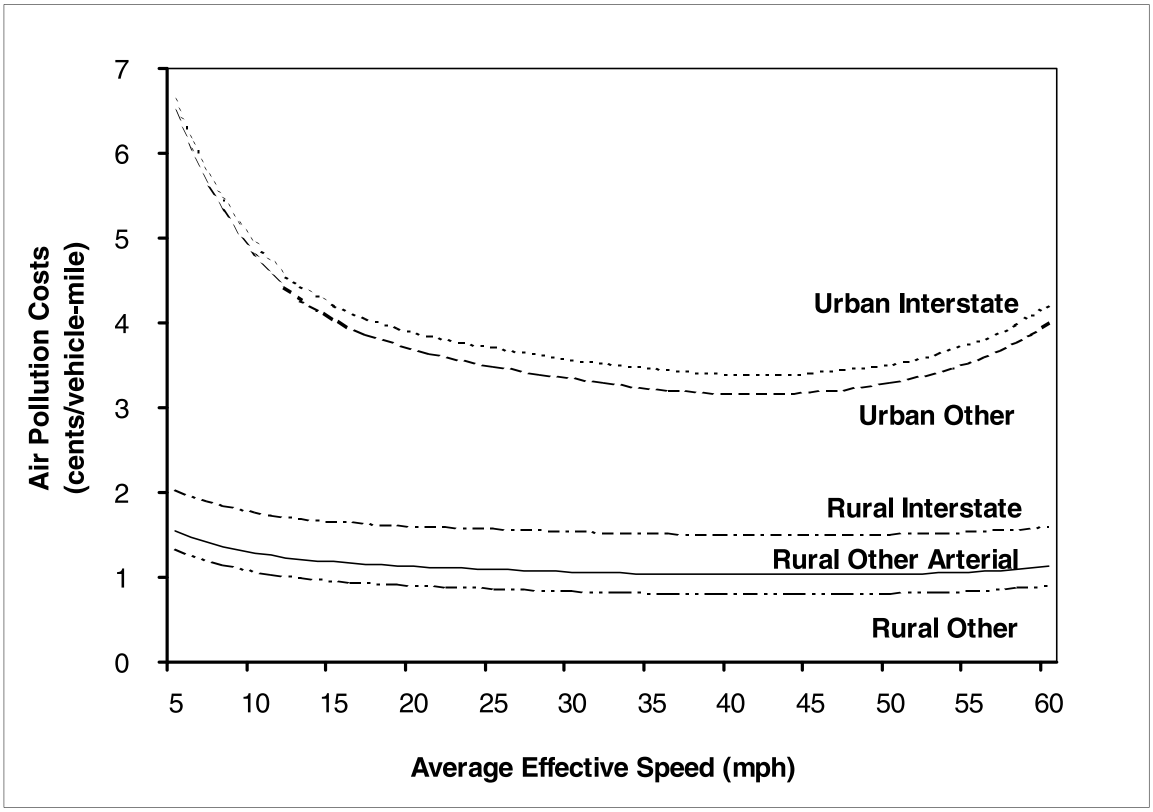

Figure F-8. Total Air Pollution Costs per Vehicle-Mile (High Damage Cost Assumptions)

Appendix G: Factors For Emissions Equations

HERS calculates the damage costs associated with vehicular emissions using Equation 7.19, as presented in paragraph 7.3, ”External Costs.” The tables in this appendix contain the values of the emission constant *EC* and the emission factors EF_n, where *n* is 1 through 6.

Each table has the values used for one of the nine functional classes recognized by HERS, except for Table G-8, which has the values used for both urban minor arterials and urban collectors. Within each table, the values are arranged by the time period to which they apply, and by high and medium estimates of damage.

Table G-1.   Emissions Factors for Rural Interstates

before 2000		
	Middle Estimate	High Estimate
EC	0.0066736739764023	0.0192991806091067
EF_1	-0.0004312829901037	-0.0016838966118592
EF_2	0.0000298524444226	0.0001224194106935
EF_3	-0.0000011479899604	-0.0000049014328546
EF_4	0.0000000245309720	0.0000001081692020
EF_5	-0.0000000002725278	-0.0000000012336357
EF_6	0.0000000000012374	0.0000000000057070
2001 - 2005		
	Middle Estimate	High Estimate
EC	0.0060386928932365	0.0171906976993052
EF_1	-0.0003574026304503	-0.0014070116211679
EF_2	0.0000247351028680	0.0001031560014857
EF_3	-0.0000009545641886	-0.0000041691450930
EF_4	0.0000000203452881	0.0000000920866172
EF_5	-0.0000000002239273	-0.0000000010427346
EF_6	0.0000000000010020	0.0000000000047616
2006 - 2010		
	Middle Estimate	High Estimate
EC	0.0058579297770238	0.0165209247339144
EF_1	-0.0003691216609313	-0.0014011346100619
EF_2	0.0000274767104917	0.0001077618519224
EF_3	-0.0000011209684601	-0.0000045073984556
EF_4	0.0000000248751686	0.0000001018203694
EF_5	-0.0000000002818905	-0.0000000011692892
EF_6	0.0000000000012847	0.0000000000053767

Table G-1. Emissions Factors for Rural Interstates

2011 - 2015		
	Middle Estimate	High Estimate
EC	0.0057571931993164	0.0162082276621329
EF_1	-0.0003585384871309	-0.0013646453917894
EF_2	0.0000267857868360	0.0001054370657176
EF_3	-0.0000010966999490	-0.0000044291135462
EF_4	0.0000000243919016	0.0000001003312980
EF_5	-0.0000000002767141	-0.0000000011539105
EF_6	0.0000000000012612	0.0000000000053081
2016 and Beyond		
	Middle Estimate	High Estimate
EC	0.0057368621326779	0.0161472168587778
EF_1	-0.0003560484730461	-0.0013560982806664
EF_2	0.0000266054813971	0.0001047955492615
EF_3	-0.0000010898566530	-0.0000044040629351
EF_4	0.0000000242459640	0.0000000997870307
EF_5	-0.0000000002750494	-0.0000000011476484
EF_6	0.0000000000012533	0.0000000000052782

Table G-2. Emissions Factors for Rural Principal Arterials - Other

	before 2000	
	Middle Estimate	High Estimate
EC	0.0077498191372221	0.0213811486147296
EF_1	-0.0004323614968793	-0.0016895613518060
EF_2	0.0000303611146413	0.0001238771933685
EF_3	-0.0000011720203746	-0.0000049687806285
EF_4	0.0000000250260909	0.0000001095739049
EF_5	-0.0000000002775025	-0.0000000012480721
EF_6	0.0000000000012565	0.0000000000057645
	2001 - 2005	
	Middle Estimate	High Estimate
EC	0.0071837246782220	0.0194225976974947
EF_1	-0.0003591403371926	-0.0014137605329950
EF_2	0.0000251978251724	0.0001044654978661
EF_3	-0.0000009754317733	-0.0000042273129303
EF_4	0.0000000207624232	0.0000000932672993
EF_5	-0.0000000002279727	-0.0000000010544982
EF_6	0.0000000000010169	0.0000000000048068
	2006 - 2010	
	Middle Estimate	High Estimate
EC	0.0070455177216117	0.0188485364967403
EF_1	-0.0003740637389053	-0.0014159412360271
EF_2	0.0000282331458461	0.0001098249830978
EF_3	-0.0000011558986918	-0.0000046018882106
EF_4	0.0000000256431208	0.0000001039090030
EF_5	-0.0000000002902570	-0.0000000011922446
EF_6	0.0000000000013205	0.0000000000054760

Table G-2. Emissions Factors for Rural Principal Arterials - Other

2011 - 2015		
	Middle Estimate	High Estimate
EC	0.0069578563784465	0.0185643592492463
EF_1	-0.0003638684856802	-0.0013803704172682
EF_2	0.0000275623804269	0.0001075494237865
EF_3	-0.0000011323952878	-0.0000045255159834
EF_4	0.0000000251777596	0.0000001024650968
EF_5	-0.0000000002852937	-0.0000000011774050
EF_6	0.0000000000012980	0.0000000000054099
2016 and Beyond		
	Middle Estimate	High Estimate
EC	0.0069393089907029	0.0185075645491830
EF_1	-0.0003614548091862	-0.0013720156960436
EF_2	0.0000273898628230	0.0001069279281944
EF_3	-0.0000011260129692	-0.0000045016419820
EF_4	0.0000000250455068	0.0000001019554293
EF_5	-0.0000000002838208	-0.0000000011716243
EF_6	0.0000000000012911	0.0000000000053826

Table G-3.   Emissions Factors for Rural Minor Arterials

before 2000		
	Middle Estimate	High Estimate
EC	0.0076885186416274	0.0212570948151702
EF_1	-0.0004323614968793	-0.0016895613518060
EF_2	0.0000303611146413	0.0001238771933685
EF_3	-0.0000011720203746	-0.0000049687806285
EF_4	0.0000000250260909	0.0000001095739049
EF_5	-0.0000000002775025	-0.0000000012480721
EF_6	0.0000000000012565	0.0000000000057645
2001 - 2005		
	Middle Estimate	High Estimate
EC	0.0071264252839489	0.0193065097569660
EF_1	-0.0003591403371926	-0.0014137605329950
EF_2	0.0000251978251724	0.0001044654978661
EF_3	-0.0000009754317733	-0.0000042273129303
EF_4	0.0000000207624232	0.0000000932672993
EF_5	-0.0000000002279727	-0.0000000010544982
EF_6	0.0000000000010169	0.0000000000048068
2006 - 2010		
	Middle Estimate	High Estimate
EC	0.0069909738890126	0.0187382217390310
EF_1	-0.0003740637389053	-0.0014159412360271
EF_2	0.0000282331458461	0.0001098249830978
EF_3	-0.0000011558986918	-0.0000046018882106
EF_4	0.0000000256431208	0.0000001039090030
EF_5	-0.0000000002902570	-0.0000000011922446
EF_6	0.0000000000013205	0.0000000000054760

Table G-3. Emissions Factors for Rural Minor Arterials

2011 - 2015		
	Middle Estimate	High Estimate
EC	0.0069046462462879	0.0184566997778807
EF_1	-0.0003638684856802	-0.0013803704172682
EF_2	0.0000275623804269	0.0001075494237865
EF_3	-0.0000011323952878	-0.0000045255159834
EF_4	0.0000000251777596	0.0000001024650968
EF_5	-0.0000000002852937	-0.0000000011774050
EF_6	0.0000000000012980	0.0000000000054099
2016 and Beyond		
	Middle Estimate	High Estimate
EC	0.0068865893871786	0.0184003075007249
EF_1	-0.0003614548091862	-0.0013720156960436
EF_2	0.0000273898628230	0.0001069279281944
EF_3	-0.0000011260129692	-0.0000045016419820
EF_4	0.0000000250455068	0.0000001019554293
EF_5	-0.0000000002838208	-0.0000000011716243
EF_6	0.0000000000012911	0.0000000000053826

Table G-4. Emissions Factors for Rural Major Collectors

	before 2000	
	Middle Estimate	High Estimate
EC	0.0102209877129227	0.0264767267459185
EF_1	-0.0004428179758092	-0.0017343377346272
EF_2	0.0000311092354037	0.0001270827861341
EF_3	-0.0000012011506517	-0.0000050972952155
EF_4	0.0000000256710323	0.0000001125245967
EF_5	-0.0000000002851373	-0.0000000012841070
EF_6	0.0000000000012937	0.0000000000059444
	2001 - 2005	
	Middle Estimate	High Estimate
EC	0.0096283359747267	0.0243907296492784
EF_1	-0.0003642392841651	-0.0014370988131024
EF_2	0.0000255188413594	0.0001060488524501
EF_3	-0.0000009863469712	-0.0000042885395527
EF_4	0.0000000209806270	0.0000000946608346
EF_5	-0.0000000002304476	-0.0000000010717611
EF_6	0.0000000000010290	0.0000000000048951
	2006 - 2010	
	Middle Estimate	High Estimate
EC	0.0094924782429603	0.0238022404542355
EF_1	-0.0003808191693937	-0.0014412230337514
EF_2	0.0000287908299966	0.0001118819162382
EF_3	-0.0000011795832681	-0.0000046913997439
EF_4	0.0000000261901325	0.0000001060543610
EF_5	-0.0000000002967981	-0.0000000012188711
EF_6	0.0000000000013521	0.0000000000056088

Table G-4. Emissions Factors for Rural Major Collectors

2011 - 2015		
	Middle Estimate	High Estimate
EC	0.0094020159468260	0.0235058878048074
EF_1	-0.0003705439926383	-0.0014051027369533
EF_2	0.0000281279423698	0.0001096205060764
EF_3	-0.0000011568384242	-0.0000046172606685
EF_4	0.0000000257480447	0.0000001046827879
EF_5	-0.0000000002921430	-0.0000000012049928
EF_6	0.0000000000013311	0.0000000000055474

2016 and Beyond		
	Middle Estimate	High Estimate
EC	0.0093856929156729	0.0234538136334222
EF_1	-0.0003681142720372	-0.0013966484426352
EF_2	0.0000279577289703	0.0001090012230531
EF_3	-0.0000011506921312	-0.0000045938574876
EF_4	0.0000000256236568	0.0000001041898525
EF_5	-0.0000000002907833	-0.0000000011994500
EF_6	0.0000000000013247	0.0000000000055213

Table G-5. Emissions Factors for Urban Interstates

before 2000

	Middle Estimate	High Estimate
EC	0.0370407853506139	0.1001359035395760
EF_1	-0.0033258536991350	-0.0097548109344024
EF_2	0.0002119290144181	0.0006448871989167
EF_3	-0.0000073423555991	-0.0000232948657868
EF_4	0.0000001404693583	0.0000004658928012
EF_5	-0.0000000013990605	-0.0000000048574147
EF_6	0.0000000000057744	0.0000000000208836

2001 - 2005

	Middle Estimate	High Estimate
EC	0.0325569295593406	0.0878323120042830
EF_1	-0.0027682738512599	-0.0081476412371307
EF_2	0.0001727289422456	0.0005308562887439
EF_3	-0.0000058847428571	-0.0000190003208712
EF_4	0.0000001104152742	0.0000003756144869
EF_5	-0.0000000010733459	-0.0000000038546774
EF_6	0.0000000000043082	0.0000000000162573

2006 - 2010

	Middle Estimate	High Estimate
EC	0.0320800500149673	0.0863184476309264
EF_1	-0.0031497051476667	-0.0090767750050779
EF_2	0.0002264822473426	0.0006660666450034
EF_3	-0.0000088157115482	-0.0000264421492324
EF_4	0.0000001873412132	0.0000005715459571
EF_5	-0.0000000020469318	-0.0000000063355407
EF_6	0.0000000000090705	0.0000000000283808

Table G-5. Emissions Factors for Urban Interstates

	2011 - 2015	
	Middle Estimate	High Estimate
EC	0.0312805540879535	0.0841794992026911
EF_1	-0.0030493591077134	-0.0087997046903578
EF_2	0.0002192866712628	0.0006463031876213
EF_3	-0.0000085372572098	-0.0000256839383836
EF_4	0.0000001813115084	0.0000005552560603
EF_5	-0.0000000019782995	-0.0000000061510743
EF_6	0.0000000000087494	0.0000000000275197
	2016 and Beyond	
	Middle Estimate	High Estimate
EC	0.0310985606735560	0.0837078387441724
EF_1	-0.0030259533217892	-0.0087370520853707
EF_2	0.0002177120342536	0.0006420660131590
EF_3	-0.0000084822982934	-0.0000255354723682
EF_4	0.0000001802218375	0.0000005523108563
EF_5	-0.0000000019664159	-0.0000000061190729
EF_6	0.0000000000086934	0.0000000000273699

Table G-6. Emissions Factors for Urban Principal Arterials - Other Freeways and Expressways

before 2000

	Middle Estimate	High Estimate
EC	0.0368689863418033	0.0996991265571968
EF_1	-0.0033258536991350	-0.0097548109344024
EF_2	0.0002119290144181	0.0006448871989167
EF_3	-0.0000073423555991	-0.0000232948657868
EF_4	0.0000001404693583	0.0000004658928012
EF_5	-0.0000000013990605	-0.0000000048574147
EF_6	0.0000000000057744	0.0000000000208836

2001 - 2005

	Middle Estimate	High Estimate
EC	0.0324091258699132	0.0874476140417280
EF_1	-0.0027682738512599	-0.0081476412371307
EF_2	0.0001727289422456	0.0005308562887439
EF_3	-0.0000058847428571	-0.0000190003208712
EF_4	0.0000001104152742	0.0000003756144869
EF_5	-0.0000000010733459	-0.0000000038546774
EF_6	0.0000000000043082	0.0000000000162573

2006 - 2010

	Middle Estimate	High Estimate
EC	0.0319455720413990	0.0859645863974462
EF_1	-0.0031497051476667	-0.0090767750050779
EF_2	0.0002264822473426	0.0006660666450034
EF_3	-0.0000088157115482	-0.0000264421492324
EF_4	0.0000001873412132	0.0000005715459571
EF_5	-0.0000000020469318	-0.0000000063355407
EF_6	0.0000000000090705	0.0000000000283808

Table G-6. Emissions Factors for Urban Principal Arterials - Other Freeways and Expressways

	2011 - 2015	
	Middle Estimate	High Estimate
EC	0.0311487548038125	0.0838266646762594
EF_1	-0.0030493591077134	-0.0087997046903578
EF_2	0.0002192866712628	0.0006463031876213
EF_3	-0.0000085372572098	-0.0000256839383836
EF_4	0.0000001813115084	0.0000005552560603
EF_5	-0.0000000019782995	-0.0000000061510743
EF_6	0.0000000000087494	0.0000000000275197
	2016 and Beyond	
	Middle Estimate	High Estimate
EC	0.0309654389775208	0.0833480650657583
EF_1	-0.0030259533217892	-0.0087370520853707
EF_2	0.0002177120342536	0.0006420660131590
EF_3	-0.0000084822982934	-0.0000255354723682
EF_4	0.0000001802218375	0.0000005523108563
EF_5	-0.0000000019664159	-0.0000000061190729
EF_6	0.0000000000086934	0.0000000000273699

Table G-7. Emissions Factors for Urban Other Principal Arterials

before 2000		
	Middle Estimate	High Estimate
EC	0.0379380280904431	0.1017402335665360
EF_1	-0.0033574405285091	-0.0098897840386732
EF_2	0.0002176204350076	0.0006637028545145
EF_3	-0.0000076091220203	-0.0000241641502121
EF_4	0.0000001463537646	0.0000004854817264
EF_5	-0.0000000014634508	-0.0000000050777350
EF_6	0.0000000000060529	0.0000000000218706
2001 - 2005		
	Middle Estimate	High Estimate
EC	0.0337583391462996	0.0901247069012903
EF_1	-0.0028069489366237	-0.0082918742942117
EF_2	0.0001784045809670	0.0005490351363872
EF_3	-0.0000063602353561[a]	-0.0000203412438723[b]
EF_4	0.0000001161000457	0.0000003941232874
EF_5	-0.0000000011352019	-0.0000000040615811
EF_6	0.0000000000045736	0.0000000000171741
2006 - 2010		
	Middle Estimate	High Estimate
EC	0.0334511916765737	0.0890133747016897
EF_1	-0.0031998290189279	-0.0092482916283977
EF_2	0.0002330475396797	0.0006864460108822
EF_3	-0.0000091164948714	-0.0000273741081376
EF_4	0.0000001940391845	0.0000005926384618
EF_5	-0.0000000021211355	-0.0000000065738950
EF_6	0.0000000000093950	0.0000000000294471

Table G-7. Emissions Factors for Urban Other Principal Arterials

	2011 - 2015	
	Middle Estimate	High Estimate
EC	0.0327091964733301	0.0870126408375894
EF_1	-0.0031032942123778	-0.0089815378275186
EF_2	0.0002261209483755	0.0006674580939598
EF_3	-0.0000088497325836	-0.0000266507073881
EF_4	0.0000001882898681	0.0000005771927449
EF_5	-0.0000000020558516	-0.0000000063995504
EF_6	0.0000000000090897	0.0000000000286337
	2016 and Beyond	
	Middle Estimate	High Estimate
EC	0.0325302389064216	0.0865456237172695
EF_1	-0.0030805552938200	-0.0089208590150048
EF_2	0.0002246325271390	0.0006634703487265
EF_3	-0.0000087997926609	-0.0000265164180250
EF_4	0.0000001873424048	0.0000005746408352
EF_5	-0.0000000020458904	-0.0000000063727733
EF_6	0.0000000000090436	0.0000000000285106

a. After completion of the 1999 *C&P Report*, this value was corrected to: -0.0000061445419586.

b. After completion of the 1999 *C&P Report*, this value was corrected to: -0.0000198285300585.

Table G-8. Emissions Factors for Urban Minor Arterials and Collectors

	before 2000	
	Middle Estimate	High Estimate
EC	0.0378980170772273	0.1016605749762280
EF_1	-0.0033574405285091	-0.0098897840386732
EF_2	0.0002176204350076	0.0006637028545145
EF_3	-0.0000076091220203	-0.0000241641502121
EF_4	0.0000001463537646	0.0000004854817264
EF_5	-0.0000000014634508	-0.0000000050777350
EF_6	0.0000000000060529	0.0000000000218706
	2001 - 2005	
	Middle Estimate	High Estimate
EC	0.0337183281330837	0.0900450483109819
EF_1	-0.0028069489366237	-0.0082918742942117
EF_2	0.0001784045809670	0.0005490351363872
EF_3	-0.0000061445419586	-0.0000198285300585
EF_4	0.0000001161000457	0.0000003941232874
EF_5	-0.0000000011352019	-0.0000000040615811
EF_6	0.0000000000045736	0.0000000000171741
	2006 - 2010	
	Middle Estimate	High Estimate
EC	0.0334111806633579	0.0889337161113813
EF_1	-0.0031998290189279	-0.0092482916283977
EF_2	0.0002330475396797	0.0006864460108822
EF_3	-0.0000091164948714	-0.0000273741081376
EF_4	0.0000001940391845	0.0000005926384618
EF_5	-0.0000000021211355	-0.0000000065738950
EF_6	0.0000000000093950	0.0000000000294471

Table G-8. Emissions Factors for Urban Minor Arterials and Collectors

2011 - 2015		
	Middle Estimate	High Estimate
EC	0.0326691854601142	0.0869329822472811
EF_1	-0.0031032942123778	-0.0089815378275186
EF_2	0.0002261209483755	0.0006674580939598
EF_3	-0.0000088497325836	-0.0000266507073881
EF_4	0.0000001882898681	0.0000005771927449
EF_5	-0.0000000020558516	-0.0000000063995504
EF_6	0.0000000000090897	0.0000000000286337
2016 and Beyond		
	Middle Estimate	High Estimate
EC	0.0324902278932057	0.0864659651269611
EF_1	-0.0030805552938200	-0.0089208590150048
EF_2	0.0002246325271390	0.0006634703487265
EF_3	-0.0000087997926609	-0.0000265164180250
EF_4	0.0000001873424048	0.0000005746408352
EF_5	-0.0000000020458904	-0.0000000063727733
EF_6	0.0000000000090436	0.0000000000285106

Appendix H: A Numerical Example

This appendix offers an example of the calculations documented in the body of the Technical Report as they are used by the HERS model in selecting an improvement for a sample section. The example will proceed in order, first forecasting conditions at the end of the funding period if no improvement is implemented; determining that the section is deficient; identifying a candidate improvement; calculating benefits and costs for the candidate improvement; and determining whether the improvement meets the requirements for implementation.

This appendix is intended to be illustrative, but not comprehensive. It demonstrates only the forms of the algorithms which are suitable for processing the example section. Sections of differing functional classes, pavement types, and belonging to different volume groups will be subject to different forms of the equations for pavement wear, congestion delay, and so forth. Calculations which are repeated will be shown only the first time. (For example, the aggregate probabilistic limiting velocity model is invoked 119 times during the processing of the example section: only one numerical example will be provided.) Additionally, tests or processes with null results (such as deficiency checks for median width) may escape mention. Also, certain conditions have been arranged to provide for illustrative opportunities. For example, the Federal widening feasibility override value has been set to allow the addition of high cost lanes, which is illustrated in the example section, but which was not the case in the runs for the 1999 *C&P Report*.

The sequence in which the various processes are presented has been selected to allow each process to be shown without interruption. For example, although the speed calculations are called by the routine which applies short run elasticity, the speed algorithms are shown within the context of the operating cost calculation.

The numbers in the example calculations have been subjected to truncation and rounding.

H.1 Preparing the Example

This appendix follows the evaluation and improvement of an Urban Interstate section. The example is taken from the third funding period. The section has a robust growth rate and has been resurfaced during each of the first two funding periods.

The three tables which follow introduce the salient characteristics of the example section. The first, Table H-1, “Section Characteristics,” addresses the “stable” qualities of the section which change infrequently if at all. For example, section length never changes, and the number of lanes changes only as a result of an improvement to the section. In this table, “Geometric Growth Rate” is the annual growth rate as discussed in paragraph 6.3.2.1, ”Option One - Concave Geometric Growth.” The entry “Linear Growth Rate” is discussed in paragraph 6.3.2.2, ”Option Two - Linear Growth.” These data items originate with the HPMS data file.

In contrast to the stable characteristics listed in Table H-1, Table H-2, “Section Data Values,” lists the initial values of those items which are subject to frequent change. These items are directly related to traffic volume and pavement condition, and change every funding period whether the section is improved or not. The items “Price to users” and ESALS are not from the HPMS data, but are calculated by the model.

Table H-1. Section Characteristics

Characteristic	Value	Characteristic	Value
System and Operation			
Functional Class	Urban Interstate	Section Length	1.416
Type of Facility	2-way	Number of Lanes	4
Median Type	Unprotected	Access Control	Full control
Pavement			
Surface/Pavement Type	High Flexible	Structural Number (SNorD)	6.9
Pavement Section	Heavy		
Geometrics			
Lane Width	12 feet	Shoulder Type	Surfaced
Peak Parking	None allowed	Shoulder Width	10 feet
Widening Feasibility	Three or more lanes	Median Width	60 feet
Traffic/Capacity			
Speed Limit	65 m.p.h.	Weighted Design Speed	70 m.p.h.
% Avg. Single Unit Trucks	4 %	% Avg. Combination Trucks	7 %
% Peak Trucks	7 %	Directional Factor	55 %
Peak Capacity (One-way)	4124	K-Factor	12 %
Geometric Growth Rate	1.03291	Linear Growth Rate	1911.56
Environment			
Intersections w/ Signals	0	Intersections w/ Stop Signs	0
Uncontrolled Intersections	0		

Note that in Table H-2 that the entries are associated with a specific point in time, beginning with funding period zero. Other than for a few special cases (such as changes in emissions factors and the accumulation of output statistics), the model treats the funding period under analysis as funding period one, and the previous period as funding period zero. As the analysis enters the third funding period, then, values calculated for the mid-point and end of the second funding period are retrieved as values for the mid-point and end for funding period zero. Some values which were calculated for funding period three and saved are retrieved as values for funding period one. The “current” point in time (sometimes referred to as t_0 in the equations which follow) is the beginning of funding period one (which is concurrent with the end of funding period zero).

Table H-2. Section Data Values

Data Item	Funding Period 0		Funding Period 1	
	mid-point	end	mid-point	end
AADT	60,488.6	65,366.7	70,244.9	73,374.8
Adjusted traffic volume	58,148.4	--	69,174.9	--
Price to users ($ per VMT)	0.591194	--	0.611616	--
PSR	3.62052	3.32218	3.04842	--
ESALS	10,660,600	14,792,500	19,364,500	--

Note also that the model does not compute end-of-period values for adjusted traffic volume and price to users. The model will calculate values of PSR and ESALS for the end of funding period one, but has not yet done so as the numerical example opens.

Parameters which are set by the user and which affect all sections are listed in Table H-3, “System-Wide Run Parameters.”

Table H-3. System-Wide Run Parameters

Characteristic	Value	Characteristic	Value
Truck growth rate	1.0 (no growth[a])	Discount rate	7 %
Long run share of elasticity	-0.6	Short run share of elasticity	-1.0
Length of funding period	5 years	Design period	20 years
Type of traffic growth	Linear	Emissions damage estimate rate	High
Minimum BCR	1.0	Federal widening feasibility override	5 (3 or more lanes)
Type of analysis	economic efficiency	Correct unacceptable conditions?	No
Maximum pavement life (for heavy flexible sections)	35 years	Maximum pavement deterioration rate (PSR/ year)	0.3
Pavement deterioration rate adjustment factor	1.0		

[a] That is, the percentage of trucks to other vehicles on the section remains constant: the actual number of trucks on the section will grow at the same rate as automobiles.

H.2 Predicting Conditions at the End of the Funding Period

The two end-of-period values HERS uses in evaluating section deficiencies are PSR and volume/capacity (V/C) ratio, which is derived from the section's AADT, capacity, and K-factor. The AADT values for the middle and end of the current funding period were calculated and saved during analysis of the previous funding period (as shown in Table H-2). However, a PSR value was not saved for the end of the funding period, and must be calculated.

HERS uses Equation 6.13 and the AADT values from Table H-2, "Section Data Values," to calculate total traffic for the first half of the funding period:

$$\begin{aligned} TOTRAF &= \frac{(AADT_{t_0} + AADT_{t_f})}{2} \times 365 \times (t_f - t_0) \\ &= \frac{(65366.7 + 70244.9)}{2} \times 365 \times (2.5 - 0) \qquad \text{Eq. H.1} \\ &= 61872792.5 \end{aligned}$$

Next HERS uses Equation 6.14 to determine ESALs for the first half of the funding period:

$$\begin{aligned} ESALS &= (TOTRAF \times PCAVSU \times ELF_{SU} \times LF) \\ &\quad + (TOTRAF \times PCAVCM \times ELF_{CM} \times LF) \\ &= (61872792.5 \times 0.04 \times 0.2291 \times 0.9) \qquad \text{Eq. H.2} \\ &\quad + (61872792.5 \times 0.07 \times 1.0205 \times 0.9) \\ &= 4488196 \end{aligned}$$

where:

$PCAVSU$ = percent average single unit trucks (from Table H-1);
ELF_{SU} = equivalent load factor for single unit trucks (from Table 6-7, "Equivalent 18-KIP Load Applications per Truck");
$PCAVCM$ = percent average combination trucks (from Table H-1);
ELF_{CM} = equivalent load factor for combination trucks (from Table 6-7); and
LF = lane factor (from Table 6-8, "Lane Load Distribution Factors").

HERS repeats the calculations for the second half of the funding period. Due to increased traffic volume, the second half generates 4,753,232 ESALs. In our example, the growth rate for trucks is set to zero; had the percentage of trucks been increasing, the ESALs for the second half would have been yet higher. Total ESALs accumulated during the funding period are 9,241,429; adding this sum to the ESALs accumulated at the start of the funding period brings the total ESALs to 24,033,929.

Because of the section's pavement type, HERS uses the equations in paragraph 6.2.2.1, "Flexible Pavement," to estimate PSR at the end of the period. HERS first employs Equations 6.20, 6.17, and 6.18 to calculate the intermediate variables *SNA*, *XA*, and *XB*, respectively:

$$\begin{aligned} SNA &= SN + \sqrt{(6/SN)} \\ &= 6.9 + \sqrt{(6/6.9)} \qquad \textit{Eq. H.3} \\ &= 7.83250 \end{aligned}$$

where *SN* is taken from Table H-1.

$$\begin{aligned} XA &= 9.36 \times \log(SNA) - 0.2 \\ &= 9.36 \times \log(7.83250) - 0.2 \qquad \textit{Eq. H.4} \\ &= 8.16691 \end{aligned}$$

$$\begin{aligned} XB &= 0.4 + 1094/SNA^{5.19} \\ &= 0.4 + 1094/7.83250^{5.19} \qquad \textit{Eq. H.5} \\ &= 0.425099 \end{aligned}$$

HERS substitutes the total accumulated ESALs for the variable *ESAL* in Equation 6.22 to derive a value for *XG*:

$$\begin{aligned} XG &= XB \times (\log(ESAL) - XA) \\ &= 0.425099 \times (\log(24033929) - 8.16691) \qquad \textit{Eq. H.6} \\ &= -0.334164 \end{aligned}$$

HERS is now ready to solve for PSR at the end of the period using Equation 6.21. *PDRAF*, the pavement deterioration rate adjustment factor, is set to one (from Table H-3, “System-Wide Run Parameters”).

$$\begin{aligned} PSRF &= 5 - 3.5 \times PDRAF_{pt} \times 10^{XG} \\ &= 5 - 3.5 \times 1.0 \times 10^{-0.334164} \qquad \textit{Eq. H.7} \\ &= 3.37855 \end{aligned}$$

HERS then enforces a minimum deterioration rate using Equation 6.25:

$$\begin{aligned} PSRMAX_t &= PSR_{t_0} \times 0.3^{((t - t_0)/(ML))} \\ &= 3.32218 \times 0.3^{((5-0)/(35))} \qquad \textit{Eq. H.8} \\ &= 2.79721 \end{aligned}$$

where:

PSRMAX_t	=	the maximum PSR at time *t*, the end of the period;
PSR_{t0}	=	the PSR at time t_0, the beginning of the period, from Table H-2;
ML	=	the maximum pavement life for a pavement of this type (flexible) and this pavement section (heavy) (from Table H-1), as reported in Table H-3.

HERS takes the lower of the two values (*PSRF* and $PSRMAX_t$) and, substituting it for $PSRMX_t$, proceeds to enforce the maximum pavement deterioration rate using Equation 6.27.

$$PSR_t = \text{the larger of} \begin{cases} PSR_{t_0} - MAXPDR \times (t - t_0) \\ PSRMX_t \end{cases}$$

$$= \text{the larger of} \begin{cases} 3.32218 - 0.3 \times (5 - 0) \\ 2.79721 \end{cases} \qquad \textit{Eq. H.9}$$

$$= 2.79721$$

Thus 2.79721 (PSR_t) is the forecast value for PSR at the end of the funding period.

HERS now calculates the section's V/C ratio using the traffic volume at the end of the funding period. The HPMS database reports peak capacity in both directions for rural two- and three-lane sections, and in one direction for all other sections. The formula for V/C (*VC* in the equation) for the example section is:

$$VC = AADT/CAPAC \times KFAC \times DFAC \qquad \textit{Eq. H.10}$$

where:

CAPAC = one-way peak capacity;
KFAC = K-factor; and
DFAC = directional factor.

For sections with two-way capacity, the formula is the same except for the omission of *DFAC*. Substituting values from Tables H-1 and H-2:

$$\begin{aligned} VC &= 73374.8/4124 \times 0.12 \times 0.55 \\ &= 1.17428 \end{aligned} \qquad \textit{Eq. H.11}$$

H.3 Identifying Candidate Improvements

HERS checks whether the pavement is deficient by comparing the PSR at the end of the period (2.79721) to the appropriate deficiency criteria. As shown in Table 3-2, "Default Pavement Condition Criteria (PSR)," the deficiency level for the example section is 3.4. The example section's PSR is clearly deficient.

HERS also compares the PSR at the beginning of the period (3.32218) with the appropriate reconstruction level, shown in Table 3-2 to be 2.2. As the section's PSR at the beginning of the period was above this level, the section will not require reconstruction if improved during this funding period. The model also checks the section's surface type to see whether reconstruction is required to upgrade a gravel surface: in this case, it is not.

The section's V/C ratio is compared to the criteria in Table 3-4, "Default Volume/Capacity Ratio Criteria." The section's V/C ratio(1.17428) violates both the deficiency level and the serious deficiency level for urban interstate sections (0.90 and 0.95 respectively).

HERS next checks to see whether the section can be widened. The section's widening feasibility code is 5. This permits the addition of new lanes without reference to the Federal widening feasibility override code.

HERS forecasts the AADT for the section in the design year. The design period of 20 years is measured from the midpoint of the funding period, when an improvement to the section would be implemented. With a five year funding period, the design year is 22.5 years from the beginning of the current funding period. When forecasting design year volume, HERS does not apply elasticity to the estimate. Using Equation 6.30, HERS estimates design year AADT:

$$\begin{aligned} DYAADT &= AADT_{t_0} \times AADTGR^{(t_1 - t_0)} \\ &= 65366.7 \times 1.03291^{(22.5 - 0)} \\ &= 135444.8 \end{aligned} \qquad \textit{Eq. H.12}$$

HERS calculates the design year hourly volume DHV in the peak direction.

$$\begin{aligned} DHV &= DYAADT \times KFAC \times DFAC \\ &= 135444.8 \times 0.12 \times 0.55 \\ &= 8939.3 \end{aligned} \qquad \textit{Eq. H.13}$$

Because the example section is an urban freeway, HERS calculates the "unadjusted capacity per lane" (*UC*) using the formula from Table 6-19, "Design Year Lane Parameters." The section's weighted design speed, 70 miles per hour, is taken from Table H-1.

$$\begin{aligned} UC &= -835.3 + (0.9188 \times 10^{-5} \times DS^4) - (0.002212 \times DS^3) \\ &\quad -(0.2631 \times DS^2) + 66.82 \times DS \\ &= -835.3 + (0.9188 \times 10^{-5} \times 70^4) - (0.002212 \times 70^3) \\ &\quad -(0.2631 \times 70^2) + 66.82 \times 70 \\ &= 2014.8 \end{aligned} \qquad \textit{Eq. H.14}$$

HERS then determines *DN*, the number of lanes needed in the peak direction for the design year, using Equation 6.50. Because the percentage of trucks does not change over time, the "% Peak Trucks" value from Table H-1 is used for the variable *PCTRFP*:

$$\begin{aligned} DN &= DHV \div \left(\frac{UC \times RDMLF}{(1 + PCTRFP \times (ET - 1))}\right) \\ &= 8939.3 \div \left(\frac{2014.8 \times 1}{1 + 0.07 \times (1.5 - 1)}\right) \\ &= 4.59 \end{aligned} \qquad \textit{Eq. H.15}$$

where:

RDMLF = rural dense multilane factor (set to 0.9 for rural multilane highways in densely developed areas; otherwise set to 1);
PCTRFP = peak percent trucks (in the design year); and
ET = passenger car equivalent for trucks (from Table 6-19, "Design Year Lane Parameters").

Rounding DN up to five lanes per direction identifies a single candidate improvement with the following characteristics:

- six lanes will be added for a total of ten lanes;
- the existing pavement will be resurfaced; and
- the existing alignment will be utilized.

The candidate improvement is assigned improvement number 10, and selected section characteristics are forwarded from the unimproved section (the base case, or improvement number zero) to the new improvement.

H.4 Determining the Effects of the Improvement

HERS continues constructing an "image" of the section after the improvement is implemented at the midpoint of the funding period. Most data items are forwarded unchanged from the base case, but those which change include:

Capacity (one-way)	Increases to 10,482.7;
PSR	Improves to 4.30 (from 3.04842 at the midpoint of the funding period);[1]
ESALs	Are set to 3,331,660 at the time of improvement.

H.4.1 Forecasting Future Travel: Elasticity

The model next determines the effect of the improvement upon traffic volume. As discussed in paragraph 6.3, "The Travel Forecast Model," forecasting future volume consists of three distinct steps:

1. forecasting baseline travel;
2. adjusting the baseline forecast for long run elasticity; and
3. applying the short run elasticity to yield a traffic volume forecast (the "simultaneous solution").

Recognizing that the improvement begins to affect traffic volume as soon as it is implemented (at the middle of the funding period), the model applies short run elasticity to the mid-period volume to simulate the immediate impact of the improvement. The initial volume used is the one calculated for the base (unimproved) case, and the process is the simultaneous solution used in

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[1] This is the maximum value to which an urban interstate's PSR can be raised after resurfacing--the maximum increase is 1.8.

step three above. The model then forecasts the traffic volume for the middle of the next funding period.

So at this point in the example, the model would execute the above steps in the sequence: three, one, two, and three. In order to demonstrate the three steps in succession (as presented in paragraph 6.3), we will skip the initial application of short run elasticity and simply note when values calculated during step three are utilized in the forecast of future volumes.

In the equations below, time zero (t_0) corresponds to the middle of the first funding period (when the improvement is implemented), and the time for which we will calculate the traffic volume is the middle of the second funding period (time one, or t_1). Table H-4, "Initial Value of Terms for Elasticity Example," lists pertinent values entering the forecast process. The baseline price and the "adjusted" volume at t_0 is common to both the unimproved and the improved cases. The user price at t_0 ($FINPRI_{t0}$) and the final traffic volume at t_0 ($AADT_{t0}$) were calculated during the application of short run elasticity to the improved case at the time of improvement. First, we'll identify these values with the terminology used in the equations:

Table H-4. Initial Value of Terms for Elasticity Example

Term	Description	Value	Units
SRE	short run elasticity	-1.0	factor
LRS	long run share	-0.6	factor
Capacity	hourly two-way capacity	20965.4	vehicles per hour
VOT	value of time	18.0099	dollars per hour
$AADT_{t0}$	final volume (improved) at time t_0	76105.8	vehicles per day
$FINPRI_{t0}$	final price (improved) at time t_0	0.555555	dollars per vehicle mile
BASPRI	baseline price	0.613370	dollars per vehicle mile
$VADJ_{t0}$	adjusted volume at time t_0	69174.9	AADT
AAGRSL	straight-line growth rate	1911.56	AADT

H.4.1.1 The Baseline Travel Forecast

Because we have selected the linear growth method, HERS uses the first form of Equation 6.34 to calculate $VBASEt_1$, baseline traffic volume at t_1:

$$\begin{aligned} VBASE_{t_1} &= VADJ_{t_0} + (AAGRSL \times LFP) \\ &= 69174.9 + (1911.56 \times 5) \qquad \textit{Eq. H.16} \\ &= 78732.7 \end{aligned}$$

where:

AAGRSL = straight-line annual growth rate; and
LFP = the length of a funding period.

H.4.1.2 Applying Long Run Elasticity

HERS next uses Equation 6.35, which applies the effects of long run elasticity, to calculate the adjusted volume at t_1:

$$\begin{aligned} VADJ_{t_1} &= VBASE_{t_1} \times (1 + LRS \times (FINPRI_{t_0} - BASPRI)/BASPRI) \\ &= 78732.7 \times (1 + (-0.6) \times (0.555555 - 0.613370)/0.613370) \\ &= 83185.4 \end{aligned} \qquad \text{Eq. H.17}$$

The next step is to compute the term *ALPHA*:

$$\begin{aligned} ALPHA &= VADJ_{t_1}/BASPRI^{SRE} \\ &= 83185.4/0.613370^{-1.0} \\ &= 51023.4 \end{aligned} \qquad \text{Eq. H.18}$$

Using *ALPHA* and Equation 6.36 HERS can estimate an initial volume with which to enter the simultaneous solution:

$$\begin{aligned} VINIT_{t_1} &= ALPHA \times FINPRI_{t_0}^{SRE} \\ &= 51023.4 \times 0.555555^{-1.0} \\ &= 91842.2 \end{aligned} \qquad \text{Eq. H.19}$$

HERS uses this initial volume to estimate the pavement condition at time t_1. This estimate is achieved using the process shown in Equations H.1 through H.9. HERS estimates that PSR at the middle of funding period two will be 3.62052.

H.4.1.3 Short Run Elasticity: the Simultaneous Solution

HERS next determines the free flow speed (that is, the speed without congestion) for each vehicle type and uses this to calculate the travel time cost without delay. HERS also computes the operating and safety costs for time t_1, and sums these costs to produce "price without delay" (*PWOD*) per vehicle mile travelled. (We'll cover the speed and cost procedures in detail later as part of the cost calculations.) In our example:

$$\begin{aligned} PWOD &= FFC + OPC + PC + IC + FC + DC \\ &= 0.243942 + 0.256426 + 0.008495 + 0.029414 + 0.010154 + 0.013914 \\ &= 0.562347 \end{aligned} \qquad \text{Eq. H.20}$$

where:

FFC = travel time cost without delay per VMT;
OPC = operating cost per VMT;
PC = property damage cost per VMT;
IC = injury cost per VMT;
FC = fatality cost per VMT; and
DC = cost of delays due to crashes per VMT.

HERS now begins the simultaneous solution by calculating the slope of the initial demand curve using Equation 6.37:

$$SDEM_i = \frac{PWOD^{(1-SRE)}}{ALPHA \times SRE} = \frac{0.562347^{(1-(-1.0))}}{51023.4 \times (-1.0)} = -6.19782\times10^{-6} \qquad \textit{Eq. H.21}$$

HERS uses the initial volume calculated above (in Equation H.19) to calculate the initial AADT to capacity ratio ACR_i, with *Capacity* taken from Table H-4:

$$ACR_i = VINIT_{t_1}/Capacity = 91842.2/20965.4 = 4.38065 \qquad \textit{Eq. H.22}$$

HERS determines which equations to use for estimating delay and the slope of the delay function based upon the section's road type and *ACR*. The example section is a freeway, for which the applicable equations are shown in Table 6-11, "Demand Equations for Freeways and Multilane Rural Highways." As the initial ACR (ACR_i) is less than eight, HERS employs the first pair of equations. Therefore, to estimate initial delay on the example section, HERS replaces Equation 6.38 with:

$$EDLAY_i = (0.0797 \times ACR + 0.00385 \times ACR^2) \times VOT/1000 = (0.0797 \times 4.38065 + 0.00385 \times 4.38065^2) \times 18.0099/1000 = 7.61856 \times 10^{-3} \qquad \textit{Eq. H.23}$$

To calculate the initial slope of the delay curve, HERS replaces Equation 6.39 with:

$$SDLAY = (0.0797 + 0.00385 \times 2 \times ACR) \times VOT/(Capacity \times 1000) = (0.0797 + 0.00385 \times 2 \times 4.38065) \times 18.0099/(20965.4 \times 1000) = 9.74407 \times 10^{-8} \qquad \textit{Eq. H.24}$$

where *Capacity* and *VOT* are taken from Table H-4.

HERS is now ready to approximate a revised volume (using the approach shown in Exhibit 6-4, "Details of Successive Approximation") with Equation 6.40:

$$RVOL = VINIT_{t_1} + \frac{EDLAY_i}{SDEM_i - SDLAY_i} = 91842.2 + \frac{7.61856 \times 10^{-3}}{-6.19782\times10^{-6} - 9.74407 \times 10^{-8}} = 90632.06 \qquad \textit{Eq. H.25}$$

The next step is to calculate a revised estimate of delay using the revised volume. Once again, because this section is a freeway, the model will use an equation from Table 6-11. Before selecting an equation, HERS computes a revised AADT/Capacity ratio using the revised volume:

$$\begin{aligned} ACR_r &= RVOL/Capacity \\ &= 90632.06/20965.4 \\ &= 4.322935 \end{aligned} \qquad \text{Eq. H.26}$$

The revised AADT/Capacity ratio ACR_r is used to select the specific form of the equation from Table 6-11. In this case, the same form is selected:

$$\begin{aligned} EDLAY_r &= (0.0797 \times ACR_r + 0.00385 \times ACR_r^2) \times VOT/1000 \\ &= (0.0797 \times 4.322935 + 0.00385 \times 4.322935^2) \times 18.0099/1000 \\ &= 7.500869 \times 10^{-3} \end{aligned} \qquad \text{Eq. H.27}$$

Next, HERS uses Equation 6.41 to calculate the price associated with the initial volume:

$$\begin{aligned} Price_{VINIT_{t_1}} &= (VINIT_{t_1}/ALPHA)^{(1/(SRE))} \\ &= (91842.2/51023.4)^{(1/(-1.0))} \\ &= 0.555555 \end{aligned} \qquad \text{Eq. H.28}$$

The same formula is used to calculate the price associated with the revised volume:

$$\begin{aligned} Price_{RVOL} &= (RVOL/ALPHA)^{(1/(SRE))} \\ &= (90632.06/51023.4)^{(1/(-1.0))} \\ &= 0.562973 \end{aligned} \qquad \text{Eq. H.29}$$

HERS next computes revised slopes for the demand and delay functions. As shown in Equation 6.43, the revised demand slope is taken as the difference between the prices over the difference between the volumes:

$$\begin{aligned} SDEM_r &= \frac{(Price_{RVOL} - Price_{VINIT_{t_1}})}{(RVOL - VINIT_{t_1})} \\ &= \frac{(0.562973 - 0.555555)}{(90632.06 - 91842.2)} \\ &= -6.12978 \times 10^{-6} \end{aligned} \qquad \text{Eq. H.30}$$

The revised delay slope is taken as the difference in the delay estimates over the difference between the volumes:

$$SDLAY_r = \frac{(EDLAY_r - EDLAY_i)}{(RVOL - VINIT_{t_1})}$$

$$= \frac{(7.500869 \times 10^{-3} - 7.61856 \times 10^{-3})}{(90632.06 - 91842.2)} \qquad \text{Eq. H.31}$$

$$= 9.72497 \times 10^{-8}$$

HERS computes the price of delay at the intersection of the revised slopes using Equation 6.45:

$$Price_{Delay} = EDLAY_i \times \frac{SDEM_r}{(SDEM_r - SDLAY_r)}$$

$$= 7.61856 \times 10^{-3} \times \frac{-6.12978 \times 10^{-6}}{(-6.12978 \times 10^{-6} - 9.72497 \times 10^{-8})} \qquad \text{Eq. H.32}$$

$$= 7.499579 \times 10^{-3}$$

Finally, HERS uses the sum of the price without delay and the price of delay to estimate the elasticized volume:

$$V_{elas} = ALPHA \times (PWOD + Price_{Delay})^{SRE}$$

$$= 51023.4 \times (0.562347 + 7.499579 \times 10^{-3})^{-1.0} \qquad \text{Eq. H.33}$$

$$= 89538.89$$

In our example, then, 89538.89 is the elasticized volume projected for the middle of the second funding period for the improved case. HERS uses linear interpolation to fix the volume at the end of the first funding period (which is also the beginning of the second funding period) at 82822.4.

H.5 Benefit Cost Analysis of the Candidate Improvement

The process of evaluating improvements is presented in Chapter 4, ”Evaluating Improvements.” The paragraphs below take the example section through each of the seven steps outlined in Section 4.

H.5.1 Identifying The Base Case

At this point in the analysis of the example section, no improvement has been selected for implementation. The only opportunity for an improvement to have been previously selected would have required the user to have instructed the model to correct unacceptable conditions, and for such conditions to have existed on the section (they did not). Therefore, the base case against which the candidate improvement will be evaluated will be the unimproved section.

H.5.2 Determining the Length of the Analysis Period

HERS examines the section's status as presented in Table 4-1, "Length of BCA Period." That table, with a column denoting the example section's status, is reproduced in Table H-5.

Table H-5. Length of BCA Period

Situation Being Analyzed	Funding Period in Which BCA Period Ends	Example Section Status
Section for which no improvement has yet been selected during the current funding period:		True
If section is in unacceptable condition or unpaved;	Next funding period	False
Otherwise, if current funding period is the last one in which resurfacing is practical;	Period in which condition first becomes unacceptable[a]	False
Otherwise, if traffic volume is declining and improvement involves reconstruction;	Period in which condition first becomes unacceptable[a]	False
Otherwise, if traffic volume is declining;	Last period in which resurfacing is practical	False
Otherwise.	Next funding period	**True**
Section for which an improvement has already been selected during the current funding period.	Next period in which pavement would "normally" be improved or period in which condition becomes unacceptable[a], whichever occurs first.	False

a. Unacceptable conditions that cannot be corrected (e.g., those that require more widening than is feasible) are excluded from consideration in this test.

No improvement has yet been selected for the example section, it is not in unacceptable condition, it is paved, this is not the last period in which the section can be resurfaced (that is, its PSR will not fall below the reconstruction level during the current period), and traffic volume is growing on the section. Therefore, the benefit-cost analysis period (BCAP) will end in the next (second) funding period.

H.5.3 Determining Costs Associated with the Base Case

The model is now prepared to calculate the various costs associated with the unimproved section during the BCAP. In the case of the example, the BCAP is one period (five years) in length, beginning at the middle of funding period one (when the improvement will be implemented) and ending at the middle of funding period two. The model calculates the operating costs first (it includes the speed calculations), then the safety costs, the travel time costs, the maintenance costs, and finally the emissions costs.

While identifying section deficiencies, the model has already calculated traffic volume and pavement condition data for the first two funding periods.

The speed and cost calculations are performed separately for each of the seven vehicle types in HERS: small autos, large autos, pickup trucks, six-tire trucks, three-or-four axle trucks, four axle combination trucks, and five axle combination trucks. Speed is calculated once for four-tire vehicles as HERS assumes that their speed is unaffected by grade. For the four heavier truck categories, speed is calculated separately for both up- and down- hill directions. In the example, we will calculate the speed of small autos.

H.5.3.1 Calculating Speed

The model first determines free flow speed (both uphill and downhill), and then calculates the effect of congestion and traffic control devices. Data items affecting the speed calculations are presented in Table H-6. Values for PSR and AADT are from the mid-point of the BCAP: that is, the end of the first funding period.

Table H-6. Section Characteristics and Speed Factors

Characteristic	Value
DC (degrees of curvature)	0.524294
FRATIO (autos and single-unit trucks)	0.155
FRATIO (combination trucks)	0.103
VR1 (value of *VROUGH* when *PSR* is zero)	5.0
VR2 (value of *VROUGH* when *PSR* = *PSRB*)	20.0
VRSLOP (slope of the function when *PSR* > *PSRB*)	32.5
PSRB (breakpoint)	1.0
PSR (unimproved, end of funding period one)	2.79722
SPDLIM (speed limit)	65
AADT (unimproved, end of funding period one)	73374.8
Capacity (unimproved, two-way)	8248
GR (grade, in percent)	2.14209

HERS calculates three limiting velocities for input to the aggregate probabilistic limiting velocity model: limiting velocities due to curves, pavement roughness, and speed limit. The model first utilizes Equation 6.3 to determine a value for superelevation (*SP*):

$$SP = \begin{cases} 0.0 & \text{for} DC \le 1 \\ 0.1 & \text{for} DC \ge 10\text{, otherwise:} \\ 0.0318 + 0.0972 \times \ln(DC) - 0.0317 \times DC + 0.007 \times DC \times \ln(DC) \end{cases} \qquad \textit{Eq. H.34}$$

$$= 0.0$$

HERS then uses Equation 6.2 to calculate *VCURVE*, the limiting velocity due to curves. *FRATIO* is selected from Equation H-6 for automobiles.

$$\begin{aligned} VCURVE &= 292.5 \times \sqrt{(FRATIO + SP)/DC} \\ &= 292.5 \times \sqrt{(0.155 + 0.0)/0.524294} \qquad \textit{Eq. H.35} \\ &= 159.039 \end{aligned}$$

As the section's PSR at the middle of the BCAP is greater than the breakpoint *PSRB*, HERS employs the lower portion of Equation 6.4 to determine *VROUGH*, the limiting velocity due to pavement roughness:

$$VROUGH = \begin{cases} VR1 + (VR2 - VR1) \times \dfrac{PSR}{PSRB} & \text{if } PSR \le PSRB \\ VR2 + VRSLOP \times (PSR - PSRB) & \text{if } PSR > PSRB \end{cases} \qquad \textit{Eq. H.36}$$

$$\begin{aligned} &= 20.0 + 32.5 \times (2.79722 - 1.0) \\ &= 78.4097 \end{aligned}$$

Because the section qualifies as an urban freeway by design, *VSPLIM*, the limiting velocity due to speed limit, is set to the section's speed limit, 65, plus 9.323 miles per hour: 74.323. HERS uses Equation 6.6 to determine free-flow speed, *FFS*:

$$\begin{aligned} FFS &= ((1/\text{VCURVE})^{10} + (1/\text{VROUGH})^{10} + (1/\text{VSPLIM})^{10})^{-0.1} \\ &= ((1/159.039)^{10} + (1/78.4097)^{10} + (1/74.323)^{10})^{-0.1} \qquad \textit{Eq. H.37} \\ &= 70.9729 \end{aligned}$$

HERS assumes that grades have no effect on free-flow speed for automobiles and pickup trucks, so the same value is used for both the up- and down- hill directions. Next, HERS calculates the average effective speed for this vehicle type by applying the effects of congestion and traffic control devices to the free-flow speed. HERS first determines the section's AADT/Capacity ratio *ACR*:

$$\begin{aligned} ACR &= AADT/Capacity \\ &= 73374.8/8248 \qquad \textit{Eq. H.38} \\ &= 8.89607 \end{aligned}$$

This being an urban interstate without traffic control devices, HERS selects an equation from Table 6-6, "Delay Equations for Freeways and Multilane Rural Highways," based upon the section's *ACR*. It executes this equation to determine D_{cong}, the average congestion delay in hours per 1000 vehicle miles:

$$\begin{aligned} D_{cong} &= 12.1 - 2.95 \times ACR + 0.193 \times ACR^2 \\ &= (12.1 - 2.95 \times 8.89607 + 0.193 \times 8.89607^2) \\ &= 1.13063 \end{aligned} \qquad \text{Eq. H.39}$$

It then applies Equation 6.12 to convert free-flow speed and the congestion delay into an average effective speed (AES_{vt}) for this particular vehicle type (small auto).

$$\begin{aligned} AES_{vt} &= 1/(1/FFS + D_{cong}/1000) \\ &= 1/(1/70.9729 + 1.13063/1000) \\ &= 65.7008 \end{aligned} \qquad \text{Eq. H.40}$$

H.5.3.2 Calculating Operating Costs

HERS calculates operating costs under three different conditions: constant-speed operating costs, excess operating costs due to curves, and excess operating costs due to traffic control devices. Because the example section has no traffic control devices, those calculations are not used for the example section. Once costs have been computed for all vehicle types, the model uses section-specific percentages of trucks and functional class-specific aggregation factors to construct an average operating cost for all vehicles on the section.

H.5.3.2.1 Constant-Speed Operating Costs

For small autos, HERS selects constant-speed operating cost equations from Exhibit E-1, "Constant-Speed Operating Costs: Small Automobiles." These equations generate consumption rates for fuel and oil; a tire wear rate; a maintenance and repair rate, and a depreciation rate. The equations are selected based upon *GR*, the section's percent of grade[2], and *AES*. HERS first calculates costs for the downhill direction. Adjusting *GR* to the downhill direction gives it a value of -2.14209.

To calculate the constant speed fuel consumption rate *CSFC* (in gallons per 1000 miles) for small autos:

$$\begin{aligned} CSFC &= \exp(-6.86 + 0.001872 \times AES^2 - 0.285 \times AES + 4.97 \\ &\quad \times \ln(AES) + 0.0739 \times GR) \\ &= \exp(-6.86 + 0.001872 \times 65.7008^2 - 0.285 \times 65.7008 + 4.97 \\ &\quad \times \ln(65.7008) + 0.0739 \times (-2.14209)) \\ &= 23.0494 \end{aligned} \qquad \text{Eq. H.41}$$

To calculate the constant-speed oil consumption rate *CSOC* (in quarts per 1000 miles) for small autos:

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[2] Percent of grade, *GR*, is calculated by the HERS PreProcessor, and is a positive value in the uphill direction. For the downhill direction, the value of *GR* is inverted.

$$\begin{aligned} CSOC &= -170.4 + 34.02 \times \ln(AES) + 1939/AES \\ &= -170.4 + 34.02 \times \ln(65.7008) + 1939/65.7008 \qquad \textit{Eq. H.42} \\ &= 1.49006 \end{aligned}$$

To calculate the constant-speed tire wear rate *CSTW* (in percent worn per 1000 miles) for small autos:

$$\begin{aligned} CSTW &= 0.1959 + 2.51 \times 10^{-6} \times AES^3 - 0.0352 \times \ln(AES) + 0.01754 \\ &\quad \times GR^2 + 0.00348 \times AES \times GR \\ &= (0.1959 + 2.51 \times 10^{-6} \times 65.7008^3 - 0.0352 \times \ln(65.7008) + 0.01754 \qquad \textit{Eq. H.43} \\ &\quad \times (-2.14209)^2 + 0.00348 \times 65.7008 \times (-2.14209)) \\ &= 0.35115 \end{aligned}$$

To calculate the constant-speed maintenance and repair cost *CSMR* (in percent of the average maintenance and repair cost per 1000 miles) for small autos:

$$\begin{aligned} CSMR &= 73.35 + 0.01397 \times AES^2 - 0.7398 \times AES \\ &\quad + 0.04994 \times AES \times GR \\ &= 73.35 + 0.01397 \times 65.7008^2 - 0.7398 \times 65.7008 \qquad \textit{Eq. H.44} \\ &\quad + 0.04994 \times 65.7008 \times (-2.14209) \\ &= 78.0190 \end{aligned}$$

To calculate the constant-speed depreciation *CSVD* (in percent of the average new price per 1000 miles) for small autos:

$$\begin{aligned} CSVD &= 2.2 + 0.001596 \times AES - 0.38 \times \ln(AES) \\ &= 2.2 + 0.001596 \times 65.7008 - 0.38 \times \ln(65.7008) \qquad \textit{Eq. H.45} \\ &= 0.71452 \end{aligned}$$

HERS next calculates the pavement condition adjustment factors for each of the cost rates calculated above.[3] The equations are taken from Exhibit E-8, “Constant-Speed Operating Costs – Pavement Condition Adjustment Factors.” As the example is for small autos, the selected equations are for “Four-Tire Vehicles.”

Using the *PSR* value from Table H-6, HERS calculates *PCAFOC*, the pavement condition adjustment factor for oil consumption:

$$\begin{aligned} PCAFOC &= 2.64 + 0.0729 \times PSR^2 - 0.722 \times PSR \\ &= 2.64 + 0.0729 \times 2.79722^2 - 0.722 \times 2.79722 \qquad \textit{Eq. H.46} \\ &= 1.19081 \end{aligned}$$

HERS calculates *PCAFTW*, the pavement condition adjustment factor for tire wear:

---

[3] *PCAFFC*, the factor for fuel consumption, is set to one. See paragraph 7.1.2.2, ”Constant-Speed Operating Costs.”

$$\begin{aligned} PCAFTW &= 2.40 - 1.111 \times \ln(PSR) \\ &= 2.40 - 1.111 \times \ln(2.79722) \qquad \textit{Eq. H.47} \\ &= 1.25720 \end{aligned}$$

HERS calculates *PCAFMR*, the pavement condition adjustment factor for maintenance and repair:

$$\begin{aligned} PCAFMR &= 3.19 + 0.0967 \times PSR^2 - 0.961 \times PSR \\ &= 3.19 + 0.0967 \times 2.79722^2 - 0.961 \times 2.79722 \qquad \textit{Eq. H.48} \\ &= 1.25849 \end{aligned}$$

HERS calculates *PCAFVD*, the pavement condition adjustment factor for depreciation:

$$\begin{aligned} PCAFVD &= 1.136 - 0.106 \times \ln(PSR) \\ &= 1.136 - 0.106 \times \ln(2.79722) \qquad \textit{Eq. H.49} \\ &= 1.02697 \end{aligned}$$

HERS is now ready to calculate the constant speed operating costs for small autos. The unit costs and efficiency adjustment factors for small autos are listed below in Table H-7, with the variable names referenced in Equation H.50. The component prices are presented in paragraph 7.1.2.1.1, ”Component Prices.” The adjustment factors are discussed in paragraph 7.1.2.1.2, ”Adjustment Factors for Consumption Rates.”

Table H-7. Cost Components for Small Autos - 1997

Cost Component	Unit Cost	Adjustment Factor
Fuel ($ per gallon)	$ 0.871 (*COSTF*)	1.536 (*FEAF*)
Oil ($ per quart)	3.573 (*COSTO*)	1.05 (*OCAF*)
Tire Wear ($ per tire)	45.20 (*COSTT*)	1.0 (*TWAF*)
Maintenance & Repair ($ per 1000 miles)	84.10 (*COSTMR*)	1.0 (*MRAF*)
Depreciable Value (vehicle price)	18,117 (*COSTV*)	1.30 (*VDAF*)

HERS uses Equation 7.2 to calculate the constant speed operating costs for small autos in the downhill direction (dollars per 1000 VMT):

$$\begin{aligned} CSOPCST = {} & CSFC \times PCAFFC \times COSTF / FEAF \\ & + CSOC \times PCAFOC \times COSTO / OCAF \\ & + 0.01 \times CSTW \times PCAFTW \times COSTT / TWAF \\ & + 0.01 \times CSMR \times PCAFMR \times COSTMR / MRAF \\ & + 0.01 \times CSVD \times PCAFVD \times COSTV / VDAF \end{aligned}$$

$$\begin{aligned} = {} & 23.0494 \times 1.0 \times 0.871 / 1.536 \\ & + 1.49006 \times 1.19081 \times 3.573 / 1.05 \\ & + 0.01 \times 0.35115 \times 1.25720 \times 45.2 / 1.0 \\ & + 0.01 \times 78.0190 \times 1.25849 \times 84.1 / 1.0 \\ & + 0.01 \times 0.71452 \times 1.02697 \times 18117 / 1.30 \end{aligned} \qquad \textit{Eq. H.50}$$

$$= 13.07034 + 6.03784 + 0.19956 + 82.61138 + 102.26357$$

$$= 204.18269$$

As this section is not flat (i.e., *GR* is not equal to zero), HERS repeats Equations H.41 through H.50 in the uphill direction (that is, with positive grade: GR = 2.14209).[4] As grade is used in the calculation of consumption rates for fuel, tires, and maintenance and repair, the constant speed operating costs for these components also differ in the uphill direction. Total constant speed operating costs per 1000 VMT for small autos in the uphill direction is $ 233.11960; HERS averages the two directions for a value of $ 218.65115.

H.5.3.2.2 Excess Operating Costs Due to Curves

As the average effective speed for small autos on the example section is greater than 55 m.p.h., HERS will use equations from Exhibit E-16, “Excess Operating Costs Due to Curvature (AES >=55): Small Automobiles,” to determine *CFC*, the excess fuel consumption rate due to curves (in gallons per 1000 miles); *CTW*, the excess tire wear rate due to curves (percent worn per 1000 miles); and *CMR*, the excess maintenance and repair rate due to curves (percent of average cost per 1000 miles).

Using degrees of curvature (*DC*) from Table H-6, “Section Characteristics and Speed Factors,” and average effective speed (*AES*) from Equation H.40, HERS calculates *CFC*:

$$\begin{aligned} CFC &= 0.5 \times DCA \times \exp(-7.262 + 0.08857 \times AES) \\ &= 0.5 \times 0.524294 \times \exp(-7.262 + 0.08857 \times 65.7008) \qquad \textit{Eq. H.51} \\ &= 0.06193 \end{aligned}$$

HERS calculates *CTW*, the excess tire wear rate due to curves:

$$\begin{aligned} CTW &= 0.5 \times DCA \times \exp(-25.262 + 6.518 \times \ln(AES)) \\ &= 0.5 \times 0.524294 \times \exp(-25.262 + 6.518 \times \ln(65.7008)) \qquad \textit{Eq. H.52} \\ &= 1.96936 \end{aligned}$$

And HERS calculates *CMR*, the excess maintenance and repair rate due to curves:

---

[4] The average effective speed remains the same, as HERS assumes that grades make no difference to four-wheel vehicles. For trucks with more than four wheels, average effective speed differs by direction

$$\begin{aligned} CMR &= 0.5 \times DCA \times \exp(-36.874 + 8.434 \times \ln(AES)) \\ &= 0.5 \times 0.524294 \times \exp(-36.874 + 8.434 \times \ln(65.7008)) \qquad \textit{Eq. H.53} \\ &= 0.05417 \end{aligned}$$

Using component costs and adjustment factors as shown in Table H-7, HERS employs Equation 7.4 to determine the total excess cost due to curves (COPCST) for small autos:

$$\begin{aligned} COPCST &= CFC \times COSTF / FEAF \\ &\quad + 0.01 \times CTW \times COSTT / TWAF \\ &\quad + 0.01 \times CMR \times COSTMR / MRAF \\ &= 0.06193 \times 0.871 / 1.536 \qquad \textit{Eq. H.54} \\ &\quad + 0.01 \times 1.96936 \times 45.2 / 1.0 \\ &\quad + 0.01 \times 0.05417 \times 84.1 / 1.0 \\ &= 0.03511 + 0.89023 + 0.04557 \\ &= 0.97094 \end{aligned}$$

HERS repeats this series of calculations (Equations H.34 through H.54) for each vehicle type. The results of these calculations are summarized in Table H-8, “Example Operating Costs by Vehicle Type,” for the example section. The slight inclination resulted in a difference in uphill/downhill speed only for the three heavier truck types. Therefore, the excess costs due to curves were calculated in the uphill direction only for these three types: for lighter vehicles, the downhill values of excess costs due to curves were used in both directions.[5]

Table H-8. Example Operating Costs by Vehicle Type

Vehicle Type	Average Effective Speed		Constant Speed Operating Cost ($ per 1000 VMT)		Excess Cost Due to Curves ($ per 1000 VMT		Total Cost
	Down-hill	Uphill	Down-hill	Uphill	Down-hill	Uphill	
Small Autos	65.700		$ 204.18	$ 233.12	$ 0.97		$ 219.62
Medium/Large Autos	65.700		225.40	266.20	1.74		247.54
Pickups & Vans	65.700		203.78	269.70	1.92		238.66
Six-Tire Trucks	65.700		364.54	525.48	4.63		449.64
3+ Axle Single Unit Trucks	65.700	63.964	429.50	754.04	8.55	7.08	599.58
3-4 Axle Combination Trucks	65.688	63.959	377.63	717.30	7.88	6.48	554.65
5+ Axle Combination Trucks	65.688	63.959	191.36	840.16	9.32	7.72	524.27

The rightmost column of Table H-8, Total Cost, is computed:

---

[5] The cells in the table are left blank to indicate that discrete values were not calculated.

$$\begin{aligned} TotalCost = {} & (CSOPCST_{uphill} + CSOPCST_{downhill})/2 \\ & + (COPCST_{uphill} + COPCST_{downhill})/2 \\ & + (VSOPCST_{uphill} + VSOPCST_{downhill})/2 \end{aligned} \qquad \text{Eq. H.55}$$

where:

CSOPCST	=	Constant speed operating costs in indicated direction;
COPCST	=	Excess operating costs due to curves in the indicated direction; and
VSOPCST	=	Variable speed operating costs in the indicated direction (which, in the case of the example, are set to zero.

H.5.3.2.3 Constructing the Average Operating Cost

HERS next uses the procedures of paragraph 6.4, ”The Fleet Composition Model,” to construct a weighted average operating cost for all vehicles on the section. Selecting factors for urban interstate sections from Table 6-16, “Fleet Disaggregation Factors,” the model employs Equation 6.47 to calculate average operating costs for each of the three vehicle categories. The numeric subscripts in Equation 6.47 indicate vehicle types, and the alphabetic subscripts (*A*, *SU*, and *CM*) indicate the vehicle category. Substituting the total cost per vehicle type (from Table H-8) for the *VT* variables permits calculation of *VCAT* as the average operating cost for the particular vehicle category. Thus, for four tire vehicles:

$$\begin{aligned} VCAT_A &= VT_1 \times FAF_{1_{fc}} + VT_2 \times FAF_{2_{fc}} + VT_3 \times FAF_{3_{fc}} \\ &= 219.62 \times 0.2521 + 247.54 \times 0.5583 + 238.66 \times 0.1896 \qquad \text{Eq. H.56} \\ &= 238.81 \end{aligned}$$

Similarly, for single unit trucks:

$$\begin{aligned} VCAT_{SU} &= VT_4 \times FAF_{4_{fc}} + VT_5 \times FAF_{5_{fc}} \\ &= 449.64 \times 0.7 + 599.58 \times 0.3 \qquad \text{Eq. H.57} \\ &= 494.62 \end{aligned}$$

Lastly, for combination trucks:

$$\begin{aligned} VCAT_{CM} &= VT_6 \times FAF_{6_{fc}} + VT_7 \times FAF_{7_{fc}} \\ &= 554.65 \times 0.1253 + 524.27 \times 0.8747 \qquad \text{Eq. H.58} \\ &= 528.08 \end{aligned}$$

In the example, as for the *1999 C&P Report*, there is no truck growth relative to other vehicles, so the calculations in Equation 6.48 are not required. Thus, substituting the section’s average percentages of single unit and combination trucks (from Table H-1, “Section Characteristics”) for the variables *PCSU* and *PCCM*, respectively, HERS uses Equation 6.49, with *TWS* representing the average operating cost per 1000 vehicle miles on the example section:

$$\begin{aligned}TWS &= VCAT_A \times (1 - PCSU - PCCM) + VCAT_{SU} \times PCSU \\ &\quad + VCAT_{CM} \times PCCM \\ &= 238.81 \times (1 - 0.04 - 0.07) + 494.62 \times 0.04 \\ &\quad + 528.08 \times 0.07 \\ &= 269.30\end{aligned} \qquad \textit{Eq. H.59}$$

The code is structured to determine the speed and operating costs for each direction of each vehicle type in order. When all vehicle types have been processed, HERS uses the above procedure to produce not only a single weighted average operating cost, but also a single weighted average effective speed. The AES for all vehicles on the section is 65.6290.

H.5.3.3 Calculating Safety Costs

HERS first determines that (for purposes of the safety routines) the example section is an urban freeway by design. HERS therefore uses Equation 7.13 to estimate *CRASH*, the number of crashes per 100 million vehicle miles:

$$\begin{aligned}CRASH &= (154.0 - 1.203 \times ACR + 0.258 \times ACR^2 - 0.00000524 \times ACR^5) \\ &\quad \times \exp(0.0082 \times (12 - LW)) \\ &= (154.0 - 1.203 \times 8.89607 + 0.258 \times 8.89607^2 - 0.00000524 \\ &\quad \times 8.89607^5) \times \exp(0.0082 \times (12 - 12)) \\ &= 163.42421\end{aligned} \qquad \textit{Eq. H.60}$$

where *ACR* (the AADT to Capacity ratio) is taken from Equation H.38 and *LW* (lane width) from Table H-1.

HERS has the capability to implement user-specified annual rates of decline in crash rates and in the ratios of fatalities and injuries per crash (see paragraph 7.1.3.3, ”Secular Trends”). Although this option was not exercised in the preparation of the 1999 *C&P Report* (the annual rates of decline were set to zero), for this example the annual decline in crash rates was set to 1.3 percent, and for injuries and fatalities per crash to 1.0 percent. HERS adjusts the crash rate for annual decline:

$$\begin{aligned}CRASH_{adj} &= CRASH \times (1 - APDCR)^{NYRC} \\ &= 163.42421 \times (1 - 0.013)^{17} \\ &= 130.83020\end{aligned} \qquad \textit{Eq. H.61}$$

where:

APDCR	=	user-specified annual percentage decline in crash rate of 1.3%; and
NYRC	=	number of years since year of crash rates (1995).

The value for *NYRC* is the difference between 1995 (the year on which the crash rates are based) and the year under analysis. The year under analysis is the mid-year of the five-year benefit-cost analysis period which begins at the middle of the third funding period (when an improvement would be implemented) and ends at the middle of the fourth funding period. This mid-year is thus the end of the third funding period, which is year 15 in the overall analysis period. The base year of the analysis in 1997, so two more years are added, yielding *NYRC* equal to 17.

HERS next determines the number of injuries and fatalities which would occur in each 100 million vehicle miles based upon the number of crashes. For *INJ*, the number of injuries per 100 million vehicle miles:

$$\begin{aligned} INJ &= CRASH_{adj} \times INJR_{fc} \times (1 - APDIPC)^{NYRFI} \\ &= 130.83020 \times 0.4908 \times (1 - 0.01)^{17} \qquad \textit{Eq. H.62} \\ &= 54.12661 \end{aligned}$$

where:

$INJR_{fc}$ = the functional class-dependent injury rate from Table 7-8, “Fatality and Injury Rates,” for urban interstate sections;
$APDIPC$ = user-specified annual percentage decline in injuries per crash of 1.0%; and
$NYRFI$ = number of years since year of injury and fatality rates (1995).

NYRFI is calculated as is *NYRC*: as both rates were set for 1995, *NYRFI* also equals 17.

To calculate *FAT*, the number of fatalities per 100 million vehicle miles:

$$\begin{aligned} FAT &= CRASH_{adj} \times FATR_{fc} \times (1 - APDFPC)^{NYRFI} \\ &= 130.83020 \times 0.00382 \times (1 - 0.01)^{17} \qquad \textit{Eq. H.63} \\ &= 0.42556 \end{aligned}$$

where:

$FATR_{fc}$ = the functional class-dependent fatality rate from Table 7-8, “Fatality and Injury Rates,” for urban interstate sections; and
$APDFPC$ = user-specified annual percentage decline in fatalities per crash of 1.0%.

HERS next calculates *PROPD*, the dollar value of property damage per 100 million vehicle miles:[6]

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[6] Preparation of this appendix revealed an error in the implementation of the equations for calculating *PROPD, INJC,* and *DELCC*. In all three cases, the calibration factors described in Table 7.1.3.4.1, “Unit Costs of Crashes in 1994,” were both applied to the input data and included in the equations. The equations as shown in the main text are correct and have been reproduced here.

$$\begin{aligned} PROPD &= CRASH_{adj} \times PROPCST_{fc} \\ &= 130.83020 \times 7093.8 \\ &= 928083 \end{aligned} \qquad \textit{Eq. H.64}$$

where:

$PROPCST_{fc}$ = functional class-specific cost of property damage from Table 7-9, “Injury and Property-Damage Costs” (in 1994 dollars), indexed to 1997 dollars by the user-specified index of 112.6.

HERS calculates *INJC*, the dollar value of injuries per 100 million vehicle miles:

$$\begin{aligned} INJC &= INJ \times INJCST_{fc} \\ &= 54.12661 \times 60875.1 \\ &= 3294962 \end{aligned} \qquad \textit{Eq. H.65}$$

where:

$INJCST_{fc}$ = functional class-specific cost of injuries from Table 7-9, “Injury and Property-Damage Costs” (in 1994 dollars), indexed to 1997 dollars by the user-specified index of 108.9.

HERS calculates *FATC*, the dollar value of fatalities per 100 million vehicle miles:

$$\begin{aligned} FATC &= FAT \times VLIFE \\ &= 0.42556 \times 2700000 \\ &= 1137452 \end{aligned} \qquad \textit{Eq. H.66}$$

where *VLIFE* is the user-specified value of life (in both the example and the 1999 *C&P Report*, HERS used the OMB-specified value).

HERS uses Equation 7.16 to calculate *DELCC*, the dollar value of delay due to crashes per 100 million vehicle miles:

$$\begin{aligned} DELCC &= \frac{AADT}{LANES} \times CRASH_{adj} \times TDCAF \\ &= \frac{73374.8}{4} \times 130.83020 \times 1.089 \\ &= 2613501 \end{aligned} \qquad \textit{Eq. H.67}$$

where:

AADT = section AADT at mid-point of benefit-cost analysis period; and
TDCAF = travel delay cost adjustment factor from paragraph 7.1.3.4.2, ”Indexing the Costs of Crashes.”

H.5.3.4 Calculating Travel Time Costs

As with operating costs, HERS calculates travel time costs separately for each vehicle type, then aggregates the costs first by vehicle category, then for the vehicle fleet. During program initialization, HERS derives the value of an hour of travel time from the four component values per vehicle type and the appropriate index values entered in the PARAMS.DAT file. The travel time cost parameters used for the example are shown in Table H-9.

Table H-9. Travel Time Cost Parameters

Vehicle Type	Travel Time Components from PARAMS.DAT (1995$)			
	$ per Person-Hour	Vehicle Cost	Inventory Cost	Average Vehicle Occupancy
Small Autos	9.51	0.11	0	1.64
Medium/Large Autos	9.51	0.15	0	1.64
Pickups & Vans	10.78	0.48	0	1.61
Six-Tire Trucks	16.50	2.65	0	1.05
3+ Axle Single Unit Trucks	16.50	7.16	0	1.0
3-4 Axle Combination Trucks	16.50	6.41	0.60	1.12
5+ Axle Combination Trucks	16.50	6.16	0.60	1.12

HERS uses index values of 1.059, 1.110, and 1.038 to convert time, vehicle, and inventory costs, respectively, from 1995 dollars to 1997 dollars. The formula for determining the value of an average hour of travel time for a specific vehicle type ($TTVAL_{vt}$) in 1997 dollars is shown below for small autos:[7]

$$\begin{aligned} TTVAL_{vt} &= AVO_{vt} \times CPPH_{vt} \times PI_{cpph} + VC_{vt} \times PI_{vc} + IC_{vt} \times PI_{ic} \\ &= 1.64 \times 9.51 \times 1.059 + 0.11 \times 1.110 + 0 \times 1.038 \\ &= 16.6387 \end{aligned} \qquad \text{Eq. H.68}$$

where:

AVO_{vt} = average vehicle occupancy for vehicle of type *vt*;
$CPPH_{vt}$ = cost per person-hour for vehicle of type *vt*;
VC_{vt} = vehicle cost per hour for vehicle of type *vt*;
IC_{vt} = inventory cost per hour for vehicle of type *vt*; and
PI = price index for person-hour (*cpph*), vehicle cost (*vc*), or inventory cost (*ic*).[8]

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[7] This calculation is performed during initialization once for each vehicle type.

[8] The price indices are the same for all vehicle types.

HERS next uses Equation 7.1 to calculate the average travel-time cost in dollars per thousand vehicle miles ($TTCST_{vt}$) for each of the vehicle types across the section. The value of average effective speed (AES) is taken from Table H-8, "Example Operating Costs by Vehicle Type," and again, the example shown is for small autos:

$$\begin{aligned} TTCST_{vt} &= \frac{1000}{AES_{vt}} \times TTVAL_{vt} \\ &= \frac{1000}{65.7008} \times 16.6387 \\ &= 253.249 \end{aligned} \qquad \textit{Eq. H.69}$$

Table H-10 presents the results of calculating the travel time cost for each vehicle type.

Table H-10. Travel Time Cost by Vehicle Type (1997 Dollars)

Vehicle Type	Average Effective Speed	Value of an Hour of Travel Time	Travel Time Cost per 1000 VMT
Small Autos	65.7008	16.6387	253.249
Medium/Large Autos	65.7008	16.6831	253.925
Pickups & Vans	65.7008	18.9126	287.860
Six-Tire Trucks	65.7008	21.2887	324.025
3+ Axle Trucks	64.8324	25.4211	392.105
3-4 Axle Combinations	64.8235	27.3082	421.270
5+ Axle Combinations	64.8235	27.3037	416.989

As was the case with aggregating operating costs, HERS uses the travel time costs by vehicle type and the values from Table 6-16, "Fleet Disaggregation Factors," and Equations 6.47 through 6.49[9] to recalculate $VCAT$ as the average travel time cost per 1000 VMT for the particular vehicle category. For four tire vehicles:

$$\begin{aligned} VCAT_A &= VT_1 \times FAF_{1_{fc}} + VT_2 \times FAF_{2_{fc}} + VT_3 \times FAF_{3_{fc}} \\ &= 253.249 \times 0.2521 + 253.925 \times 0.5583 + 287.860 \times 0.1896 \\ &= 260.189 \end{aligned} \qquad \textit{Eq. H.70}$$

And, for single unit trucks:

---

[9] As with the operating cost example, however, Equation 6.48 is not needed.

$$\begin{aligned} VCAT_{SU} &= VT_4 \times FAF_{4_{fc}} + VT_5 \times FAF_{5_{fc}} \\ &= 324.025 \times 0.7 + 392.105 \times 0.3 \\ &= 344.449 \end{aligned} \tag{Eq. H.71}$$

Finally, for combination trucks:

$$\begin{aligned} VCAT_{CM} &= VT_6 \times FAF_{6_{fc}} + VT_7 \times FAF_{7_{fc}} \\ &= 421.270 \times 0.1253 + 416.989 \times 0.8747 \\ &= 417.526 \end{aligned} \tag{Eq. H.72}$$

HERS substitutes the section's average percentages of single unit and combination trucks (from Table H-1, "Section Characteristics") for the variables *PCSU* and *PCCM*, respectively, and uses Equation 6.49, calculating *TWS* to represent the average travel time cost per 1000 vehicle miles on the example section:

$$\begin{aligned} TWS &= VCAT_A \times (1 - PCSU - PCCM) + VCAT_{SU} \times PCSU \\ &\quad + VCAT_{CM} \times PCCM \\ &= 260.189 \times (1 - 0.04 - 0.07) + 344.449 \times 0.04 \\ &\quad + 417.526 \times 0.07 \\ &= 274.573 \end{aligned} \tag{Eq. H.73}$$

H.5.3.5 Calculating Maintenance Costs

Unlike the user costs calculated above, which are averages centered upon the mid-point of the five-year benefit-cost analysis period, maintenance costs are calculated for a time period based upon the section's starting and ending PSR.[10] HERS selects PSR values to bracket the BCAP. As coded, Equation 7.18 also multiplies by the number of lanes:

$$\begin{aligned} MCOST &= (-(2411 + 4355 \times SN) \times (PSR_f - PSR_i) \\ &\quad + (270.9 + 489.6 \times SN) \times (PSR_f^2 - PSR_i^2)) \times LANES \\ &= (-(2411 + 4355 \times 6.9) \times (2.56671 - 3.04842) \\ &\quad + (270.9 + 489.6 \times 6.9) \times (2.56671^2 - 3.04842^2)) \times 4 \\ &= 23064.48 \end{aligned} \tag{Eq. H.74}$$

where:

$MCOST$ = maintenance cost per mile during period;
PSR_i = PSR at beginning of BCAP (from Table H-2);
PSR_f = PSR at end of BCAP;
SN = the section's structural number (from Table H-1); and

---

[10] HERS calculates benefits and costs separately for each five-year period of the BCAP. Had the example BCAP been longer than one funding period in length, HERS would repeat the calculations for each five-year period.

$LANES$ = number of lanes (also from Table H-1).

As MCOST is in 1988 dollars, HERS multiplies it by PI_{umc}, the user-supplied price index for urban maintenance costs, to yield the maintenance cost per mile in 1997 dollars:

$$\begin{aligned} MCOST_{1997} &= MCOST \times PI_{umc} \\ &= 23064.48 \times 1.242 \\ &= 28646.10 \end{aligned} \qquad \textit{Eq. H.75}$$

H.5.3.6 Calculating Emissions Damage Costs

To determine the cost of damages from vehicular emissions, HERS substitutes indexed values in Equation 7.19. The two indices are functional class and the emissions period. The emissions equations are constructed to reflect future changes in emissions, and are grouped into the following time periods:

- pre - 2000
- 2001 - 2005
- 2006 - 2010
- 2011 - 2015
- 2016 and beyond

The data year of the example is 1997. The example is set in the third funding period, each five years long, so that ten years have passed, and the current funding period one begins in 2007. The BCAP begins at the middle of the first funding period and extends to the middle of the next; that is, from July 2009 through June 2014. The point at which the emissions costs will be analyzed[11] is the mid-point of the BCAP, which is the also the end of funding period one: January 2012. HERS therefore sets the emissions period index to the fourth of the time periods listed above.

HERS sets the functional class index to urban interstate and executes Equation 7.19, using the values from Table G-5, "Emissions Factors for Urban Interstates," to calculate the cost of emissions damage per vehicle mile:

---

[11] As were the operating costs, travel time costs, and safety costs, but not the maintenance costs.

$$
\begin{aligned}
EmCost = {} & EC + EF_1 \times AES + EF_2 \times AES^2 + EF_3 \times AES^3 + \\
& EF_4 \times AES^4 + EF_5 \times AES^5 + EF_6 \times AES^6 \\
& = 0.08417992 \\
& \quad - 0.0087997 \times 65.6290 \\
& \quad + 0.0006463 \times 65.6290^2 \\
& \quad - 0.2568 \times 10^{-4} \times 65.6290^3 \\
& \quad + 0.56 \times 10^{-6} \times 65.6290^4 \\
& \quad - 0.1 \times 10^{-7} \times 65.6290^5 \\
& \quad + 0 \times 65.6290^6 \\
= {} & 0.040983
\end{aligned}
\qquad \text{Eq. H.76}
$$

H.5.4 Determining the Benefits of the Candidate Improvement

HERS calculates costs for the candidate improvement over the same time period as for the base case. HERS employs the same procedure as used above for the base case (paragraphs H.5.3.1 through H.5.3.6). The costs for the improved case reflect the changes in PSR (due to resurfacing) and level of service (due to the additional lanes).

HERS then calculates the benefit for each of the cost components by subtracting the costs for the improved case from the base case (see Equation 4.2). This is done separately for each period of the BCAP: as the example BCAP is one period in length, this is done just once. Costs for the base case, the improved case, and the benefits are summarized in Table H-11. Except for maintenance cost, which is listed in dollars per road mile, all costs and benefits have been converted to "per vehicle mile."

HERS uses Equation 4.3 to calculate the discount rate *DFACTR* for the period under analysis:

$$
\begin{aligned}
DFACTR &= DRATE^{(LFP \times (FPC - 0.5))} \\
&= 1.07^{(5 \times (1 - 0.5))} \\
&= 1.18429
\end{aligned}
\qquad \text{Eq. H.77}
$$

where:

$DRATE$ = OMB-specified discount rate (as used in 1997 and 1999 *C&P Reports*);
LFP = length of a funding period in years; and
FPC = funding period counter pointing to funding period under analysis.

HERS next calculates the discounted "per-vehicle" benefit for user and external benefits using Equation 4.4. This value represents the average benefit accruing from driving one vehicle over the improved section (versus over the unimproved section) once each day of the analysis period.

Table H-11. Cost Summary

Cost	Base Case	Improved Case	Benefit
Operating Cost	$ 0.26930	$ 0.24955	$ 0.01975
Safety Costs			
Property Damage	0.00928	0.00870	0.00058
Injury Cost	0.03294	0.03090	0.00204
Fatality Cost	0.01137	0.01066	0.00071
Cost of Delay Due to Crashes	0.02613	0.01106	0.01507
Safety Costs (sub-total)	0.07974	0.06134	0.01840
Travel Time Cost	0.27457	0.25025	0.02432
Maintenance Cost	28646.10	30021.20	-1375.10
Cost of Emissions Damage	0.04098	0.06885	-0.02787

$$\begin{aligned} BENPV &= LFP \times 365 \times SLEN \times (OPBEN + SAFBEN + TTBEN + \\ &\quad EMBEN) / DFACTR \\ &= 5 \times 365 \times 1.416 \times (0.01975 + 0.01840 + 0.02432 - 0.02787) / 1.18429 \qquad \text{Eq. H.78} \\ &= 75.4704 \end{aligned}$$

where:

BENPV = discounted benefit per vehicle;
SLEN = the section length in miles (from Table H-1, “Section Characteristics”);
OPBEN = operating cost benefits per VMT (from Table H-11);
SAFBEN = safety benefits per VMT (from Table H-11);
TTBEN = travel time benefit per VMT (from Table H-11); and
EMBEN = emission cost benefit per VMT (from Table H-11).

HERS now calculates the total benefit for the period using Equation 4.5. This algorithm includes the benefits from “old trips”, the consumer surplus, and the discounted maintenance cost savings (as discussed in paragraph 4.7, ”The Benefit-Cost Ratio”):

$$\begin{aligned} TOTBEN &= BENPV \times AADT_B + BENPV \times \frac{AADT_I - AADT_B}{2} + \frac{MNCBEN}{DFACTR} \\ &= 75.4704 \times 73374.8 + 75.4704 \times \frac{82822.4 - 73374.8}{2} + \frac{-1375.10}{1.18429} \qquad \textit{Eq. H.79} \\ &= 5892975 \end{aligned}$$

where:

$TOTBEN$ = discounted total benefits for the funding period;
$AADT_B$ = AADT for the base case B (from Table H-2, "Section Data Values");
$AADT_I$ = AADT for the improved case I (calculated after Equation H.33); and
$MNCBEN$ = maintenance cost benefit for the period.

HERS now has one of the three main components of the benefit-cost ratio.

H.5.5 Determining the Capital Cost of the Improvement

HERS examines the improvement and the section to determine which algorithm from Table 7-12, "Improvement Cost Calculations," to apply. As determined in paragraph H.3, "Identifying Candidate Improvements," six lanes will be added on the existing alignment, and existing lanes will be resurfaced. The section is an urban interstate, and its widening feasibility is set to "three or more lanes" (in Table H-1, "Section Characteristics"). This translates into "major widening at normal cost on an urban section," which is the third entry in Table 7-12.

The model also sets up indexes to access the appropriate improvement cost. The base costs are shown in Table 7-11, "Capital Improvement Costs," in thousands of 1995 dollars per lane-mile. During program initialization, HERS multiplies these costs by the user-specified price indices in the PARAMS.DAT file to yield thousands of 1997 dollars. The value for major widening at normal cost for urban freeways and expressways is 3440 thousand dollars; the index value for urban improvement costs is 1.068. HERS will use the figure of 3673.92 thousand dollars per lane mile for this improvement.

Using the third entry from Table 7-12, HERS computes the initial cost of the improvement, $COST_{imp}$, in thousands of dollars:

$$\begin{aligned} COST_{imp} &= LANES_{norm} \times COST_{norm} \times IMPLEN \\ &= 6 \times 3673.92 \times 1.416 \qquad \textit{Eq. H.80} \\ &= 31213.6 \end{aligned}$$

where:

$LANES_{norm}$ = the number of lanes to be added at normal cost;
$COST_{norm}$ = the cost of adding normal-cost lanes for this type of improvement, in thousands of dollars per lane-mile; and
$IMPLEN$ = centerline miles being improved: in this case, the entire length of the section (from Table H-1).

For this improvement, the cost of resurfacing the existing lanes is included in the pricing of the additional lanes. The selected improvement is priced over the entire length of the section except when a portion of the section is having its alignment improved. Had a portion of the section undergone alignment improvement, that cost would be calculated separately and added to the cost of the selected improvement over the remaining portion of the section.

The last steps in calculating the capital cost are indexing the cost per the state in which the section lies and scaling to whole dollars:

$$\begin{aligned} COST_{tot} &= COST_{imp} \times STFCT_{state} \times 1000 \\ &= 31213.6 \times 0.791 \times 1000 \\ &= 24689970 \end{aligned} \qquad \text{Eq. H.81}$$

where:

$STFCT_{state}$ = the cost factor for the section's state.

H.5.6 Determining the Residual Value of the Improvement

HERS first establishes that, between the implementation of the improvement under consideration (funding period one) and the end of the BCAP (funding period two), no additional improvements to the base (unimproved) case are likely. HERS then calculates the cost of an improvement at the end of the BCAP which would bring the unimproved section to *exactly* the condition of the improved case.

The rub lies in matching the pavement condition. Ordinarily, HERS improves pavement during resurfacing by adding an increment to the existing PSR. The new PSR value is subject to a ceiling, so it is possible that the improvement under consideration did not receive the full increment. Additionally, pavement deteriorates more quickly at lower PSR levels, so the unimproved case would would degenerate more than the improved case. Furthermore, improving the section lowers the price to the users, so the improved section will experience a higher traffic volume than the unimproved case. The effect of these factors is that simply repeating the initial improvement at the end of the BCAP will not result in the same conditions as having implemented that improvement at the beginning of the BCAP.

The general algorithm used by HERS to fix the cost of the "matching" improvement (the end-of-BCAP improvement after which the section matches the condition of the improved case) is:

$$COST_m = COST_f + COST_p \times \left(\frac{PSR_i - PSR_u}{PSR_f - PSR_u} - 1\right) \qquad \text{Eq. H.82}$$

where:

$COST_m$ = the cost of the "matching" improvement;

$COST_f$ = the full cost of implementing the initial improvement at the end of the BCAP;

$COST_p$ = the cost of implementing only the pavement portion of the improvement at the end of the BCAP (includes pavement improvement of all added lanes);

PSR_i = the PSR of the improved case at the end of the BCAP (the PSR

which the end-of-BCAP improvement will match);
PSR_f = the PSR after implementing the initial improvement at the end of the BCAP (corresponds to $COST_f$); and
PSR_u = the PSR of the unimproved case at the end of the BCAP.

HERS first simulates an improvement *f*, which consists of the pavement options (resurfacing or reconstruction), widening options (add lanes, widen lanes, etc.), and alignment options (improve curves or grades or both) to bring the base case to the condition that will exist at the end of the BCAP if the improvement under consideration is implemented. The simulation does not need to be complete: it only includes calculating the capital cost and the condition of the pavement after the improvement. The capital cost of improvement *f* is the same as the improvement under consideration: $ 24,689,970. The PSR of the section received almost the full increment of 1.8 in being improved from 2.56 to 4.30 (the ceiling for resurfaced pavement).

HERS then performs capital cost calculations for only the pavement portion of improvement *f*, referred to here as improvement *p*. The calculations are performed with no widening and no alignment improvements, but to include any lanes added in improvement *f*. In the example, then, improvement *p* calculates the cost of resurfacing all ten lanes, but not the cost of adding the six new lanes. The cost of improvement *p* is $ 2,404,400.

HERS is now ready to perform the calculation in Equation H.82:

$$COST_m = COST_f + COST_p \times \left(\frac{PSR_i - PSR_u}{PSR_f - PSR_u} - 1\right)$$

$$= 24689970 + 2404400 \times \left(\frac{3.62052 - 2.56671}{4.30 - 2.56671} - 1\right) \qquad \text{Eq. H.83}$$

$$= 23747400$$

All that remains is for HERS to discount $COST_m$ back to the middle of the first funding period :

$$RESID = COST_m / DRATE^{(LFP \times (ENDBCA - 1))}$$

$$= 23747400 / 1.07^{(5 \times (2 - 1))} \qquad \text{Eq. H.84}$$

$$= 16931570$$

where:

RESID = discounted residual value of the improvement under consideration;
DRATE = annual discount factor of 7% (as suggested by OMB);
LFP = length of a funding period; and
ENDBCA = funding period in which BCAP ends.

H.5.7 Calculating the Benefit-Cost Ratio

HERS is now prepared to calculate the benefit-cost ratio using Equation 4.6:

$$
\begin{aligned}
IBCR &= \frac{TOTBEN_{SUM} + RESID}{(IMPCOST_I - IMPCOST_B)} \\
&= \frac{5892975 + 16931570}{(24689970 - 0)} \\
&= 0.924
\end{aligned}
\qquad \textit{Eq. H.85}
$$

where:

$IBCR$ = the incremental benefit-cost ratio for the improvement;

$TOTBEN_{SUM}$ = the sum of the discounted total benefits for all funding periods in the BCAP (the example's BCAP is one funding period long) ;

$RESID$ = the discounted residual value of the improvement;

$IMPCOST_I$ = the capital cost of the improvement being analyzed; and

$IMPCOST_B$ = the capital cost of the base case improvement (zero when, as in the example, the base case is "no improvement.")

Because the *IBCR* is less than 1.0, this particular improvement will not be selected for implementation. The model will save the set of values describing the condition of the unimproved base case at the end of the funding period. When processing the next funding period, these will describe the initial condition of the section upon which the model will base the next round of analysis.