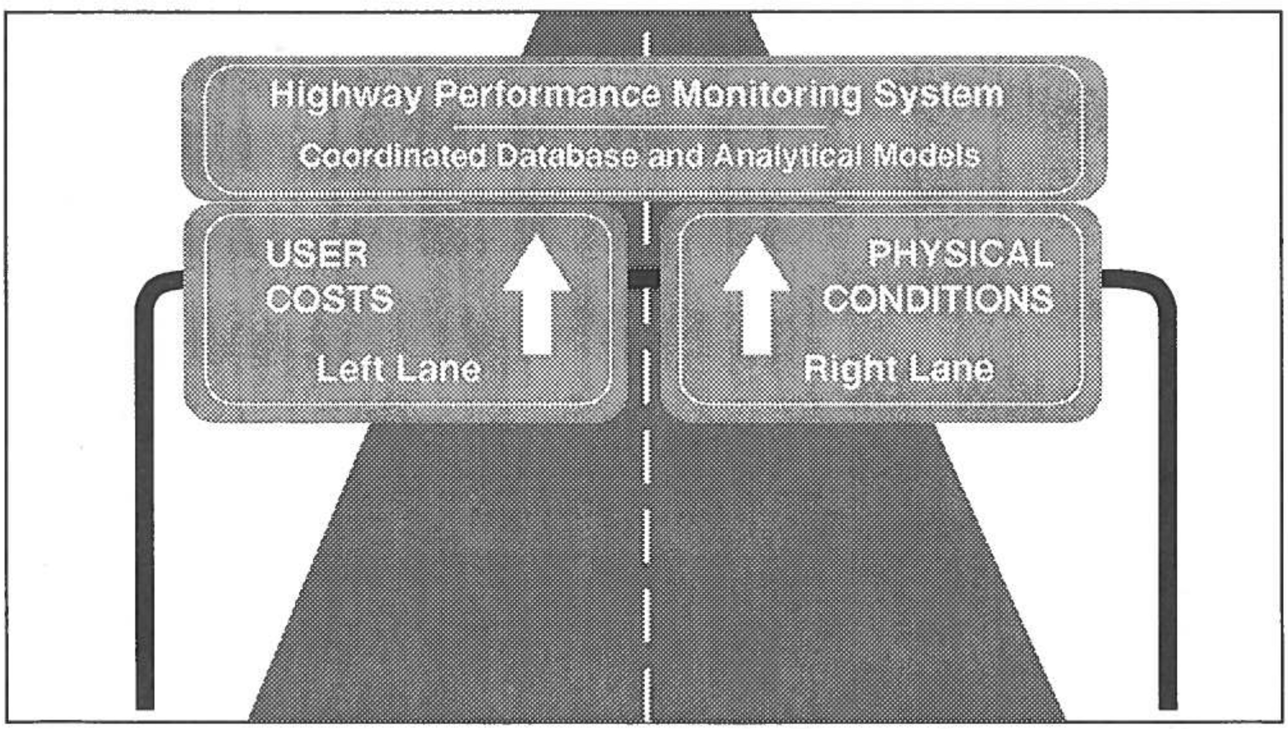
HIGHWAY ECONOMIC REQUIREMENTS SYSTEM

Volume IV: Technical Report



U.S. Department of Transportation
Federal Highway Administration

National Level Version 2

November 1996

DOT-VNTSC-FHWA-96-6

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LIST OF EXHIBITS

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 Highway and Transit Systems Report: Conditions and Performance Report (C&P Report) to Congress.

The HERS model is the result of the efforts to better examine 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 2.0 because it corresponds to program Version 2.0 which was used in the 1995 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.

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) and two types to highway agencies (maintenance costs and the "residual value" of an improvement at the end of the analysis period). The HERS model uses benefit/cost analysis to differentiate between potential improvements when selecting improvements for implementation.

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. The current implementation of HERS (version 2.0) considers resurfacing or reconstruction, possibly combined with alignment improvements and/or four alternative types of widening. To the extent that funds are available, appropriate improvements are 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 the next chapter of this report. The third chapter presents a variety of information relating to the improvements considered by HERS: descriptions of the improvements and their assumed effects on highway conditions; criteria used for identifying deficiencies and unacceptable conditions; procedures used for identifying improvements to correct these conditions; and the criteria used for selecting which of these improvements should be implemented.

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

The selection of improvements to correct deficiencies is usually controlled by incremental benefit/cost ratios calculated for each potential improvement using a relatively complex procedure that is described briefly in Chapter 4 and in more detail in an appendix. This procedure incorporates estimates of the costs of the highway improvements and their benefits to highway agencies and users. The procedures used for estimating improvement costs, agency benefits, and user benefits, are presented in Chapters 6, 7 and 8, respectively. These procedures, in turn, use forecasts of traffic volume and pavement deterioration that are developed using procedures described in Chapter 5. The benefit/cost analysis procedure also requires estimates of the residual value of improvements; a discussion of the concept is provided in Chapter 4.

The ninth chapter of this report describes the output that HERS 2.0 is capable of producing. If all optional output is requested, twenty-two pages will be produced for each funding period and another nine pages for the overall period being analyzed.

This report contains two appendices. Appendix A contains data used by the procedure for deriving the thickness of newly reconstructed rigid pavement. Appendix B describes in detail the benefit/cost evaluation procedure that controls the selection of improvements.

2 AN OUTLINE OF THE MODEL STRUCTURE

Exhibit 2-1 presents a simplified flowchart of the HERS model. As shown in the exhibit, the model contains a major loop over funding periods All funding periods must be of the same length and in an integral number of years. The funding period length and the number of funding periods to be analyzed are user specified.

In any given run, HERS is designed to perform one of three types of analysis as specified in the user input field "Objective". 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, 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.

Within the funding-period loop, there are two loops over highway sections. The first loop is entered only when the user has elected that certain types of unacceptable conditions be identified and corrected even though the improvements may be economically less desirable than improvements on sections with currently acceptable conditions.[1] For each such section, the most appropriate improvement to restore the section to acceptable condition is identified and evaluated. If sufficient funds are available, all such improvements are selected for implementation. Otherwise, only the most desirable improvements, from a benefit/cost standpoint, are selected.

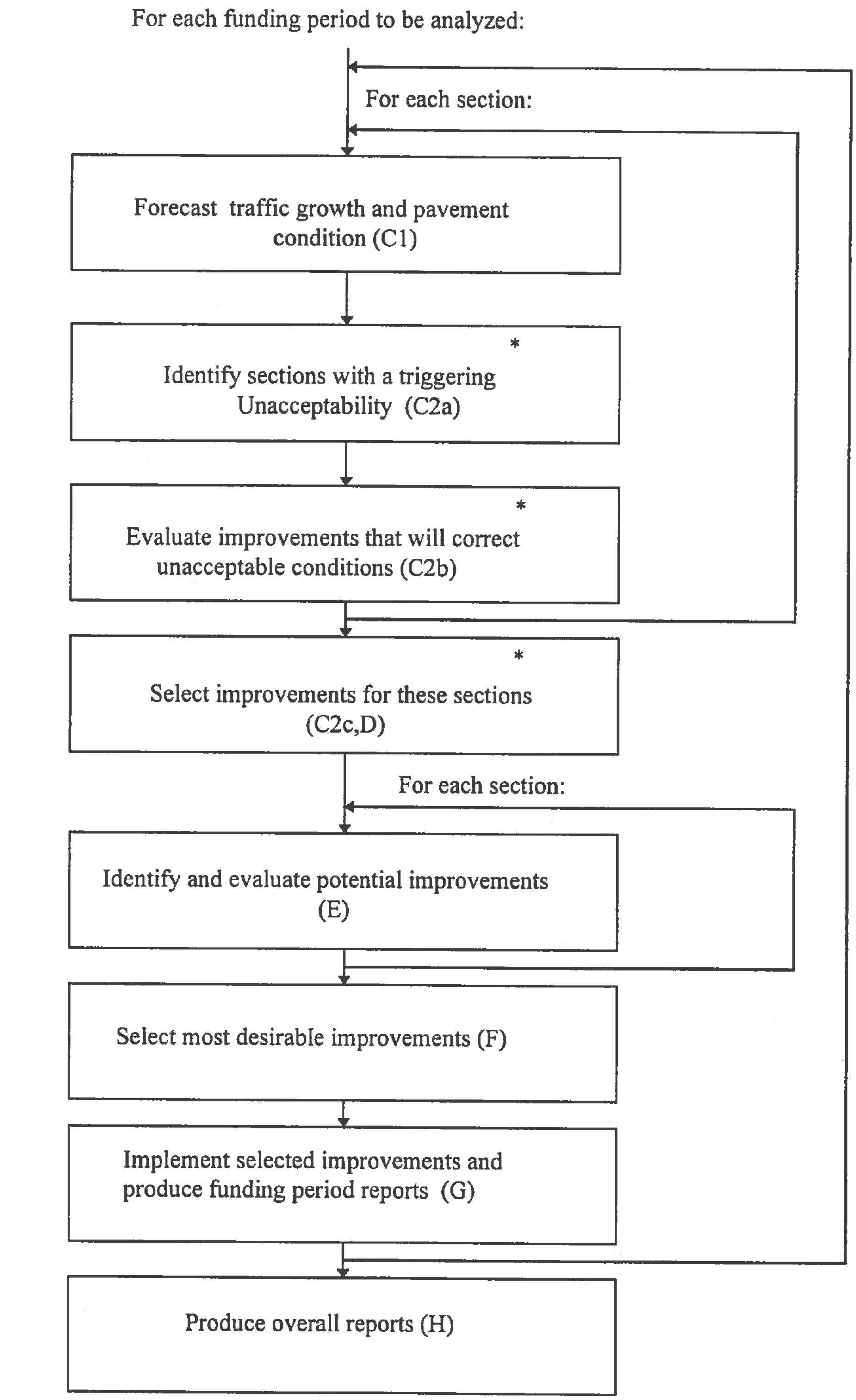
In the second loop over highway sections, improvements to correct other deficiencies are identified and evaluated. If the user has requested that all improvements achieving

[1]Sections having unacceptable conditions warranting immediate correction are said to have "triggering unacceptabilities". These sections consist of paved sections with unacceptable present serviceability rating (PSR) for pavement and unpaved sections with any unacceptable condition.

some minimum benefit/cost ratio (BCRMIN) be implemented (Objective 3), then all such improvements are implemented. Otherwise, after this loop has been completed, the most attractive improvements are selected, in sequence, until all available funds are exhausted (Objective 1) or until a user-specified minimum level of highway-system performance is reached (Objective 2).

In Exhibit 2-1. A Simplified Flowchart of the Model", the letters in parentheses refer to corresponding steps in the outlines of the model in Exhibit 2-2. An Outline of the Model Structure", Exhibit 2-3. Benefit/Cost Analysis Procedure", and Exhibit 2-4. Selection Procedure". In Exhibits 2-2 through 2-4, the steps contain references to chapters of this report that provide more detail.

Exhibit 2-1. A Simplified Flowchart of the Model



*These procedures are executed only when the user has specified the correction of uacceptable conditions.

Exhibit 2-2. An Outline of the Model Structure

A. Initialization

If Objective is 3 (i.e, implement all improvements with an incremental B/C ratio of at least x), set BCRMIN = x.

Otherwise, set BCRMIN = 1.0.

B. Begin loop over each funding period.

C. For each section:

1. Forecast conditions for the current and following funding periods (or use previously developed forecasts) (Chapter 5):

   (a) Use State forecasts of traffic growth.

   (b) Forecast pavement deterioration as a function of traffic volume.

2. If "unacceptable conditions" are to be identified and corrected, and if the section has a "triggering unacceptability" (Chapter 3):

   (a) Identify an improvement that will correct all unacceptable conditions with the lowest initial cost. (Chapter 3).

   (b) Execute the B/C Analysis Procedure (Exhibit 2-3) for an estimate of the present value of the incremental life-cycle benefits and costs of selecting the improvement.

   (c) Put improvement on list of selected improvements.

D. If "unacceptable conditions" have been identified for correction, and

1. The initial cost for all selected improvements exceeds available funds for eliminating unacceptable conditions, (Chapter 3)

   (a) use list of selected improvements as a list of improvements for potential selection and

   (b) execute the Selection Procedure (Exhibit 2-4).

2. No funds remain for implementing improvements, go to Step F.

Exhibit 2-2. An Outline of the Model Structure (cont.)

E. For each deficient section:

1. Identify improvements that warrant B/C analysis. (Chapter 3)

2. For each such improvement, execute the B/C Analysis Procedure (Exhibit 2-3) for an estimate of the present value of the incremental life-cycle benefits and costs of selecting the improvement.

3. (a) If Objective is 3, and any improvements have a B/C ratio ^{3} BCRMIN:

   - Select the improvement with the highest B/C ratio.
   - If any of the other improvements considered are more ambitious than the selected improvement, execute the B/C Analysis procedure (Exhibit 2-3) for the incremental benefit/cost ratio (IBCR) for each of these improvements and repeat Step 3 (a).

   (b) Otherwise (if Objective is 1 or 2), if any improvement has an IBCR > 1, identify the improvement with the highest IBCR and place it on a list of improvements for potential selection.

F. If Objective is 1 or 2, execute the Selection Procedure (Exhibit 2-4).

G. Implement all selected improvements, obtain the present value of life-cycle benefits and costs in appropriate disaggregate detail, and produce funding-period reports (Chapter 9).

End of funding-period loop. Go to B.

H. Produce overall reports. (Chapter 9)

Exhibit 2-3. Benefit/Cost Analysis Procedure

Estimate present value of (incremental) life-cycle benefits and costs of each potential improvement:

1. Determine the appropriate benefit/cost analysis (BCA) period for analyzing this section. (Chapter 4)

2. Estimate initial cost of improvement. (Chapter 6)

3. For the section with and without the improvement, for each funding period in the BCA period:

   (a) Obtain traffic and pavement condition forecasts for each period to be analyzed as in Step C1 (Chapter 5). (Reuse existing forecasts if available).

   (b) Estimate maintenance costs. (Chapter 7)

   (c) Calculate user costs: (Chapter 8)

   Estimate "unconstrained speed."
   Estimate effect of speed-change and stop cycles.
   Estimate travel time and cost of travel time.
   Estimate operating costs.
   Estimate safety costs.
   Estimate maintenance costs.

4. For the final funding period of the analysis period, estimate residual value. (Chapter 4, Appendix B)

5. Obtain (incremental) benefit/cost ratio.

Exhibit 2-4. Selection Procedure

1. From the list of improvements for potential selection (developed in Step D1 or E3(b) of Exhibit 2-2), select the improvement with the highest IBCR and add it to the list of selected improvements.

2. If there are any potential improvements for the section to which the selected improvement applies that are more aggressive than the selected improvement:

   (a) Use the B/C Analysis Procedure (Exhibit 2-3) to evaluate these improvements.

   (b) Identify the improvement with the highest IBCR.

   (c) If this improvement has a higher IBCR than the improvement just selected[2], select this improvement instead and execute Step 2 recursively. (Appendix B).

   (d) Otherwise, add this improvement to the list of improvements for potential selection.

3. If full implementation of the selected improvement results in just meeting or violating the specified constraint for this run:

   (a) Select only that fraction of the improvement that can be selected without violating the constraint.

      N.B. Since each sample section represents a large class of sections, selection of a fraction of an improvement is equivalent to selecting the improvement for a fraction of all sections in the class.

   (b) Return

4. Otherwise, go to Step 1.

For reasons presented in Chapter 4, the initial decision to improve a section (Step 1) differs from the selection of the best improvement for a section to be improved (Step 2(c). In the case of the initial decision, the length of the benefit/cost analysis period is generally set to a single funding period. When determining whether more aggressive improvements warrant implementation, the benefit/cost analysis period is set to the expected life of the improvement under consideration. The resulting differences in the two analyses make it possible to obtain a higher IBCR when the B/C Analysis Procedure is called from Step 2(a) than when it is called from Step E2, Exhibit 2-2.

3 HERS IMPROVEMENTS

The highway improvements analyzed by HERS 2.0 consist of various combinations of pavement, widening and alignment improvements. The first two sections of this chapter present definitions of these improvement types and descriptions of the effects these improvements are assumed to have on highway conditions; i.e., how they are simulated. The third section presents the procedures used for identifying highway deficiencies and potential improvements to correct these deficiencies. The fourth section presents suggested values for the criteria used to identify these deficiencies; and the final section describes the various criteria that can be specified by the user for determining which improvements should be implemented. The actual benefit/cost analysis procedure used by HERS for evaluating potential improvements is presented in the next chapter.

3.1 HERS Improvement Types and Kinds

The highway improvements considered by HERS 2.0 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 Exhibit 3-1. There are 32 possible combinations for the options in the three columns of Exhibit 3-1, 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.

Exhibit 3-1 shows three distinct alignment options: improve curves, improve grades, or improve both. In HERS 2.0, 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.

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.

Exhibit 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

Each of the seven kinds of improvement are described briefly in Exhibit 3-2. 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 appropriate improvements are implemented on substandard urban freeways undergoing pavement reconstruction only; sections being resurfaced are not upgraded in this manner.

Exhibit 3-2. Kinds of Improvement

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.

3.2 Effects of HERS Improvements

Each HERS improvement is simulated by changing the description of the section to reflect the changes made. Most of the effects on the "section data items" that form this description are shown in Exhibit 3-3. 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 Exhibit 3-4.

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 Exhibit 3-5.

Additional effects on substandard conditions of urban freeways are presented in Exhibit 3-6. In HERS 2.0, the changes shown in Exhibit 3-6 are implemented, if feasible, whenever a substandard urban freeway is undergoes pavement reconstruction.

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 changes in PSR and traffic volume.

Exhibit 3-3. Effects of Improvements on Section Data Items -- All Sections

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	Resurfacing W/Shoulder Improvement	Resurfacing
Widening Feasibility (1)	Reduced	Reduced	NC (8)	Reduced	Reduced	NC (8)	NC
Number of Lanes (2)	Design Number	NC	NC	Design Number	NC	NC	NC
Lane Width	DS	DS	NC (3)	DS	DS	NC	NC
Shoulder type (4)	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	Existing or MTC	NC
Right Shoulder Width (4)	DS	DS	DS (5)	DS	DS	DS (5)	NC
Pavement Condition (PSR Value) (6)	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 (7)	DS	DS	DS	DS	DS	DS	DS
Drainage Adequacy	Good	Good	Good	Good	Good	Good	Improve by 1 Code Value
Peak Capacity	Recalculate (8)	Recalculate (8)	NC (9)	Recalculate (8)	Recalculate (8)	NC (9)	NC
Volume/Capacity Ratio	Recalculate	Recalculate	NC (9)	Recalculate	Recalculate	NC (9)	NC

MTC = Minimum Tolerable Conditions, NC = No Charge, DS = Design Standard

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(1) When widening feasibility is reduced, the amount of reduction depends on the amount of widening. If unlimited widening feasibility is coded, it is not reduced.

Exhibit 3-3. Effects of Improvements on Section Data Items -- All Sections (cont.)

(2) Design number of lanes is the number of lanes needed in the design year; however, the number of lanes implemented may be limited to a lower number by a constraint on widening feasibility or by the maximum number of lanes allowed. This last number is user specified and can vary with functional class; the default values are: eight lanes on all sections in built-up urban areas and on all collectors; and ten lanes on all other arterials.

(3) For an unpaved section the improvement reconstruct pavement results in paved lane widths equal to the MTC.

(4) Curbed sections remain curbed (with zero shoulder width) after improvements.

(5) Shoulder only widened if feasible.

(6) Changes in PSR specified in Table II-14 of HPMS/AP Technical Manual.

(7) If low type pavement exists, resurfacing does not change the pavement type.

(8) No change if recalculated capacity is lower than original capacity.

(9) If the shoulders are widened, the value is recalculated.

Exhibit 3-4. 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.

Exhibit 3-5. 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.[1]
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 mph.[2]
Pavement Condition	Obtain as a weighted average of the PSR on the portion of the section with modified alignment[3] and the PSR indicated in Exhibit 3.3 for the remainder of the section.

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[1]The procedure used for determining the extent to which curves are lengthened is presented in Chapter 5.

[2]HERS contains code for adjusting weighted design speed when there is no data on curves by class, but HERS 2.0 does not consider horizontal alignment improvements when these data are not available.

[3]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.

Exhibit 3-6. Effects on Section Data Items of Addressing Substandard Conditions on Urban Freeways

Data Item	Effect
Shoulder Type	Improve to surfaced
Access Control	Improve to full control if feasible[1]
Median Type	Improve to positive barrier
Median Width	Improve to design standard if feasible[2]

[1]Improvement to full control is assumed to require one lane of right-of-way.

[2]Improvement of median width to design standard is assumed to require one lane of right-of-way.

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 regardless of their economic desirability. (These improvements, which correct "unacceptable conditions", are also referred to as "mandatory improvements".)

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.

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. Since 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

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)" to correct all existing; and
2. Identification of any less aggressive improvement types warranting B/C analysis as possible alternatives to the first, more aggressive, improvement.

These two components of the procedure are discussed below.

3.3.1.1 Aggressive Improvement Types

For each deficient section, a maximum of two "aggressive" improvement types are identified through the selection of a maximum of:

- one pavement improvement option
- two widening options
- one alignment improvement option

The procedures for selecting pavement, width and alignment options are presented in Exhibit 3-7, Exhibit 3-8, and Exhibit 3-9, respectively. These three procedures, taken together, identify a set of options that define a maximum of two improvement types. Note that HERS identifies an improvement type only when a pavement or capacity deficiency exists in the current funding period. Also, when such a deficiency exists, HERS identifies at least one improvement type, with an exception when the following set of conditions holds: the only deficiency is a capacity deficiency, 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.

Additional considerations regarding HERS' selection of improvements are:

- HERS identifies deficiencies on the basis of user-specified deficiency levels (DLs) and on the basis of user-specified serious deficiency levels (SDLs).
- HERS decides whether to repave or reconstruct on the basis of PSR at the beginning of the funding period being analyzed, assuming that the improvement can be performed early enough in the period to avoid the need for reconstruction.

Exhibit 3-7. Identification of Aggressive Pavement Option

Reconstruct if:

- PSR at the beginning of the funding period is less than reconstruction PSR;
- surface type is low and deficient, and a widening option is identified; or
- surface type is unpaved and:
  - surface type is deficient; or
  - a widening option is identified.

Otherwise resurface if:

- PSR at the end of the funding period is deficient; or
- a widening option is identified.

Exhibit 3-8. Identification of Aggressive Widening Options

1. For unpaved sections:

    a. Widen lanes if a deficiency exists in lane width or (for collectors in the lowest volume category) in sum of lane width and shoulder width.

2. For paved sections:

    a. Add lanes if lanes can be added and

        (1) more lanes are needed or

        (2) pavement requires reconstruction, and more lanes will be needed in the design year

    b. Widen lanes if lanes can be widened and

        (1) more lanes are not needed, or lanes cannot be added and

        - lane width is deficient, and PSR is deficient; or
        - design hour V/C is deficient, and capacity would be increased by widening lanes[1], 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[1], and lane width is less than the design standard, and

        - section is an urban freeway by design type; or
        - the reconstruction option has been identified solely as a result of a pavement or surface type deficiency.

    c. Otherwise, improve shoulders 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[1];

        (2) shoulder width is deficient, widening is feasible, and PSR is deficient; or

        (3) shoulder type is deficient and PSR is deficient.

N.B. "V/C is deficient" means it is deficient both now and in the design year.

[1]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 (though they may produce safety benefits not recognized by HERS). For such sections, these improvements are analyzed by HERS only if they address a "serious deficiency" (as defined subsequently in the text).

Exhibit 3-9. Identification of Aggressive Alignment Option

For rural sections:

Improve curves and/or grades if curves and/or grades by class are specified, any pavement or widening option is identified, and horizontal or vertical alignment is deficient.

For urban sections:

Improve curves if curves by class are specified, reconstruction is identified, and horizontal alignment is deficient.

Additional considerations regarding HERS' identification of improvements are:

- HERS considers both horizontal and vertical alignment improvements for rural sections and horizontal alignment improvements for urban principal arterials only if 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.)
- Under the following conditions, HERS identifies for analysis an "add lanes" option and, if appropriate, the "widen lanes" option as well: 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. This is the only situation in which two improvement types can be identified by the procedures of Exhibit 3-7 through Exhibit 3-9. HERS then uses B/C analysis to choose among the two types selected and any others identified by the procedure discussed in the next subsection.
- 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.

In HERS, decisions to reconstruct rather than to resurface are based on the PSR and, in some cases, on the adequacy of the current surface type.

3.3.1.2 Less Aggressive Alternatives

HERS has the ability to identify less aggressive improvement alternatives to the most aggressive improvement and to use B/C analysis to choose among these alternatives. In general, less aggressive improvements can be derived directly from the most aggressive improvement by selecting improvement options that are less aggressive than those identified by the procedures of Exhibit 3-7 through Exhibit 3-9:

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

Number 2 is analyzed only in relatively restricted circumstances discussed subsequently. In a given funding period, for each section examined during the second pass, HERS analyzes: only alignment improvements that bring a section up to design standards; either reconstruction or resurfacing, but not both; and usually no more than one widening option.

Replacement rules 1 and 3 involve replacing a particular option with the corresponding "zero-level" option (as defined and numbered in Exhibit 3-1). Even using only these two replacement rules for less aggressive improvements, up to six alternative improvements could be identified 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 by permitting the user to specify the circumstances in which a non-zero-level option can be replaced by a zero-level option in the generation of alternative improvements. This is done by permitting the user to specify a set of "serious deficiency levels" (SDLs). With the exception of pavement condition, there is a set of SDLs corresponding to each set of deficiency levels.

When a section has a particular characteristic that violates both a deficiency level and the corresponding serious deficiency level, any improvement option designed to address the deficiency is normally treated as "required," and the zero-level alternative is not analyzed. Further, when the capacity of a section is expected to become unacceptable (as defined in the next subsection) during the design period for improvements, a capacity improvement option is treated as a required accompaniment to the pavement improvement, regardless of whether the SDL is currently being violated. This last requirement enables HERS to avoid a situation in which capacity becomes unacceptable at a time when resurfacing (or reconstruction) is not normally performed.

Replacement Rule 2 is used only in the special case in which a non-required high-level widening option (e.g., add lanes or widen lanes) is to be incorporated into the most aggressive improvement for a given section for which a lower-level widening option (e.g., improve shoulders) is required (because of a serious shoulder-width or shoulder-type deficiency). In this case, HERS considers improvements that incorporate either the widening option of the most aggressive improvement or the highest level required widening option. Improvements incorporating widening options other than these two (or incorporating no widening option at all) are not considered.

When none of the above situations holds for a given characteristic that violates a deficiency level, but not the corresponding serious deficiency level, any improvement option designed to address the deficiency is treated as "optional," and the zero-level alternative to the option is analyzed.

If all SDLs are set equal to the corresponding deficiency levels, then normally only the "most aggressive" improvements identified by the procedure of Exhibit 3-7 - Exhibit 3-9 are analyzed. Otherwise, in at least some instances, alternatives to the "most aggressive" improvements may be analyzed. If the SDL for V/C ratio is set high and all other SDLs are set to zero, all alternatives generated by Rules 1 and 3, above, are evaluated.

The analyst has the latitude of using the DLs and SDLs to define the scope of improvements considered by HERS. Increasing the stringency of the DLs will cause the model to identify more sections as warranting examination for possible improvement. Relaxing the DLs will result in fewer sections being analyzed. Setting the SDLs equal to the DLs will cause the model to analyze fewer candidate improvements on sections warranting improvement, while relaxing the SDLs completely will prompt the model to examine the widest range of possible improvements for each section. When the SDLs are set equal to stringent deficiency levels, the model will examine the fewest alternative improvements on the smallest number of sections. Conversely, relaxed DLs and SDLs will cause HERS to evaluate and choose from a wider range of improvement alternatives. However, since evaluation of alternatives is the most time-consuming task of HERS, it may be desirable to define the deficiency levels and SDLs so as to limit the number of alternatives that HERS must consider.

3.3.2 Addressing Unacceptable Conditions: the Optional First Pass

An option is available to enable the user to identify <u>unacceptable</u> 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 3-10.

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 3-10 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 3-10 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.

[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.

Exhibit 3-10. Identification of Improvement Options for Addressing Unacceptable Conditions

1. 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:

      - Add lanes if more lanes are needed and can be added
      - Widen lanes if lanes can be widened
        - -- if lane width is unacceptable, or
        - -- if lane width is less than the design standard, and widening lanes will increase capacity, and widening shoulders will not make V/C acceptable;
      - 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,.

2. 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.

3.3.2.1 Unacceptable Conditions and the Constrained Fund Run

During a Constrained Fund run (Objective is 1), HERS uses B/C 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 B/C analysis is used to select the most economically attractive of the mandatory improvements for implementation. Those mandatory improvements not selected during the first pass will be evaluated for implementation during the second pass, but will compete (on the basis of their relative BCR values) with non-mandatory improvements for the non-reserved funds. 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 selecting improvements that are more aggressive than the inexpensive improvements selected by the procedure of Exhibit 3-10 . 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 by the procedure of Exhibit 3-10 during any funding period.

3.3.2.2 Unacceptable Conditions and the Performance Constrained Run

During a Performance Constrained run (Objective is 2), HERS uses B/C 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, the program uses B/C analysis to select the improvements with the highest B/C ratios and implements them until the desired performance level is attained. Improvements not selected are postponed until (at least) the next funding period.

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.

3.3.2.3 Unacceptable Conditions and the Minimum BCR Run

During a Minimum BCR run (Objective is 3), HERS evaluates potential improvements for all deficient sections and selects the improvement with the highest benefit/cost ratio (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. Each of these sections will be improved, either with the improvement which corrects the unacceptable condition or by a more aggressive improvement with a BCR that is above the specified minimum. In this case, as in the two above, improvements originally selected to correct unacceptable conditions are implemented regardless of their B/C ratio (unless superseded by a more aggressive improvement.)

3.4 Deficiency Criteria

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). As presented in the preceding section, the roles of these three levels in the HERS improvement-selection procedure are:

- If the DL for a particular characteristic of a section is violated, then appropriate improvements that address this condition are evaluated by the HERS benefit/cost analysis procedure and such an improvement may be selected if the resulting benefit/cost (B/C) ratio is high enough.
- If the SDL for a particular characteristic of a section is violated, then only improvements that address this condition are evaluated by the HERS benefit/cost analysis procedure.
- If the UL for a particular characteristic of a section is violated, then an improvement that addresses this condition is normally selected automatically when the correction of unacceptable conditions has been specified by the user. 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 actual values used by HERS are contained in an external ASCII file (DLTBLS.DAT) for convenient user access and modification.

3.4.1 Default Values

Suggested default values for the ULs, SDLs, and DLs for the eight section characteristics are presented in Exhibit 3-11 through Exhibit 3-18. 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 (Exhibit 3-11), 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 3-7) exist.[2]

[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.

Exhibit 3-11 through Exhibit 3-18 also show the HPMS minimum tolerable conditions[3] (MTCs) and, in several of the exhibits, the design standards (DS) for rural sections used by HERS. The corresponding design standards used for urban sections are shown in Exhibit 3-19. The design standards used for median width and for curves and grades are shown in Exhibit 3-20 and Exhibit 3-21.

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.

[3]HPMS does not provide horizontal alignment MTCs for urban sections. The suggested values shown in Exhibit 3-17 are used by HERS for statistical purposes.

Exhibit 3-11. 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	

Exhibit 3-12. Default Surface Type Criteria and Standards

UL	SDL	MTC	DL	DS†			
					Rural:		
2	2	2	2	2*		Interstate:	Flat
2	2	2	2	2*			Rolling
2	2	2	2	2*			Mountainous
2	2	2	2	2*		OPA AADT>6000:	Flat
2	2	2	2	2*			Rolling
2	2	2	2	2*			Mountainous
3	3	2	2	2*		OPA AADT<=6000:	Flat
3	3	2	2	2*			Rolling
3	3	2	2	2*			Mountainous
3	3	3	3	2*		MA AADT>2000:	Flat
3	3	3	3	2*			Rolling
3	3	3	3	2*			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	

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

* 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.

† HERS does not allow design standard of 5 (unpaved). If design standard of 5 is specified, design standard of 4 will be substituted.

Exhibit 3-13. 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	

Exhibit 3-14. Default Lane Width Criteria and Standards (feet)

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*	8*	8*	10*	10		Coll.'s AADT<400:	Flat
8*	8*	8*	10*	10			Rolling
8*	8*	8*	10*	10			Mountainous
					Urban:		
11	11	12	12			Interstate	
10	11	11	12			Other Freeway	
9	10	10	12			Other Prin. Arterial	
8	8	8	12			Minor Arterial	
8	8	8	12			Collectors	

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

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

Exhibit 3-15. 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	

Exhibit 3-16. Default Shoulder Type Criteria and Standards

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
	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	

Shoulder Type Codes:

1. Surfaced 2. Stabilized 3. Earth 4. Curbed

Exhibit 3-17. Default Horizontal Alignment Criteria

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	

Alignment Codes:

1. All curves/grades meet design standards
2. Some curves/grades below design standards
3. Curves/grades with reduced speed
4. Several curves unsafe, significant reduction of speed on grades

Exhibit 3-18. Default Vertical Alignment Criteria

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

Alignment Codes

1. All curves/grades meet design standards
2. Some curves/grades below design standards
3. Curves/grades with reduced speed
4. Several curves unsafe, significant reduction of speed on grades

Exhibit 3-19. Default Design Standards for Urban Sections

SURFACE TYPE	LANE WIDTH	SHOULDER WIDTH		
2	12	10	Freeway by design:	Built-up
2	12	10		Outlying
2	12	10	Other divided:	Built-up
2	12	10		Outlying
2	12	8	Undivided arterials:	Built-up
2	12	10		Outlying
3	12	6	Undivided collectors:	Built-up
3	12	10		Outlying

Exhibit 3-20. Default Design Standards For Median Width

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:			
16		Free/Express-way by design:		Built-up
24				Outlying

Exhibit 3-21. 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:		
8			Interstate:	Built-up
7				Outlying
8			Other Freeway:	Built-up
7				Outlying
10			Other Principal Arterial:	Built-up
8				Outlying

N.B. Curve and grade classes are defined in U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System, Field Manual, Washington, D.C., pages IV-37 and IV-39, revised July 15, 1988.

3.4.2 Discussion

The three subsections 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.

3.4.2.1 Unacceptability Levels

A review of Exhibit 3-11 indicates that the default UL values for pavement condition are slightly below the reconstruction level, and a review of Exhibit 3-12through Exhibit 3-18 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."

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. This alternative is likely to be of interest to some HERS users, but it probably does not represent an appropriate set of default values.

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 Exhibit 3-11 through Exhibit 3-18 merely represent one possible set of such values.

3.4.2.2 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 Exhibit 3-11 through Exhibit 3-18 are merely values that are tentatively suggested for use.

3.4.2.3 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 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 Exhibit 3-11 through Exhibit 3-18 are, in fact, set to the corresponding MTC values. However, to make things interesting, less stringent values are used for some SDLs. Some experimentation with the effect of SDL values on both computation time and improvements selected is clearly warranted.

3.5 Criteria for Improvement Selection

The selection of improvements to be implemented during a particular funding period is determined by a user-specified objective and the incremental benefit/cost ratio (IBCR) calculated for each potential improvement. The IBCR is the ratio of the net present value of each improvement's incremental benefits to the present value of the incremental costs. The present value of all costs and benefits is obtained by discounting the value of future costs and benefits back to the present funding period (i.e., the funding period being analyzed) using a user-specified discount rate. The Office of Management and Budget has identified seven percent as the appropriate rate for current FHWA use.

The different types of benefits and costs used in the IBCR can be weighted separately by the HERS user; e.g., agency benefits and costs can be weighted twice as heavily as highway user benefits. Also, different weights can be used for each of the ten highway functional systems distinguished by HERS. The ten functional systems are listed in Exhibit 3-22. When choosing weights for the various benefits, it is important to recognize that improvements are selected by HERS only if weighted benefits exceed cost (i.e., IBCR > 1); hence, use of weights less than one tends to reduce the set of improvements considered for implementation.

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 an IBCR greater than some specified threshold value.

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

The second form of the objective 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. 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. The goal may be specified numerically or the system can be asked to "maintain current conditions"; in the latter event, the numeric value of the goal will be derived from the highway conditions existing at the start of the run.

A request for a "full needs" analysis results in an Objective 3 run with the threshold set at $-\infty$. With this objective, all deficiencies are corrected in every funding period.

A single objective may be used for the entire highway system (exclusive of local roads and streets) or objectives may be specified separately:

- for the urban system and the rural system;
- for all principal arterials and for minor arterials and collectors;
- for urban principal arterials, for rural principal arterials, for urban minor arterials and collectors, and for rural minor arterials and collectors; or
- for each of the ten functional systems distinguished by HERS.

The ten functional systems recognized by HERS are shown in Exhibit 3-22.

Exhibit 3-22. Highway Functional Systems Distinguished by HERS

Code	Description
	Rural
01	Principal Arterial - Interstate
02	Other Principal Arterial
06	Minor Arterial
07	Major Collector
08	Minor Collector
	Urban
11	Principal Arterial - Interstate
12	Principal Arterial -- Other Freeways and Expressways
14	Other Principal Arterials
16	Minor Arterial
17	Collector

In a specific run of HERS 2.0, only one of the above forms of the objective may be used; however, for the first four funding periods, the funding constraints or overall performance goals may vary by funding period; (e.g., the budget for improvements could increase by ten percent per funding period.) In runs with more than four funding periods, HERS 2.0 uses the objectives specified for the fourth period for all subsequent funding periods.

If Objective 1 or 2 is specified, then, for each system for which separate objectives are specified, improvements are selected for implementation in the sequence indicated by their IBCRs until the objective is reached. In general, to just reach the objective, it is necessary to implement only a fraction of the last improvement; i.e., if this fraction is represented by f ($f < 1$) and the total length of all sections represented by the sample section to which this last improvement would be made is n, then HERS implements this last improvement on $f \times n$ miles of the sections represented by this sample section. To accomplish this, the sample section is replaced by a pair of sample sections: one representing sections on which the improvement is implemented and one representing sections on which it is not implemented.

4 THE BENEFIT/COST ANALYSIS PROCEDURE

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 most economically attractive improvement for this section?
- Among all sections in the highway system under analysis, which are the most economically attractive improvements? [1]

This chapter begins with a brief discussion of the IBCR equation, followed by an explanation of funding periods, benefit/cost analysis periods, and the overall analysis period. Next is a brief non-technical description of the benefit/cost analysis procedure, and the chapter concludes with a discussion of the HERS treatment of the residual value of an improvement. A more exhaustive description of the benefit/cost analysis procedure used by HERS 2.0 can be found in Appendix B.

4.1 The Benefit/Cost Ratio

An overview of the HERS incremental benefit cost/ratio (IBCR) procedure was presented in Exhibit 2-3. The HERS procedure includes estimation of the incremental costs and benefits of each potential improvement for the entire period, as well as estimation of the improvement's residual value at the end of the analysis period. The residual value of an improvement is discounted back to the initial year of the analysis period and treated as a benefit of the improvement.

[1] This question is asked only when the HERS user has set the program's objective function to either 1 or 2, placing a funding or performance constraint upon the selection of improvements. Since it is likely that not all potential improvements will be selected, HERS uses benefit cost analysis to select improvements in the order of their economic attractiveness, i.e. those with the highest IBCRs. In this case, HERS is selecting amongst improvements on different sections. Highway system means a group of sections which "compete" amongst themselves for implementation. Paragraph 3.5 discusses the objective function and highway systems.

HERS calculates the IBCR as:

$$IBCR = \frac{\left(UCost_U + ACost_U\right) - \left(UCost_I + ACost_I\right) + ResidV}{Improvement\ Cost} \tag{4.1}$$

where:

$UCost_U$	=	User costs on the unimproved section (base case) over the analysis period;
$ACost_U$	=	Agency costs on the unimproved section (base case) over the analysis period;
UCostU	=	User costs on the improved section over the analysis period;
ACostU	=	Agency costs on the improved section over the analysis period; and
ResidV	=	the discounted residual value of the improvement.

User costs include the value of the time required to travel over the section, the cost of operating a motor vehicle over the section, and the cost of safety incidents. The difference between costs on the unimproved section and the improved section constitutes user benefits. The calculation of these benefits is covered in detail in Chapter 8. Agency costs consist of maintenance costs, which are treated in Chapter 7. The way HERS calculates and uses residual value is discussed in the last section of this chapter.

4.2 Periods

In HERS, the overall analysis period (OA period) is divided into a user-specified number of funding periods. In HERS 2.0, all funding periods are user specified and of equal length. 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 OA funding periods, and extend far enough beyond the end of the OA period to permit benefit/cost analyses to be performed on all improvements that might be implemented during the OA period.

HERS performs benefit/cost (B/C) analyses on all improvements that might be implemented during each of the OA funding periods, but not on improvements that might be implemented after the end of the OA period. For purposes of the B/C analyses, HERS treats all improvements that might be implemented during a particular funding period as if they were implemented at the midpoint of the funding period. Accordingly, every benefit/cost analysis period (BCAP) extends from the midpoint of an OA funding period to the midpoint of a subsequent funding period (which can extend beyond the end of the OA period).

Exhibit 4-1 depicts the relationship between the overall analysis period, funding periods, and benefit/cost analysis periods. The exhibit shows a common HERS scenario wherein the twenty year OA period is subdivided into four funding periods each five years in length. (Years are shown along the bottom line of the exhibit.) The actual length of the post-analysis period is dynamic and is likely longer than shown in the example.

Exhibit 4-1. HERS Analytical Periods

BCAP	BCAP	BCAP	BCAP	BCAP	(etc.)
FP One	FP Two	FP Three	FP Four	FP Five	FP Six
Overall Analysis Period				Post-Analysis Period	

2.5 5 7.5 10 12.5 15 17.5 20 22.5 25 27.5 30

HERS uses benefit/cost analysis periods of varying lengths in order to accommodate section-specific situations and in response to the two different questions HERS evaluates: improve the section now? and if so, what is the best improvement? Generally, HERS uses a one funding period BCAP when evaluating whether to improve the section during the current funding period, and a longer BCAP when determining which of several candidate improvements would be the best improvement for the section. Analysis over a multi-period timeframe is more complex and requires more computation than analysis over a single period. These complexities are described in Appendix B.

4.3 A Summary of the Procedure

The estimation of incremental benefits and costs requires, among other things: the definition of a base case alternative relative to which the benefits and costs are estimated; and an analysis period, or timeframe, over which these estimates are developed. To this end, the HERS benefit/cost analysis procedure addresses, in sequence, the first two questions posed earlier:[2]

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

[2] The third question is handled by ranking potential improvements by IBCR and selecting them in order until the constraint is satisfied. See paragraph 3.5.

The phrasing of the first 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 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 of an improvement, permits frequent use of analysis periods that are only one funding period long.

First, the procedure evaluates possible improvements to a section in order to determine whether any of them warrant implementation during the funding period being analyzed. Then, if any such improvement is found, the procedure evaluates any more aggressive improvements to determine whether one of these would make a better choice. These two parts of the procedure are described briefly in the following sections. More complete details are in Appendix B.

4.3.1 Should a Section be Improved?

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; and the special case of a section with unacceptable conditions is discussed subsequently.

4.3.1.1 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 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[3], 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 2.0, 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.

4.3.1.2 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.

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[3]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).

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).

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.[4] 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 2.0 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.

4.3.2 What is the Best Improvement for the Section?

Consider a section for which the above procedure has resulted in identifying an improvement that warrants implementation in the current funding period. This improvement need 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.

To determine whether a more desirable improvement exists, HERS identifies all more aggressive improvements worth analyzing. HERS then estimates the incremental benefits and costs of implementing each improvement relative to a base case choice for implementing the improvement that was selected by the above procedure.

In general, the more aggressive improvement will incorporate some widening and/or alignment option not included in the initially selected 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

[4]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.

timeframe that ends when the section would normally next be resurfaced. In HERS 2.0, the length of this timeframe 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.[5]

There are two possible reasons why the more aggressive improvement might be the better choice for implementation in the current funding period.

- 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. If this is the case, the IBCR obtained for the more aggressive improvement (relative to the less aggressive improvement) will be higher than the B/C ratio obtained for the original improvement, and an immediate decision will be made to select the more aggressive improvement.[6]

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[5] 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.

[6] The decision as to whether or not to postpone the improvement for one period is based on the B/C ratio 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

- The above is not the case, but sufficient funds exist to gain the extra benefits of implementing the more costly improvement[7]. In this case, eventually, a decision will be made to select the more aggressive improvement instead of the less aggressive one, but not until all improvements (for all sections) with IBCRs greater than the one calculated for the aggressive improvement under consideration have been selected.

4.3.3 Length of the BCA Period -- A Summary Exhibit

Exhibit 4-2. Length of BCA Period provides a brief summary of how the last funding period of any BCA period is determined.

remaining mileage; the number of miles to be improved is determined so that the specified objective is just reached.

[7] If the analysis being performed requires the model to achieve a specific level of system performance, then improvements in this category will be implemented until that performance level has been reached.

Exhibit 4-2. Length of BCA Period

Situation Being Analyzed	Funding Period in Which BCA Period Ends
1. Section for which no improvement has yet been selected during the current funding period:	
a) If section is in unacceptable condition.	Next funding period
b) Otherwise, if current funding period is the last one in which resurfacing is practical.	Period in which condition first becomes unacceptable[1].
c) Otherwise, if traffic volume is declining and improvement involves reconstruction.	Period in which condition first becomes unacceptable[1].
d) Otherwise, if traffic volume is declining	Last period in which resurfacing is practical.
e) Otherwise.	Next funding period.
2. 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,[1] whichever occurs first.

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

4.4 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.

4.4.1 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.

4.4.2 Detailed Description of Residual Value

This section presents a formal definition of the residual value of an improvement, I_1, at the end of the benefit/cost analysis (BCA) period over which it is analyzed.

Assume that the BCA period starts at time T_1 and ends at time T_2.

First consider the case in which no improvements are likely between T_1 and T_2 regardless of whether I_1 is implemented. Then, let I_3 be the most likely improvement (if any) to be made at T_2 if I_1 is implemented at T_1. Next consider the case in which I_1 is not implemented and let I_2 be the more extensive improvement required at T_2 in order to produce the same conditions that would exist if I_1 were implemented at T_1 and I_3 were implemented at T_2. Then the residual value of I_1 at time T_2 is the cost of I_2 minus the cost of I_3. 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 I_2 involves reconstruction while I_1 and I_3 do not, the residual value of I_1 at time T_2 can be appreciably greater than the initial cost of I_1.

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, $n=T_2-T_1$). If, for example, a value of five percent is used for the discount rate, the residual value of an improvement at the end of twenty years is divided by 2.65 ($= 1.05^{20}$) to obtain its net present value.

A common special case of the above definition occurs when no improvement would normally be made at time T_2 if I_1 is implemented at time T_1. In this case, I_2 is the improvement implemented at time T_2 to produce the same conditions at T_2 that would exist if I_1 were implemented at T_1. If one or more improvements are likely between T_1 and T_2, the definition of the discounted value of residual value becomes more complex. To develop a more general definition, let A_1 be the set of improvements, if any, to be made during or at the end of the BCA period if I_1 is implemented at T_1; and let S_2 represent the resulting condition at T_2. Let A_0 be the set of improvements, if any, that would be made during the BCA period if I_1 is not implemented at T_1; and let S_3 be the resulting condition at T_2. Let I_2 be the improvement that would bring the section from condition S_3 to condition S_2. Finally, discount the costs of I_2 and of all improvements in A_0 and A_1 back to time T_1 by dividing the cost of each improvement by $(1+r)^n$, where $n = T_i - T_1$, and T_i is the year in which the improvement is implemented. Then the (net) present value of the residual value of I_1 is obtained by subtracting the discounted cost of any improvements in A_1 from the sum of the discounted cost of I_1 and the discounted cost of any improvements in A_0. 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.

5 FORECASTS OF HIGHWAY CONDITIONS

This chapter describes the HERS procedures for forecasting traffic volume data (including future average annual daily traffic (AADT) and total cumulative traffic over a specified time period), equivalent single-axle loads (ESALs), and pavement condition.

5.1 Total Traffic

HERS provides the user with the flexibility to project total traffic using one of three options, each reflecting different travel growth characteristics. As shown in Exhibit 5-1, Option 1 projects total traffic by applying a slower rate of growth in the first half of the analysis period and a faster rate of growth in the second half. Option 2 applies a linear, or constant, growth function throughout the period. Option 3 is a mirror image of Option 1 with a faster growth rate followed by a slower growth rate. Exhibit 5-1 illustrates the effects of the three growth options on a section which doubles its traffic from 5000 to 10000 vehicles per day over the twenty year period beginning in 1990. HERS implements each of these options as described below:

__Option 1__

This Option projects total traffic for a funding period by integrating under a concave travel growth curve using the following equation:

$$Total\ Traffic = 365\left(AADT_{t_0}\right)\int_{t_0}^{t_n}\left(AADTGR\right)^{t}dt \qquad (5.1)$$

where:

AADT t_n	=	AADT at year *n*
AADTGR	=	Annual growth factor
t_o	=	Base year
t_n	=	Analysis year
t	=	Length of analysis period (t_n - t_o)

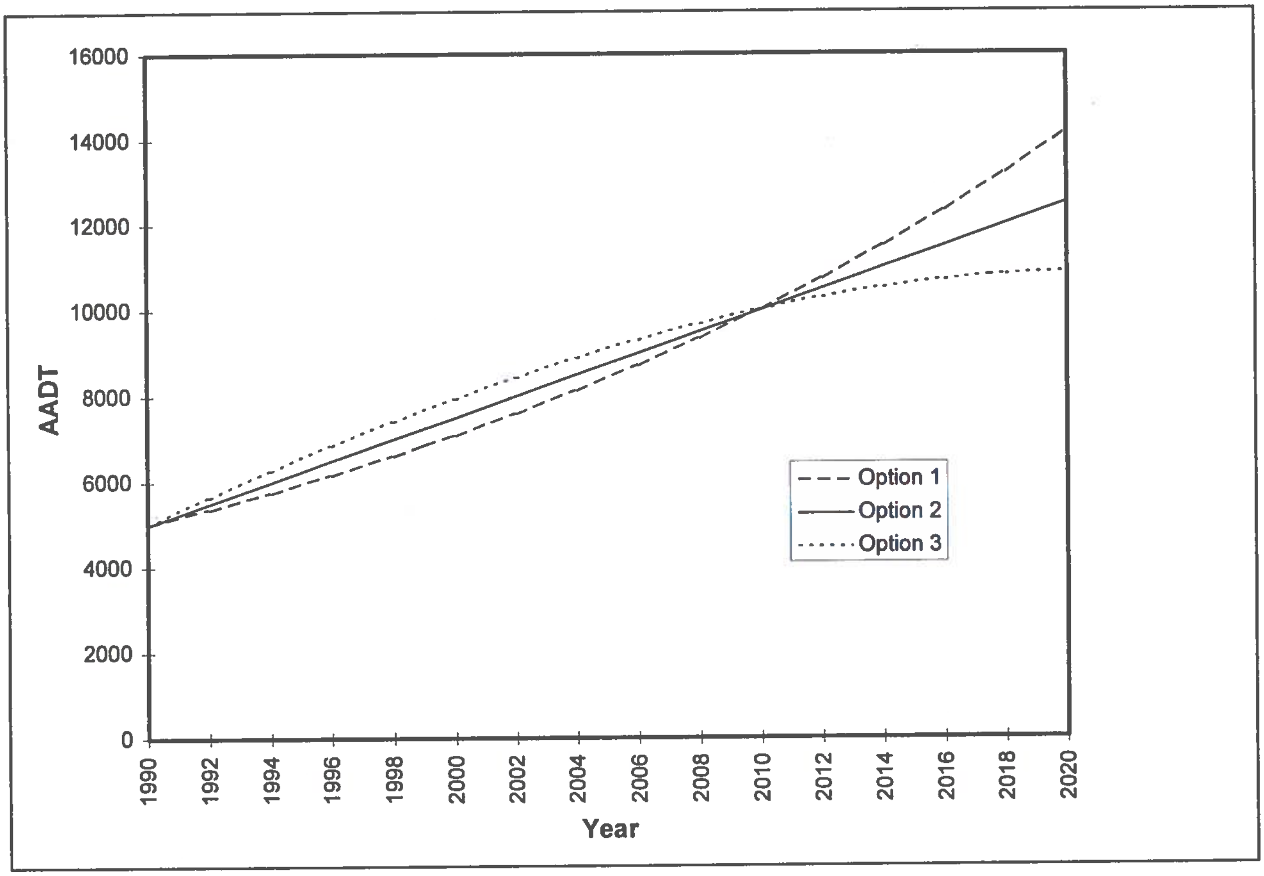
The growth factor (AADTGR) is calculated using:

$$AADTGR = \left(\frac{AADT_{t_f}}{AADT_{t_o}}\right)^{1/(t_f - t_o)} \qquad (5.2)$$

where:

t_f = Future year f with known AADT

Exhibit 5-1. Travel Growth



Option 2

This option projects total traffic for a funding period using a linear growth function as shown below:

$$Total\ Traffic = \left[\frac{(2 \times AADT_{t_o}) + (AAGRSL \times t)}{2} \right] \times 365t \tag{5.3}$$

where:

$AADT_{t_o}$	=	Base year AADT
AAGRSL	=	Straight-line growth factor
t	=	Length of analysis period (in years)

The growth factor (AAGRSL) is calculated using:

$$AAGRSL = \frac{AADT_{tf} - AADT_{to}}{t_f - t_o} \tag{5.4}$$

Option 3

This option projects total traffic for a funding period using the convex travel growth curve that mirrors the concave curve used for Option 1. This procedure utilizes the following function of Equations 5.1 and 5.3:

$$Total\ Traffic = 2\left[\frac{(2 x\ AADT_{t_o}) + (AAGRSL\ x\ t)}{2} x\ 365t\right] - 365(AADT_{t_o})_{t_o}\int^{t_n} (AADTGR)^t\ dt \tag{5.5}$$

HERS' projections of total traffic are subsequently used to determine future ESALs and pavement condition.

5.2 Average Annual Daily Traffic and V/C Ratio

HERS projects volume-to-capacity (V/C) ratios for each section based on its design-hour volume (DHV) and capacity. The DHV is calculated by applying a K-factor to the section's projected average annual daily traffic (AADT). The K-factor represents the percentage of the AADT that occurs during the design hour. A section's initial capacity is included in the HPMS database and HERS contains a subroutine that can subsequently recalculate the capacity based on the improvement options being analyzed. The HERS procedures for projecting AADT, DHV and K-factor are described below:

5.2.1 AADT Projections

HERS projects AADT by applying a growth factor to a base year AADT. As in the projection of total traffic, HERS offers three options with respect to the prediction of future AADT. These options are each derived from the travel growth curves shown in Exhibit 5-1.

Applying the concave travel growth function of Option 1, HERS projects AADT:

$$AADT_{t_n}(1) = AADT_{t_o} x\ (AADTGR)^t \tag{5.6}$$

where:

$AADT_{t_n}(1)$	=	Analysis Year AADT using Option 1
$AADT_{t_o}$	=	Base year AADT
AADTGR	=	Growth factor (from Eq. 5.2)
t	=	Length of analysis period

Assuming the linear growth function of Option 2, HERS projects AADT using:

$$AADT_{t_n}(2) = AADT_{t_o} + (AAGRSL \times t) \tag{5.7}$$

where:

$AADT_{t_n}(2)$	=	Analysis year AADT using Option 2
AAGRSL	=	Linear growth factor (from Eq. 5.4)

Applying the convex travel growth function of Option 3, HERS projects AADT using:

$$AADT_{t_n}(3) = (2 \times AADT_{t_n}(2)) - AADT_{t_n}(1) \tag{5.8}$$

A comparison of the results of these three options follows:

Using the example in Exhibit 5-1, assume:

Base year	=	1990
Future year	=	2010
Analysis year	=	2000

then:

$$AADT_{t_n}(1) = 5{,}OOO \times \left[\left(\frac{10{,}000}{5{,}000}\right)^{\frac{1}{20}}\right]^{10}$$

$$= 7{,}071$$

$$AADT_{t_n}(2) = 5{,}000 + \left(\frac{10{,}000 - 5{,}000}{20} \times 10\right)$$

$$= 7{,}500$$

$$AADT_{t_n}(3) = (2 \times 7{,}500) - 7{,}071$$

$$= 7{,}929$$

5.2.2 Peak Spreading and the V/C Ratio

HERS normally applies the existing K-factor of a section to its projected AADT to arrive at a peak, or design-hour traffic volume that is then used in the calculation of the V/C ratio. Experience has shown for urban areas, however, that as a section becomes more congested (e.g. near capacity) the peak travel demand will spread itself over a two hour to four hour peak period. This "spreading of the peak" causes the peak-hour percentage (K-factor) of total daily traffic to decrease relative to the existing K-factor. A refined procedure to address this phenomenon for urban facilities that takes into account a section's facility type, area type, number of lanes, peak-hour directional distribution, and capacity has been implemented within the HERS model.

For each funding period, HERS calculates the section's V/C ratio using the existing K-factor from the HPMS database, the projected AADT and the section's capacity, as shown:

$$\begin{aligned} &AADT \times KFAC \times DFAC = PHV \\ &PHV \,/\, Capacity = VC\text{-}ratio \end{aligned} \qquad (5.9)$$

where:

PHV	=	Peak Hour Volume
KFAC	=	K-factor
DFAC	=	Directional factor.

The directional factor (D-factor) is applied only to sections with a Rural/Urban Designation of small urban or urbanized, and for sections with more than three lanes: it is not applied to sections designated rural (as distinct from the functional class) and having fewer than four lanes.

The model re-calculates a section's K-factor when the two following conditions are met:

- Functional Class (FC) of section is either urban principal arterial-interstate (FC=11), urban principal arterial-other freeways and expressways (FC=12), other principal arterial (FC=14) or minor arterial (FC=16); and,
- V/C ratio of section computed for funding period is greater than a user-specified V/C threshold. (A threshold of 0.8 is suggested. Note that an absurdly high threshold can be specified to prevent any K-factor re-calculation.)

The re-calculation proceeds in several steps. First, the model calculates the difference (DIF) in peak hour volume between the beginning and end of the current funding period using the initial K-factor.

$$
\begin{aligned}
PHV_{t_0} &= AADT_{t_0} \times KFAC \times DFAC \\
PHV_{t_n} &= AADT_{t_n} \times KFAC \times DFAC \\
DIF &= PHV_{t_n} - PHV_{t_0}
\end{aligned}
\qquad (5.10)
$$

where:

PHV_{t0}	=	peak hour volume at the beginning of the funding period
PHV_{tn}	=	peak hour volume at the end of the funding period.

This difference (DIF) is then adjusted for the effects of peak spreading and an adjusted peak hour volume is calculated:

$$PHV_{ADJ} = PHV_{t_0} + \frac{DIF}{VC_{t_n}^{\ 2} + 2} \qquad (5.11)$$

where:

VC_{tn}	=	the VC ratio at the end of the funding period before adjustment for peak spreading

The adjusted K-factor is calculated as:

$$KFAC_{ADJ} = \frac{PHV_{ADJ}}{AADT_{t_n} \times DFAC} \qquad (5.12)$$

where:

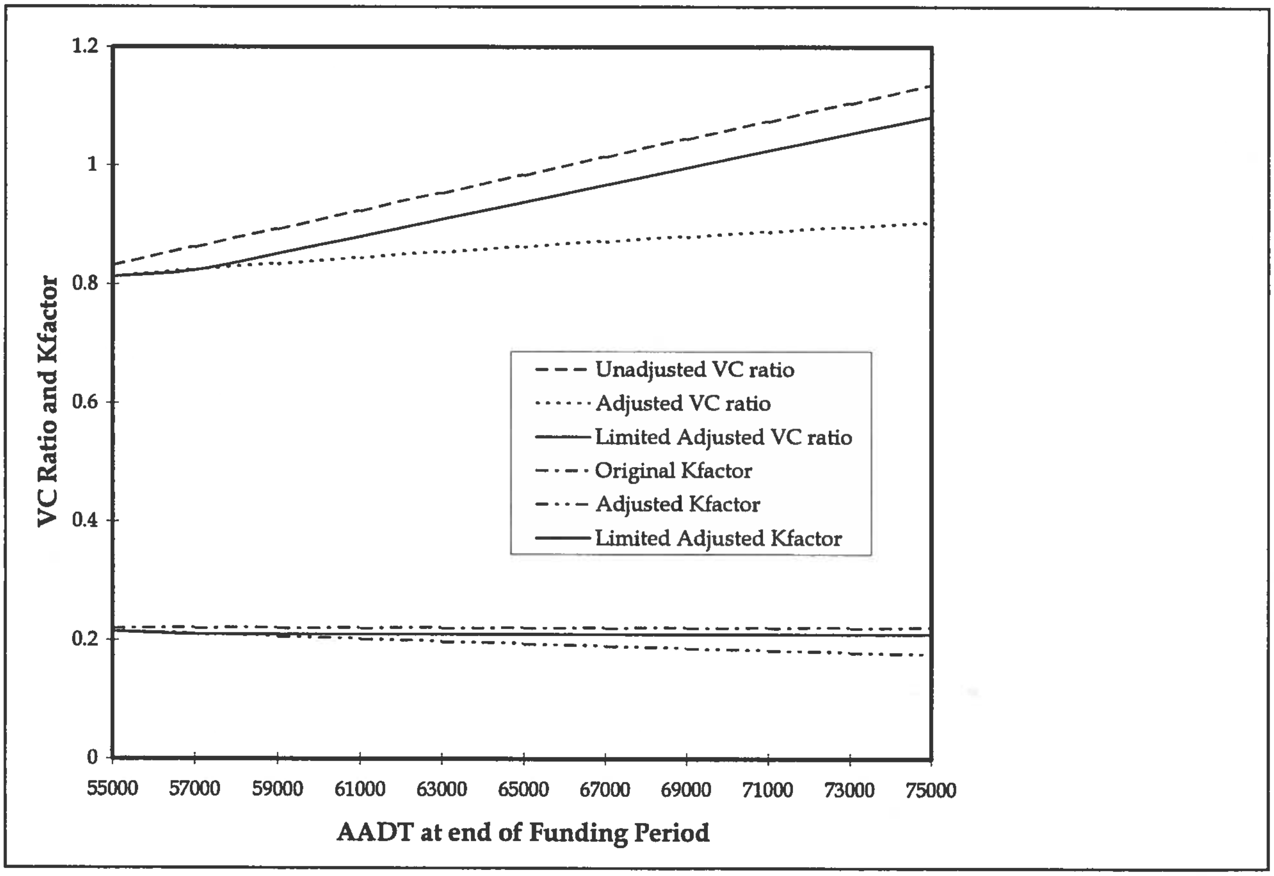
$AADT_{tn}$	=	forecast AADT at the end of the funding period.

The model then applies the following limitations to the adjusted K-factor:

- The adjusted K-factor may never be less than the lesser of 0.07 or the initial K-factor.
- The adjusted K-factor may not decline by more than 0.002 for each year of the funding period.
- The adjusted K-factor may not increase unless traffic is declining on the section.

Exhibit 5-2 shows the effect of peak spreading on an eight lane urban interstate. This section has an AADT of 53,000 at the beginning of the five year funding period. The bottom axis indicates the AADT at the end of the funding period. The bottom axis thus represents a continuum of scenarios dependent upon the rate of growth for the section. The three top lines represent the V/C ratios. The "Unadjusted" ratio demonstrates the growth in congestion without applying the peak spreading algorithm. The "Adjusted" ratio shows the results of the basic peak spreading algorithm, and the "Limited Adjusted" ratio illustrates the result of limiting the peak spreading algorithm (as discussed above: here, the second of the limitations has been enforced). The graph demonstrates that the initial effect of the algorithm is soon controlled by the limitations placed upon it.

Exhibit 5-2. Effect of Peak Spreading



The lower set of lines in Exhibit 5-2 shows the resultant K-factors passed as input to the next analysis period. The original K-factor is unchanged. The "Adjusted" but unlimited K-factor continues to decline with increased traffic growth, while the "Limited" K-factor is held within 0.01 of the original value.

5.3 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,
- percentage of vehicles on the sample section with six or more tires (referred to as percent trucks),
- 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 rural or urban location; values for this factor are given in Exhibit 5-3. 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[1] and are given in Exhibit 5-4.

Exhibit 5-3. Equivalent 18-KIP Load Applications per Truck

	Rigid		Flexible	
	Rural	**Urban**	**Rural**	**Urban**
Interstate & Other Freeways Expressways	2.122	2.192	1.398	1.478
Other Principal Arterials	2.033	1.645	1.332	1.185
Minor Arterials	1.503	1.281	1.033	0.939
Collectors	1.681	2.218	1.154	1.688

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

Exhibit 5-4. 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

HERS estimates pavement deterioration using a 50/50 average of peak and off-peak percent trucks. HERS allows the user to specify a set of annual growth factors to be applied to each section's percent trucks. Separate growth factors can be specified for each functional class. A default value of 1.005 is used for the annual growth factors for percent trucks for all functional classes.[2]

5.4 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 Exhibit 5-5 to obtain values describing the initial pavement. When the pavement is improved, procedures described in Chapter 6 are used to obtain the thickness of the overlays or of the new pavement and, for flexible pavements, a new value of SN.

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[2]Derived from 1988 and 2008 forecasts of total VMT of trucks and four-tire vehicles from Jack Faucett Associates, The FHWA/Faucett VMT Forecasting Model, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1988, Exhibits 2.18 and 3.28.

Exhibit 5-5. 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

5.4.1 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:

$$ESAL = 10^{LOGELA} \quad (5.13)$$

where:

LOGELA	=	XA + XG/XB	(5.14)
XA	=	9.36 × LOG(SNA) - 0.2	(5.15)
XB	=	$0.4 + 1094/SNA^{5.19}$	(5.16)
XG	=	LOG((5-PSRI)/(3.5 × PDRAF(PT))	(5.17)
SNA	=	$SN + \sqrt{(6 / SN)}$	(5.18)
PSRI	=	PSR at the beginning of the base year	
PDRAF(PT)	=	A user-specified pavement deterioration rate adjustment factor, normally set to one[3] 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 ESAL, substituting PSRF for PSRI in Equation 5.17, solving the above system of equations for

[3]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.

PSRF, and performing the indicated computations. Solving Equation 5.17 for PSRF produces:

$$PSRF = 5 - 3.5 \times PDRAF(PT) \times 10^{XG} \tag{5.19}$$

and solving Equations 5.13 and 5.14 for XG produces:

$$XG = XB \times \left(\mathrm{LOG}(ESAL) - XA\right) \tag{5.20}$$

5.4.2 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:

$$XA = 7.35 \times \mathrm{LOG}(D + 1) - 0.06 \tag{5.21}$$

$$XB = 1 + 16.24 \times 10^{6} \,/\, (D + 1)^{8.46} \tag{5.22}$$

where D is pavement thickness.

5.4.3 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.

5.4.4 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:

$$PSRMAX_t = PSR_{t_0} \times 0.3^{((t - t_0) / ML)} \tag{5.23}$$

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	=	(user-specified) maximum life of the section;

The use of Equation 5.23 requires knowing the time that each section was last improved (t_o) and the PSR immediately after the improvement (PSR (t_o)). 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 pavement 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 conservatively assumes that the PSR immediately following the improvement (PSR(t_o)) is the maximum possible for the improvement. In the latter case, the PSR immediately following 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.

HERS allows the user to specify maximum pavement life separately for rigid and flexible pavements for three types of pavement section (light, medium and heavy). The default values are shown in Exhibit 5-6.

Exhibit 5-6. Maximum Pavement Life Default Values (Years)

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

6 IMPROVEMENT COSTS

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.

This chapter contains four sections. The first presents the initial costs of pavement and widening improvements used by HERS 2.0, and the second presents the procedure that HERS uses for estimating pavement thickness for resurfacing and reconstruction improvements. Pavement thickness is used by HERS in estimating the cost of alignment improvements and, directly or indirectly, in estimating the rate of pavement deterioration (see the preceding chapter). Using pavement thickness to estimate the cost of pavement improvements has not been incorporated into HERS v2.0.

The third section of this chapter 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 section of this chapter presents the procedure used to estimate the improvement costs and safety benefits of correcting substandard conditions on urban freeways.

All figures for improvement costs presented in this chapter are expressed in 1993 dollars. Users wishing output expressed in another year dollars can adjust these costs individually or all costs can be adjusted uniformly using index variables. FHWA's Composite Bid Price Index for Federal-Aid Highway Construction[1] may be used as the basis for adjusting improvement costs to dollars of another year.

6.1 Pavement and Widening Improvements

HERS 2.0 distinguishes seven kinds of pavement and widening improvements (described in Exhibit 3-2). In HERS 2.0, the costs of pavement and widening improvements are in 1993 dollars and are derived from the 1993 HPMS costs. The HERS costs include both improvement and right of way (ROW) costs, but do not

[1]Office of Engineering, Federal-Aid and Design Division, Price Trends for Federal-Aid Highway Construction, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., quarterly.

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 2.0 are shown in Exhibit 6-1 (rural costs) Exhibit 6-2 (urban costs). These costs are expressed in 1993 dollars but can be scaled to any other-year dollars by the user.[2]

For 1993, the HERS 2.0 costs distinguish between adding normal and high cost lanes on urban sections only. (The output statistics reports 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.

[2] Costs shown are from the improvement cost file (IMPRCOST.DAT) used in preparation of the 1995 Conditions and Performance Report (which reports on the 1993 highway system). In this file, improvement costs are entered in 1993 dollars, although some other values are entered in 1988 dollars and indexed to 1993 dollars.

Exhibit 6-1. Initial Improvement Costs - Rural Sections

(1993)

INTERSTATE

Improvement kind	Flat	Rolling	Mountainous
Reconst. with more high cost lanes	484	566	652
Reconst. with more normal cost lanes	484	566	652
Reconst. with wider lanes	545	602	798
Pavement reconstruction	455	468	664
Major widening w/ high cost lanes	304	324	427
Major widening w/ normal cost lanes	304	324	427
Minor widening	247	265	363
Resurf. with shoulder imp.	169	178	218
Resurfacing	95	92	118

OTHER PRINCIPAL ARTERIAL

Improvement Kind	Flat	Rolling	Mountainous
Reconst. with more high cost lanes	611	631	898
Reconst. with more normal cost lanes	611	631	898
Reconst. with wider lanes	465	523	685
Pavement reconstruction	397	449	561
Major widening w/ high cost lanes	312	349	650
Major widening w/ normal cost lanes	312	349	650
Minor widening	241	266	378
Resurf. with shoulder imp.	117	128	174
Resurfacing	60	60	88

MINOR ARTERIAL

Improvement Kind	Flat	Rolling	Mountainous
Reconst. with more high cost lanes	530	577	780
Reconst. with more normal cost lanes	530	577	780
Reconst. with wider lanes	358	451	703
Pavement reconstruction	283	385	505
Major widening w/ high cost lanes	308	425	541
Major widening w/ normal cost lanes	308	425	541
Minor widening	200	210	278
Resurf. with shoulder imp.	118	120	149
Resurfacing	50	54	84

(thousands of 1993 dollars per lane mile)

Exhibit 6-1. Initial Improvement Costs - Rural Sections (cont.)

MAJOR COLLECTOR

Improvement kind	Flat	Rolling	Mountainous
Reconst. with more high cost lanes	467	511	684
Reconst. with more normal cost lanes	467	511	684
Reconst. with wider lanes	408	495	633
Pavement reconstruction	289	358	493
Major widening w/ high cost lanes	293	291	498
Major widening w/ normal cost lanes	293	291	498
Minor widening	162	170	226
Resurf. with shoulder imp.	82	90	115
Resurfacing	28	33	42

MINOR COLLECTOR

Improvement Kind	Flat	Rolling	Mountainous
Reconst. with more high cost lanes	355	381	518
Reconst. with more normal cost lanes	355	381	518
Reconst. with wider lanes	272	427	481
Pavement reconstruction	198	281	298
Major widening w/ high cost lanes	317	339	498
Major widening w/ normal cost lanes	317	339	498
Minor widening	149	166	227
Resurf. with shoulder imp.	70	76	103
Resurfacing	22	29	36

(thousands of 1993 dollars per lane mile)

Exhibit 6-2. Initial Improvement Costs - Urban Sections (1993)

FREEWAYS AND EXPRESSWAYS

Improvement kind	Cost
Reconst. with more high cost lanes	4103
Reconst. with more normal cost lanes	2817
Reconst. with wider lanes	2066
Pavement reconstruction	1265
Major widening w/ high cost lanes	4121
Major widening w/ normal cost lanes	2915
Minor widening	1227
Resurf. with shoulder imp.	367
Resurfacing	170

OTHER DIVIDED

Improvement Kind	Cost
Reconst. with more high cost lanes	2594
Reconst. with more normal cost lanes	1556
Reconst. with wider lanes	1272
Pavement reconstruction	721
Major widening w/ high cost lanes	2898
Major widening w/ normal cost lanes	1826
Minor widening	676
Resurf. with shoulder imp.	251
Resurfacing	114

OTHER UNDIVIDED

Improvement Kind	Cost
Reconst. with more high cost lanes	1810
Reconst. with more normal cost lanes	1006
Reconst. with wider lanes	1106
Pavement reconstruction	659
Major widening w/ high cost lanes	2138
Major widening w/ normal cost lanes	1363
Minor widening	716
Resurf. with shoulder imp.	219
Resurfacing	130

(thousands of 1993 dollars per lane mile)

6.2 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 Chapter 5, SN is used as one of the influences on the deterioration rate of flexible pavement, and the deterioration rate of rigid pavement depends directly on pavement thickness. In HERS 2.0, only 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, in HERS 2.0, modifying this variable will affect pavement thickness (and hence pavement durability), but 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.

6.2.1 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 2.0 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 Exhibit 6-3 as are thicknesses for reconstruction of rigid (Portland cement concrete) pavements. For low-type flexible pavement, only a surface treatment is used.

Exhibit 6-3. Pavement Thickness for Reconstruction (inches)

	Pavement Type	
Forecast ESALs over design life	Flexible[1,2,3]	Rigid[4]
≤ 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

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

[2]Thickness shown for flexible pavements are also used for resurfacing flexible pavements with a flexible overlay.

[3]For low-type pavement, assume a surface treatment only.

[4]E.J. Yoder and M.W. Witczak, Principles of Pavement Design, John Wiley, New York City, 1975.

6.2.2 Simple Resurfacing

HERS assumes that resurfacing is always performed using a flexible overlay. For flexible overlays over flexible or composite pavement, the overlay thickness used by HERS vary with traffic load in the same way as for reconstruction with flexible pavement. These thicknesses are shown in Exhibit 6-3.

For flexible overlays over rigid pavement, overlay thickness is a function of pavement slab length (i.e., pavement joint spacing) and the "annual temperature differential," defined as the difference between the average high temperature for the hottest month of the year and the average low temperature for the coldest month of the year. For these pavements, overlay thickness is given by:

$$D = \text{MAX}(4, 0.0026 \times T + 0.0033 \times T \times L) \qquad (6.1)$$

where:

D = overlay thickness (inches);
T = temperature differential (degrees Fahrenheit); and
L = slab length (feet)

Equation 6.1 was obtained by regression using tabular data from the AASHTO Guide for Design of Pavement Structures.[3] For continuously reinforced concrete, HERS uses a slab length of 40 feet for L.

The HERS model references a file of temperature differentials, by state and county, developed for use in Equation 6.1. The temperature differentials are defined as the difference between the mean high temperature for the warmest month of the year and the mean low for the coldest month. The values used were obtained from National Oceanographic and Atmospheric Administration data[4] for observation points throughout the country. For states for which there is little variation in the temperature differential (generally defined as up to four degrees Fahrenheit) across observation points, a single average value is used for the entire state. For other states, counties are grouped into sub-state regions on the basis of geographical and climatological characteristics (location of mountain ranges, proximity to water, etc.), and separate values are used for each such region. Exhibit 6-4 shows the geographical pattern of the temperature differentials used. A complete list of these temperature differentials, by state and county, is presented in Appendix A.

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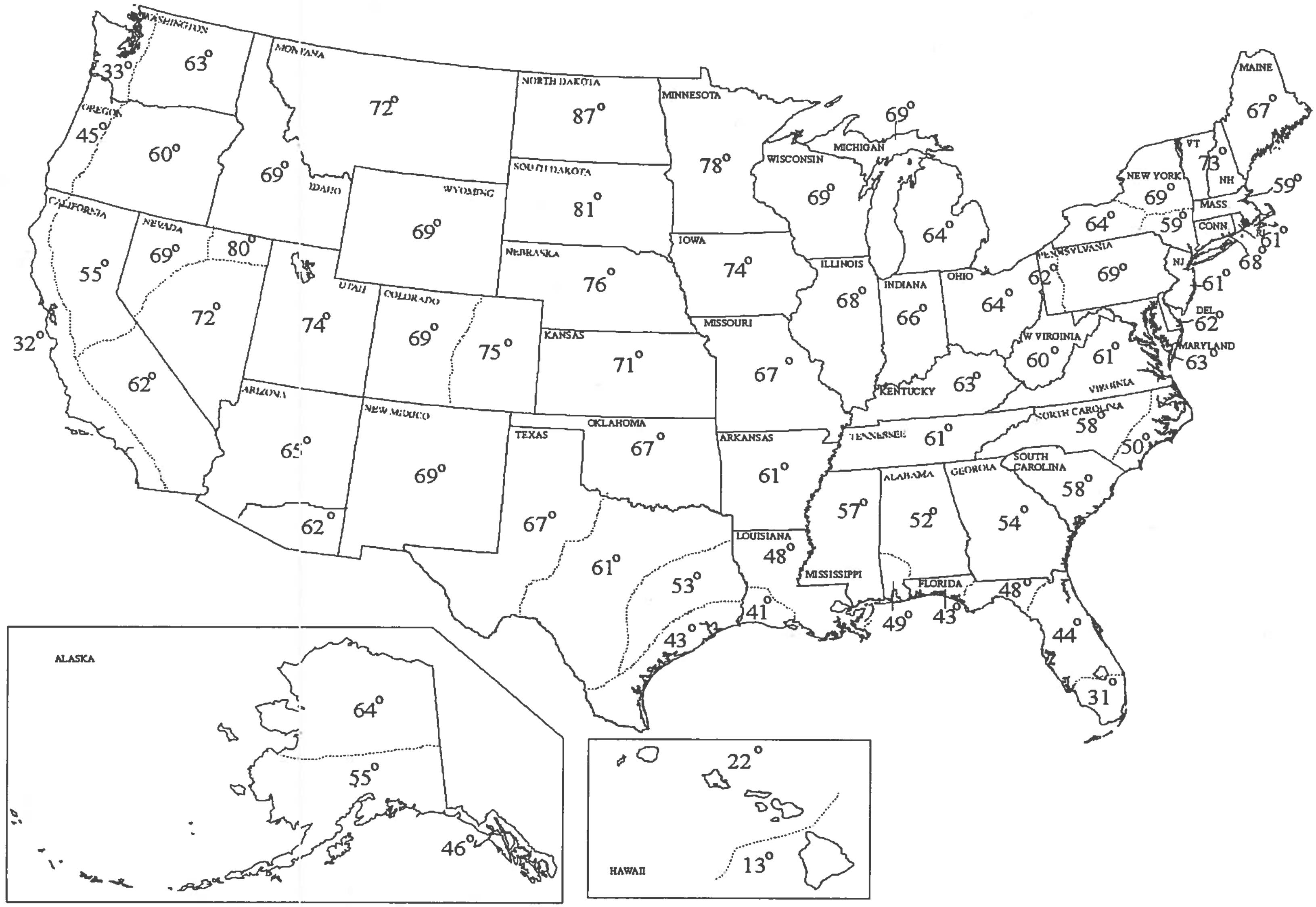
[3]American Association of State Highway and Transportation Officials, Guide for Design of Pavement Structures, Washington, D.C., 1986.

[4]National Oceanographic and Atmospheric Administration, Local Climatological Data: Annual Summary with Comparative Data, Asheville, North Carolina, 1987.

Exhibit 6-4. Annual Temperature Differentials



6.2.3 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.

6.2.4 Structural Number

HERS 2.0 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[5]. This equation is:

$$SN = 1.5 + 0.75\ D_f \qquad (6.2)$$

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.

6.3 Alignment Improvements

In HERS, any of the pavement and widening improvements listed in Exhibit 3-1, Improvement Options, 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. 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[6].

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[5]U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Field Manual, Washington, D.C., Table IV-2, December 1, 1987.

[6]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.

6.3.1 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 Exhibit 3-21). 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 (see Exhibit 3-21). The total length of these segments before improvement is denoted LVERT, and the corresponding length after improvement is denoted LAFTV. In HERS 2.0, LAFTV is taken to be equal to LVERT.

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 2.0, the former effect is ignored, while the latter effect is estimated by calculating LAFTH:

$$LAFTH = \mathrm{MIN}\left(SLEN,\ \sum_{I} \frac{C_i}{C^*} L_i\right) \tag{6.3}$$

where

SLEN	=	original length of the section (miles);
Li	=	total length of curves in class i;
Ci	=	average curvature of curves in class i;
C*	=	average curvature of curves in class that just meets the designed 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.[7]

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.

6.3.2 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 1993 dollars, used by these procedures are shown in Exhibit 6-5[8], and parameter values used in Equations 6.4-6.7 are shown in Exhibit 6-6. 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 they may be converted individually using the component indexes for excavation, structures, surfacing with Portland cement concrete, and resurfacing with bituminous concrete.[9]

6.3.2.1 Clearing and Grubbing

Site preparation consists of clearing and grubbing. The total cost of clearing and grubbing, TCCG, is estimated:

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[7]The HERS variables LBOTH, LAFTV and LAFTH correspond to the quantities L_{both}, ($L_{after(v)}$ - L_{both}), and ($L_{after(h)}$ - L_{both}), respectively, in the Cambridge Systematics report (op. cit., pp. 4-2 through 4-4).

[8] The costs shown in Exhibit 6-5 are expressed in 1993 dollars. In the improvement cost file, they are entered in 1988 dollars, and are converted to 1993 dollars by applying a factor of 1.02.

[9] U.S. Department of Transportation, Federal Highway Administration, Office of Engineering, Price Trends for Federal-Aid Highway Construction, Washington, D.C., quarterly. The composite index (but not the component indexes) is also published in U.S. Department of Commerce, Bureau of Economic Analysis, Survey of Current Business, U.S. Government Printing Office, Washington, D.C., monthly.

$$TCCG = PCG(1,terrn) \times RW^{PCG(2,terrn)} \times UCCG \times LNEW \tag{6.4}$$

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(i,terrn)	=	estimated parameters that vary with terrain type.

Exhibit 6-5. Unit Costs Used for Alignment Cost Computation

(1993 dollars)

Clearing and Grubbing	$ 1.47 per square yard
Earthwork: Flat terrain Rolling terrain Mountainous terrain	 $ 4.69 per cubic yard 4.69 5.51
Drainage: Narrow pipe culverts Wide pipe culverts Small box culverts Wide box culverts	 $ 55.92 per foot 112.13 507.63 1193.80
Structures	$748,322 each
Guard rails and curbs: Curbed median or shoulder Guard rail or concrete median Guard rail at shoulder	 $126,376 per mile 156,550 152,794
Fencing	$ 80,378 per mile
Lighting	$ 558,952 per mile

Exhibit 6-5. Unit Costs Used for Alignment Cost Computation (cont.)

Painting of Traffic Lanes (per mile) Number of Lanes			
2	4	6	8
$14,778	$24,508	$31,710	$35,810

Pavement Costs (per square yard)			
Layer Thickness (inches)	Aggregates	Asphaltic Concrete	Portland Cement Concrete*
2		$4.97	
3		5.79	
4	$3.30	7.89	
6	4.78	11.61	$14.98
7			17.33
8	6.34	16.30	18.85
9			20.56
10			23.50
12	9.52		27.42
13	11.40		
15			33.29

Surface treatment (for light pavement sections): $ 1.73
*Continuously reinforced concrete: Add $ 6.31

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 1993 dollars by applying a factor of 1.02.

Exhibit 6-6. Parameter Values for Alignment Cost Computation

	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

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.

6.3.2.2 Earthwork

For flat terrain (terrn = 1), total earthwork costs, TCEW, are estimated:

$$TCEW(1) = PEW(1,1) \times RW^{PEW(2,1)} \times \left[PEW(3,1) + WET \times PEW(4,1)\right] \times UCEW(1) \times LNEW \tag{6.5}$$

and total earthwork costs for rolling or mountainous terrain are estimated:

$$TCEW(i) = UCEW(terrn) \times PEW(1,terrn) \times RW^{PEW(2,terrn)} \times \left\{ \begin{array}{l} \left[PEW(3,terrn) + e^{PEW(4,terrn) \times \left[ARGV - PEW(5,terrn)\right]}\right] \\ + \left[PEW(3,terrn) + e^{PEW(4,terrn) \times \left[ARGH - PEW(5,terrn)\right]}\right] \\ \times (LAFTH - LBOTH) \end{array} \right\} \tag{6.6}$$

where:

WET	=	1 in wet climate zones 0 in other climate zones
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 = 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 = average road gradient of all segments that currently meet the design standard; and
PEW(i,terrn)	=	estimated parameters that vary with terrain type.

6.3.2.3 Drainage

Total cost of drainage culverts, TCDR, is estimated:

$$TCDR = \left[ANBC(terrn) \times UCBC(s) + ANPC(terrn) \times UCPC(s)\right] \times PDR(1,terrn) \times RW^{PDR(2,terrn)} \times LNEW \qquad (6.7)$$

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 (small or large);
UCPC(s)	=	unit cost of pipe culverts (dollars per mile) by size (narrow or wide); and
PDR(i,terrn)	=	estimated parameters that vary with terrain type.

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.

6.3.2.4 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:

$$TCSTR = \frac{NSTR}{SLEN} \times LNEW \times ACSTR \qquad (6.8)$$

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).

6.3.2.5 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[10]), 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 Exhibit 6-3, and the structural number (SN) is obtained from Equation 6.2 (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 ≤ 3.0), medium (3.0 < SN ≤ 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 Exhibit 6-7[11].

The total cost of pavement, TCP, for the portion of the section being reconstructed is then estimated:

$$TCP = 1760 \times PW \times [\sum_{i=1}^{I} UCPL(i,t)] \times LNEW \qquad (6.9)$$

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.

The costs per square yard of aggregate, asphaltic concrete, and Portland cement concrete layers are shown in Exhibit 6-5 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 and the extra cost per square yard for continuous reinforcement of rigid pavements; this last cost is used only for sections that were coded as having continuously reinforced pavement prior to the improvement.

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[10] See Exhibit 3.12.

[11] The pavement-section-type classification and the thicknesses assumed for the base and sub-base are from the HPMS Field Manual, Table IV-2, December 1987.

Exhibit 6-7. Thickness of Base and Sub-base of Reconstructed Sections

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"

Source:

U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System, Field Manual, Washington, D.C., Table IV-3, August 30, 1993.

6.3.2.6 Right-of-Way

Total right-of-way costs, TCROW, are estimated:

$$TCROW = NL \times UCROW(i,j,k) \times LNEW \qquad (6.10)$$

where UCROW are unit costs for right-of-way (in dollars per lane-mile). For rural areas (i=1), these costs are specified by functional system and terrain type; and for urban areas (i=2), by facility type and location type. The unit costs for right-of-way, in 1993 dollars, are shown in Exhibit 6-8[12]. They may be converted to dollars of another year using the appropriate R.S. Means index.[13]

[12] The costs shown in Exhibit 6-8 are expressed in 1993 dollars. In the improvement cost file, they are entered in 1988 dollars, and are converted to 1993 dollars by applying a factor of 1.02.

[13] R.S. Means Company, Inc., Means Heavy Construction Cost Data, Kingston, MA, annual.

Exhibit 6-8. Unit Costs of Right-of-Way for Alignment Improvements
(thousands of 1993 dollars per lane-mile)

Rural Sections			
	Terrain		
	Flat	Rolling	Mountainous
Interstates	$ 74	$ 66	$ 59
Other Principal Arterials	66	59	53
Minor Arterials	61	53	46
Major Collectors	59	51	46
Minor Collectors	53	46	41

Urban Sections		
	Location	
	Built-Up	Outlying
Freeways and Expressways	$ 464	$ 186
Other Divided Roads	418	168
Other Undivided Roads	377	153

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. Adjusted to 1988 dollars by applying a factor of 0.96; 1988 dollars adjusted to 1993 dollars by applying a factor of 1.02.

6.3.2.7 Miscellaneous Costs

Miscellaneous costs estimated by HERS consist of the costs of guard rails and curbs, fencing, lighting, and the painting of traffic lines[14]. Total miscellaneous costs, TMC, are estimated:

$$TMC = LNEW \times i = \sum_{i=1}^{5} UMC(i,j) \qquad (6.11)$$

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:

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.
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.
3. Fencing is assessed for urban freeways only.
4. Painting of traffic lines (j = Number of Lanes/2).
5. Lighting is assessed for urban sections only.

6.3.3 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, and miscellaneous costs (from Equations 6.4 - 6.11). The latter cost is obtained by multiplying the cost per lane-mile for the pavement and widening improvements (Exhibit 6-1 and Exhibit 6-2) 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).

[14] See Exhibit 6-5.

6.3.4 Effect 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 2.0 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 2.0 uses the relative length of the two portions of the section to determine whether to treat the section as having rigid or composite pavement.

6.4 Correcting Substandard Conditions on Urban Freeways

HERS distinguishes four improvements to eliminate substandard conditions on urban freeways:

1. Improving shoulder type to surfaced
2. Improving access control to full
3. Improving median type to positive barrier[15], and
4. Improving median width to design standard.

Improvement costs for each are estimated using the cost data in Exhibit 6-9[16]. HERS 2.0 will only upgrade these conditions on urban freeways which have substandard conditions and are being reconstructed.

[15] As defined in the HPMS Field Manual, "A positive barrier would normally consist of a guard-rail or concrete, but could consist of a line of closely-spaced (large) trees or of thick, impenetrable shrubbery on most of the section". For the purpose of implementation into HERS, a concrete (Jersey) barrier is considered a positive barrier.

Exhibit 6-9. Improvement Costs - Substandard Urban Freeways

(thousands of 1993 dollars per lane-mile)

Improvement Type	Built-up	Outlying
1. Shoulder Type to be Surfaced	$ 184	$ 154
2. Access Control to Full	464	186
3. Median Type to Positive Barrier	136	122
4. Median Width to Design Standard	606	316

Assumptions:

1. Cost for improving shoulder type to surfaced is taken as the difference between costs of resurface with shoulder improvement and resurface for urban freeways (Exhibit 6-2).
2. Improving access control to full assumes cost of one additional lane right-of-way (Exhibit 6-8).
3. Median barrier costs were derived from recent work[1] and adjusted to 1988 dollars for consistency. Cost for outlying areas is assumed at 90 percent of that for built-up area.
4. Median width to design standard is taken as the combination of one additional lane of right-of-way (Exhibit 6-8) and the cost for resurfacing (Exhibit 6-2).

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[1]McNally, M.G. and Merheb, O., "Impacts of Jersey Median Barriers on the Frequency and Severity of Freeways Accidents", AAA Foundation for Traffic Safety, Washington, D.C., 1991.

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[16] The costs shown in Exhibit 6-9 are expressed in 1993 dollars. In the improvement cost file, they are entered in 1988 dollars, and are converted to 1993 dollars by applying a factor of 1.02.

7 AGENCY BENEFITS

For agencies in charge of building and maintaining highways, HERS recognizes two potentially accruing benefits resulting from improving a highway section:

1. a reduction in the cost of routine maintenance resulting from resurfacing or reconstruction of pavement; and
2. 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 in Chapter 4. This chapter presents the HERS 2.0 procedure for estimating the other type of agency benefit: reductions in maintenance costs.

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.

7.1 Maintenance Costs for Flexible Pavements

Estimates of maintenance costs per lane-mile for flexible pavements have been developed by Witczak and Rada[1] as a function of PSR and structural number (SN). Their results are presented in Exhibit 7-1. The first column of this exhibit 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 second 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.

[1]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.

Exhibit 7-1. Maintenance Costs for Flexible Pavements

(1984 Dollars)

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

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

Regressing the values for cumulative maintenance costs shown in Exhibit 7-1 against the values for PSR (or PSI) and SN yields the following equation:

$$COST = 4427.24 - 1989.7\ PSR + 223.57\ PSR2 + 7996.11\ SN - 3594.56\ SN \times PSR + 403.99\ SN \times PSR^2 \quad (7.1)$$

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 indicated final PSR. The R2 for the above equation exceeds 0.9999.

Equation 7.1 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.[2]

To estimate maintenance costs per lane-mile on any section during a period beginning at time t and ending at time t+k, Equation 7.1 is evaluated using the section's PSR at times t and t+k, and the difference between the two results is obtained. The general form of the HERS 2.0 equation to provide this result, MCOST, in 1988 dollars, is:

$$MCOST = -\ (2411 + 4355\ SN)\ (PSR_{t+k} - PSR_t) + (270.9 + 489.6\ SN)\left(PSR^2{}_{t+k} - PSR^2{}_t\right) \quad (7.2)$$

These costs can be adjusted to dollars of another year by using the Cost Index for Highway Maintenance and Operation.[3] A factor of 1.02 was used to index the 1988 dollars to 1993 dollars for use in the 1995 Conditions and Performance Report.

7.2 Maintenance Costs for Rigid Pavements

In the absence of readily available information about maintenance costs for rigid pavements, HERS 2.0 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 2.0.

[2]U.S. Department of Transportation, Federal Highway Administration, Highway Statistics: 1988, U.S. Government Printing Office, Washington, D.C., 1989, Table PT-5.

8 USER BENEFITS

This chapter presents descriptions of HERS procedures for estimating user benefits resulting from improvements. User benefits are generally measured as cost savings that result from decreases in travel time, operating costs, and crashes.

This chapter contains four major sections. The first presents the HERS speed model, which determines the average effective speed of traffic accross a section. The final three sections provide the HERS procedures for estimating user benefits. The second section describes the calculation of benefits due to reductions in travel time; the third discusses benefits due to reductions in operating costs; and the last section addresses the estimation of the number and severity of crashes and the resultant user benefits. HERS 2.0 does not produce estimates of fuel consumption or emissions impacts.

8.1 The HERS Speed Model

For purposes of analysis, highway sections are characterized either as "unrestricted-flow facilities" (i.e., facilities with no stop signs or traffic signals), or as "restricted-flow facilities." For "unrestricted-flow facilities," unconstrained speed represents average speed. For "restricted-flow facilities," unconstrained speed represents an estimate of the average speed that would exist in the absence of stop signs and traffic signals.

This section contains two parts. The first presents the HERS procedure for estimating "unconstrained speed"; i.e., the average speed that would exist in the absence of stop signs and traffic signals. The second part presents the procedure for modifying these estimates to reflect the effects of speed-change cycles and stop cycles, thus producing the average effective speed across "restricted flow facilities".

8.1.1 Unconstrained Speed and the APLVM

The HERS procedure for estimating unconstrained speed is based on the Texas Research and Development Foundation (TRDF) adaptation[1] of the "Aggregate Probabilistic Limiting Velocity Model" (APLVM), one of four related procedures originally developed by the World Bank.[2] The APLVM uses aggregate data in estimating the effects of curves and grades on speed. All speed estimates developed in

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[1]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.

[2]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.

this and the next section are developed separately for each of seven vehicle types for each of twelve volume/capacity ratios. For all sections, HERS obtains separate estimates of unconstrained speed for the two directions of travel.[3]

The HERS version of APLVM involves a five-step procedure; the first four of which involve the computation of four "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 four limiting velocities[4] are:

VDRIVE	=	maximum possible driving speed;
VCURVE	=	maximum allowable speed on a curve;
VROUGH	=	maximum allowable ride-severity speed; and
VMISC	=	maximum speed resulting from speed limits, safety concerns, and congestion.

In APLVM, the dominant role in the determination of unconstrained speed[5] is played by the smallest of the limiting velocities. 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 unconstrained speed tends to be negligible.

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

[3]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.

[4]The fourth limiting velocity, VMISC, is a replacement for a factor called "desired speed" (VDESIR) by the World Bank and TRDF. 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.

[5]The World Bank and TRDF use the term "steady-state speed," or V_{ss}, to refer to unconstrained speed.

8.1.1.1 Estimating Velocity Limited by Grades

VDRIVE represents the maximum driving speed attainable. It is a potential constraint on relatively flat sections, as well as those with positive grades and is a significant constraint wherever grades are relatively large.

VDRIVE is a function of vehicle characteristics and average grade. To obtain VDRIVE, an estimate[6] is made of the speed, VD1, that will eventually be obtained on a section with constant nonnegative grade where the only constraint on vehicle speed is the vehicle's ability to overcome gravity and air and rolling resistance:

$$VD1 = (d^{1/2} + b)^{1/3} - (d^{1/2} - b)^{1/3} \quad (8.1)$$

where[7]:

$$d = b^2 + c^3$$

$$b = 73{,}907 \frac{HP}{C \times AR} (mph)^3$$

$$c = 133.4 \frac{GVW \times (GR + CR)}{CD \times AR} = e \times (GR + CR)(mph)^2$$

GR	=	average grade of section (fraction)
GVW	=	gross vehicle weight (lbs)
AR	=	frontal area of vehicle (sq. ft.)
CD	=	coefficient of air drag
HP	=	maximum available driving horsepower[8]
CR	=	coefficient of rolling resistance (intercept[9]).

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[6]See Watanatada, et al., op. cit., pp. 51-52 and 78-79.

[7]The formulas for b and c are derived from:

$$b = \frac{736\,HP}{2a} (m / sec)^3$$

$$c = \frac{1}{3a} GVW \times g \times (GR + CR)\ (m / sec)^2$$

where

$$a = 0.5\ rho \times CD \times AR$$

$$rho = density\ of\ air = 1.2\ kg / m^3$$

[8]It should be noted that, as a result of internal power losses, maximum available driving horsepower is less than rated engine horsepower.

[9]Rolling resistance is actually a linear function of velocity; i.e., it is of the form CR1 + CR2 × V. However, the second term is negligible at the speeds of interest. Accordingly, the World Bank sets CR = CR1 and ignores CR2.

TRDF provides estimates of GVW, AR, CD, HP and CR for the 1985 and 1990 in-use vehicle fleets.[10] The estimates for these parameters for the 1990 fleet are shown in Exhibit 8-1, along with values for b and e derived from these estimates. The parameter values are shown for the seven vehicle types that are distinguished by HERS.[11]

For trucks operating on sections with positive grades, VD1 represents vehicle crawl speed. If a truck enters a section from a section with zero or negative grade, the truck will initially be travelling at a speed in excess of VD1 and will only gradually slow to VD1. Thus, for sections with positive grades, the truck's average speed on a section may well be greater than VD1. For all arterial sections, with the exception of urban minor arterials, a weighted average value of grade can be obtained from detailed data on grades by class contained in the HPMS database.[12] For all collectors and for urban minor arterials, typical values of grade are produced by existing HPMS/AP software using vertical alignment adequacy and type of terrain.

To correct for this situation, HERS 2.0 assumes a 50 percent probability that trucks will enter such sections at crawl speed and an equal probability that they will enter at a.higher speed, VENTR. For the latter case, HERS 2.0 also adopts the assumption that deceleration is uniform and that trucks travel 3000 feet (0.5682 miles) before crawl speed is reached. Given these assumptions, the final speed for this case, V_f, is estimated:

$$V_f = \begin{cases} VENTR - \dfrac{SLEN}{0.5682} \times (VENTR - VD1) & \text{if } SLEN < 0.5682 \\ VD1 & \text{otherwise} \end{cases} \qquad (8.2)$$

where:

VENTR	=	speed when entering a section with a positive grade from a downhill or level section;
SLEN	=	length of section (miles).

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[10]Except for values of GVW, AR and CD for automobiles, the two sets of estimates are identical.

[11]TRDF presents separate estimates for medium and large automobiles. To improve computational efficiency, these two size classes are treated as a single vehicle type in HERS. TRDF parameters for medium autos (which are about ten times as numerous as large autos) are used for medium/large autos.

[12]Since the HPMS database does not contain information on the direction of grade, it is assumed that all grades are positive for vehicles traveling in one direction and negative for vehicles traveling in the opposite direction. For sections which actually have a mix of positive and negative grades in one direction, this assumption may result in overestimating the effect of the grades on speed (i.e., in underestimating unconstrained speed).

HERS relates entrance speed to the speed limit[13]:

$$VENTR = SPDLIM + DVENTR \tag{8.3}$$

where:

SPDLIM	=	speed limit; and
DVENTR	=	a user-specified delta with a default value of 5 mph.

Average speed, VD2, on an uphill section entered at speed VENTR is estimated as:

$$VD2 = \frac{SLEN}{TIME} \tag{8.4}$$

[13]Alternative specifications considered for VENTR were setting it equal to VDRIVE for sections with zero grade or to unconstrained speed for such sections. The former alternative produces too high a value (77 mph for five-axle combination trucks); while the latter alternative ignores the common practice of speeding up before entering a speed-limiting upgrade. Also, these two alternatives, and particularly the second, would be computationally less efficient than Equation 8.3.

Exhibit 8-1. Parameters for Use in Estimating Driving Speed

Vehicle Class	GVW Gross Vehicle Weight (lbs.)	AR Frontal Area (sq.ft.)	CD Air Drag Coef.	HP Horse Power	CR Rolling Resistance Coefficient Intercept	b	e
1. Small Autos	2,790	20.7	0.31	93	0.0125	1,071,000	58,000
2. Medium/Large Autos	3,700	22.3	0.35	140	0.0125	1,326,000	63,200
3. Four-Tire Trucks	5,000	30.8	0.59	175	0.0160	711,700	36,700
4. Six-Tire Single-Unit Trucks	12,000	36.9	0.70	230	0.0076	658,000	62,000
5. Three-Axle Single-Unit Trucks	35,000	55.0	0.70	275	0.0076	528,000	121,300
6. Four-Axle Combination Trucks	50,000	90.0	0.80	325	0.0076	334,000	92,600
7. Five-Axle Combination Trucks	62,500	90.0	0.80	325	0.0076	334,000	115,800

where TIME is the time required to traverse the section and is given by:

$$TIME = \begin{cases} \dfrac{SLEN}{\frac{1}{2}(VENTR + V_f)} & \text{if } SLEN < 0.5682 \\[2ex] \dfrac{0.5682}{\frac{1}{2}(VENTR + VD1)} + \dfrac{SLEN - 0.5682}{VD1} & \text{otherwise} \end{cases} \qquad (8.5)$$

For the vehicle parameters of Exhibit 8-1, the entrance speed correction presented in Equations 8.2 -8.5 is potentially significant for medium and heavy trucks (vehicle types 4-7) but not for automobiles or four-tire trucks. This correction is included in the HERS estimates of VDRIVE for medium and heavy trucks, despite the increased computational requirements, but excluded from the estimates for automobiles and four-tire trucks. Accordingly, for positive grades, HERS obtains VDRIVE:

$$VDRIVE = \tfrac{1}{2}(VD1 + VD2) \qquad (8.6)$$

where:

VD1 is given by Équation 8.1; and
VD2 is set equal to VD1 for automobiles and four-tire trucks and given by Equation 8.4 for other vehicle types.

For negative grades, VDRIVE is set to VD1 as given in Equation 8.1, with the restriction that d is never allowed to become negative.[14]

8.1.1.2 Estimating Velocity Limited by 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:

$$VCURVE = \sqrt{(FRATIO + SP) \times g \times RC} \qquad (8.7)$$

where:

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

[14]In theory, a different equation is required when d is negative. However, for such grades, VDRIVE is never an important limiting velocity; and so, for simplicity, HERS uses Equation 8.1 with d set to zero.

The remaining variable in Equation 8.7, 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 2.0 uses these values.

Replacing radius of curvature in Equation 8.7 by degrees of curvature (DC) and converting the equation to estimate VCURVE in miles per hour produces:

$$VCURVE = 292.5 \times \sqrt{(FRATIO + SP) \times \frac{1}{DC}} \qquad (8.8)$$

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 softare 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:

$$SP = \begin{cases} 0 & for DC \leq 1 \\ 0.1 & for DC \geq 10 \\ & otherwise: \\ 0.0318 + 0.0972 \times \ln(DC) - 0.317\,DC + 0.007\,DC \times \ln(DC) \end{cases} \qquad (8.9)$$

This equation was derived by regression from a table presented by Zaniewski[15], but fits so well ($R^2 = 0.9999$) as to suggest that it may be the equation that was used to derive the values in the table.

8.1.1.3 Estimating Velocity Limited by Pavement Roughness

The effect of pavement roughness on speed is represented by VROUGH.

Descriptions of pavement characteristics corresponding to the various PSRs are presented in Exhibit 8-2. A review of these descriptions indicates that pavement condition begins to become a limiting factor on high speed roads at approximately the

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[15]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.

Exhibit 8-2. Pavement Condition Rating

PSR & Verbal Rating	Description
5.0 Very Good 4.0	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.
Good 3.0	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.
Fair 2.0	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.
Poor 1.0	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.
Very Poor 0.0	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.

Source:

U.S. Department of Transportation, Federal Highway Administration, Highway Performance Monitoring System Field Manual, Washington, D.C., December 1987, p.IV-28.

boundary between the good (3.0 to 4.0) and fair (2.0 to 3.0) ratings, suggesting a value of 60 mph for VROUGH when PSR = 3.0. Similarly, the descriptions appear to suggest 40 mph as an appropriate value for VROUGH when PSR = 2.0. These observations suggest the following linear formula for VROUGH:

$$VROUGH = 20\ PSR \tag{8.10}$$

Unfortunately, when PSR drops to zero (which can occur in HERS when funds are short), this formula produces a speed of zero. To allow the user to avoid this condition, and also 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. More specifically, HERS 2.0 uses the function:

$$VROUGH = \begin{cases} VR1 + (VR2 - VR1) \times \frac{PSR}{PSRB} & \text{if } PSR \leq PSRB \\ VR2 + VRSLOP \times (PSR - PSRB) & \text{if } PSR > PSRB \end{cases} \tag{8.11}$$

where:

VR1	=	value of VROUGH when PSR is zero;
VR2	=	value of VROUGH when PSR = PSRB (the breakpoint)
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	=	20

For PSR below 2.5, the default values produce intentionally lower estimates of unconstrained speed than either the current AP procedure or that proposed by TRDF. For PSR = 1.5, they produce VROUGH = 30 mph, while TRDF's formula would produce values of 48 mph for automobiles and 44 mph for large trucks,[16] and the AP procedure would permit speeds of 49 mph. On the basis of the preceding discussion, 30 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.

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[16]The TRDF formulas are:

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

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

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 VRSLOP are set to their default values, VROUGH for unpaved sections is 20 mph); the user may change this PSR value if desired.

For HERS 2.0, the same formula for VROUGH is used for all vehicle classes. Using Brazilian data, the World Bank study[17] 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.

8.1.1.4 Estimating Velocity Limited by Other Factors

A fourth limiting velocity in the World Bank procedure is VDESIR, which stands for "desired speed." VDESIR is meant to be set to the speed that would be used on straight, flat, smooth roads on which hills, curves, pavement roughness and engine horsepower have no limiting effect. Conceptually, VDESIR represents the effects of speed-limit enforcement and concern about fuel economy, vehicle wear and safety.

TRDF proposes equating VDESIR with what HPMS calls "initial running speed" (IRS). IRS is a function of the facility type, number of lanes, speed limit, volume/capacity (v/c) ratio, and "weighted design speed;"[18] for two-lane rural roads, IRS is also a function of passing sight distance. The "weighted design speed" of a section is estimated by obtaining the design speed for each curve and each straight stretch and obtaining an appropriately weighted average of these speeds.

Except for the effect of curves, the factors reflected in the AP estimates of IRS are not reflected in any of the limiting velocities used in the World Bank procedure. Three alternatives exist for incorporating these factors into HERS estimates of unconstrained speed:

1. The use of IRS in addition to VCURVE, as suggested by TRDF. (This would have the undesirable effect of depressing the estimate of unconstrained speed when the values of IRS and VCURVE are similar and lower than those of VDRIVE and VROUGH.)

2. The use of IRS instead of VCURVE.

3. The elimination of the effect of curves from the tables for IRS.

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

[18]HPMS' tables for initial running speed use the term "average highway speed" to mean "weighted design speed."

Of these three alternatives, the last appears to be the most desirable. The VCURVE equation is a continuous function of the radius of curvature while, for each facility type, the IRS tables only reflect the effect of curves through a small number of weighted design speeds (six for two-lane rural roads and three for all other facility types). VCURVE is also appreciably easier and faster to derive. Accordingly, as a fourth limiting velocity, HERS uses the speed obtained from the IRS tables for sections with no curves (i.e., for high values of weighted design speed[19]). To avoid undesirable discontinuities in the estimates of this limiting velocity, for two-lane rural roads, piecewise linear interpolation is used to make IRS a continuous function of passing sight distance.

This fourth limiting velocity can be seen to reflect the effects of speed limits, safety concerns, and congestion. Since congestion produces a most undesired limit on speed, the World Bank name, VDESIR, is inappropriate for this limiting velocity. Accordingly, in HERS it has been renamed VMISC.

For any given highway section, separate values of VMISC are obtained (from the IRS tables) for each of twelve different V/C ratios.[20] These values are then used to obtain corresponding values of unconstrained speed which, in turn, are used to obtain values of average effective speed, travel time, and operating costs using procedures presented below.

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[19]With one pair of exceptions, the IRS tables used are those for the highest value of weighted design speed (WDS). The exceptions are for urban two and three lane streets and urban one way streets. For these streets, the IRS tables produce unrealistically high speeds when the V/C ratio is low.

For these streets, HERS uses modified versions of the IRS tables for WDS > 40 mph. In the case of urban one-way streets, the modification is obtained for each speed-limit range by limiting IRS to no greater than the corresponding value of IRS for uncongested four-or-more-lane urban streets with WDS 40 mph and the same speed-limit range. For urban two and three lane streets, the modification is obtained by limiting IRS to at least 3 mph less than the corresponding value of IRS for uncongested four-or-more-lane urban streets with WDS 40 mph and the same speed-limit range. The 3 mph difference in IRS values for uncongested streets is the same as the difference that exists between the IRS tables for rural two and three lane roads and for rural roads with four or more lanes.

[20]It has been found that reducing from eight to four the number of v/c ratios used to represent all v/c ratios between 0.0 and 0.8 has a significant effect on results. However, it has since been postulated that, because congestion generally has relatively little effect on speed when the v/c ratio is below 0.7, a better result might have been obtained with a more limited collapsing of the number of v/c ratios. Any collapsing that does not have a significant effect on results would be desirable.

8.1.1.5 Determining Unconstrained Speed

The general formula for estimating unconstrained speed, USPD, is:

$$USPD = \frac{\exp(\sigma^2 / 2)}{((1/VDRIVE)^{\frac{1}{\beta}} + (1/VCURVE)^{\frac{1}{\beta}} + (1/VROUGH)^{\frac{1}{\beta}} + (1/VMISC)^{\frac{1}{\beta}})^{\beta}} \quad (8.12)$$

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[21] used Brázilian 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 USPD equation, TRDF recommended a value of 0.1 for all vehicle classes.[22]

In Equation 8.12, 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[23] for σ^2 are between 0.007 and 0.036; and TRDF[24] suggests using 0.01. The effect of these values for σ^2 is a small upward adjustment in USPD (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 8.12 becomes:

$$USPD = ((1/VDRIVE)^{10} + (1/VCURVE)^{10} + (1/VROUGH)^{10} + (1/VMISC)^{10})^{-0.1} \quad (8.13)$$

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[21]Watanatada <u>et al.</u>, <u>op. cit.</u>, Table 4.3(a), p. 85.

[22]Elkins, <u>et al.</u>, <u>op. cit.</u>, p. 156.

[23]Watanatada <u>et al.</u>, Table 4.3(c), p. 86. The reference uses σ_e^2 to represent our σ^2.

[24]Elkins, <u>et al.</u>, <u>op. cit.</u>, p. 156.

where VDRIVE is given by Equation 8.6 for uphill travel and by Equation 8.1 for downhill travel, VCURVE and VROUGH are given by Equations 8.8 and 8.11, and VMISC is given by the HPMS tables for initial running speed for high values of weighted design speed. For sections with two-way traffic, this procedure produces different values of USPD for the uphill and downhill directions; both values are retained by HERS for use in all subsequent calculations.[25]

Equation 8.13 produces estimates of unconstrained 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.

8.1.2 The Effects of Speed-Change and Stop Cycles

Once unconstrained speed has been estimated, to obtain an estimate of average speed, the effects of speed-change and stop cycles must be determined. The HERS procedures for accomplishing this are based in part on TRDF procedures.[26] Separate procedures are used for unrestricted-flow facilities and for restricted-flow facilities. The two procedures are presented in the sections that follow.

8.1.2.1 Unrestricted-Flow Facilities

The HERS estimates of unconstrained speed (USPD) represent average travel speed on an unrestricted-flow facility. For these facilities, HERS sets the average effective speed[27] (AES) to USPD and then performs a more extensive analysis to produce estimates of the extent to which actual speeds vary about this average. The analysis involves the estimation of the maximum and minimum speeds[28] for each cycle and the number of

[25]For automobiles and four-tire trucks, when the Exhibit 8.1 parameters are used in conjunction with the HERS1 values for VMISC, VDRIVE is never a significant limiting velocity. To reduce computation time, HERS 2.0 calculates VDRIVE and USPD for these vehicle types for the uphill direction only and uses only this value in subsequent computations. The appropriateness of this computational shortcut should be re-evaluated if changes are made in either the Exhibit 8.1 parameters or the VMISC values.

[26]G.C. Elkins, et al., op. cit., pp. 182-192 and pp. 42-49.

[27]The term "average effective speed" corresponds to a variable called average travel speed (ATS) by TRDF. We choose to reserve the term average travel speed to refer to an average obtained while excluding idling time (i.e., average speed while traveling), though the procedures presented here do not use average travel speed.

[28]The maximum and minimum speeds are referred to by TRDF as start and final speeds (of the deceleration phase of the cycle).

cycles required to traverse the section - information that is required by the subsequent analysis of operating costs and fuel consumption.

8.1.2.1.1 Estimating Maximum Speed

TRDF proposes setting the maximum speed of each cycle equal to the unconstrained speed that exists in the absence of congestion. A review of the HPMS Initial Running Speed (IRS) Tables,[29] however, indicates that this assumption would lead to excessive fluctuations in speed for some facilities.[30] For HERS 2.0, the maximum speed of a cycle is set to the unconstrained speed obtained when the volume/capacity ratio (v/c) is reduced according to the following rules:

Reduce by 0.2	if $0.25 < v/c < 0.9$
Reduce to 0.05	if $v/c < 0.25$
Reduce to 0.75	if $v/c > 0.9$

These rules produce maximum speeds whose relationship to average speed depends on congestion. When congestion is not a significant constraint on speed, the maximum and average speeds can be almost identical. On the other hand, when congestion is the most binding constraint, the rules produce maximum speeds somewhat higher than average speed (typically by about 3 to 5 mph) when congestion is low to moderate, and substantially higher than average speed (by as much as 20 or 25 mph) when congestion is high. The overall effect is to produce estimates of substantial benefits for increasing capacity on congested sections, but only if congestion is the most significant constraint on speed.

The HERS 2.0 procedure produces estimates of maximum speed that are more realistic than the TRDF procedure, but it warrants further review, especially for facilities with low speed limits.

8.1.2.1.2 Estimating Minimum Speed

The minimum speed of each speed-change cycle is derived so that, in conjunction with estimates of strong acceleration and strong deceleration, the average effective speed over the cycle is equal to the original estimate of unconstrained speed. TRDF estimated (strong) deceleration for all vehicle types as 11,880 mph per hour (3.3 mph/sec.) for

[29]HPMS Technical Manual, Appendix N.

[30]For very congested freeways and expressways with speed limits of 50 mph or more, the fluctuations would be between zero mph and a speed exceeding the speed limit.

speeds in excess of 30 mph, and 19,800 mph per hour (5.5 mph/sec.) for speeds below 30 mph.

TRDF estimated (strong) acceleration using the equation:

$$ACCEL = A - B \times V \tag{8.14}$$

where V is the velocity (speed) of the vehicle and A and B are parameters that vary by vehicle type. In this formulation, A represents maximum acceleration attained (assumed to be attained at zero speed), while A/B represents the maximum attainable speed. The values of A and B used in HERS 2.0 are shown in Exhibit 8-3, along with the corresponding maximum attainable speed (in mph).

Exhibit 8-3. Acceleration Coefficients

	A ($ft./sec^2$)	A (mph/hr)	B (1/sec.)	B (1/hr.)	Maximum Speed (mph)
Small Autos	7.2	17,672.3	0.060	216.0	81.8
Medium Autos	8.6	21,108.5	0.076	273.6	77.2
Four-Tire Trucks	7.9	19,390.4	0.070	252.0	76.9
Two-Axle Six-Tire Trucks	2.8	6,872.5	0.026	93.6	73.4
Larger Trucks	1.8	4,418.1	0.016	57.6	76.7

Source:

Adapted from 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, Table 7. The 0.07/sec. value for B shown for four-tire trucks has been reduced from 0.08/sec.

The parameter values shown in Exhibit 8-3 are the same as those proposed by TRDF[31] with one exception: the value of B for four-tire trucks has been changed,[32] from 0.08 to 0.07. This change is necessary to produce a maximum attainable speed for these vehicles that is greater than the highest value of VMISC contained in the IRS Tables (a computational requirement of the procedure). The higher maximum attainable speed for four-tire trucks is also more in line with those for automobiles (though all values shown in Exhibit 8-3 for maximum attainable speed appear to be somewhat low).

Exhibit 8-3 shows values for A expressed in both feet/sec.^{2} (as originally presented by TRDF) and in mph/hr. Similarly, the values for B are expressed in both 1/sec. (as originally presented by TRDF) and in 1/hr. To avoid unnecessary conversion between units, HERS performs all computations using miles, hours and mph.

The TRDF assumptions do not permit a closed-form solution to be obtained for minimum speed. Instead, TRDF used the following numerical procedure: for each vehicle class, average effective speed (AES) was derived for various combinations of maximum and minimum speed; and equations for minimum speed over the cycle (CSMIN) were then estimated by regression using AES and maximum speed (CSMAX) as the independent variables. The resulting equations for the minimum speed of a cycle for each vehicle type are presented in Exhibit 8-4[33]. In HERS[34] the values of CSMIN produced by these equations are replaced by:

[31]TRDF also provides parameters for "large autos." HERS1 uses all parameters and equations presented by TRDF for "medium autos" for both medium and large automobiles. With this convention, HERS avoids the need to split the HPMS category of medium and large automobiles and computation time is reduced somewhat. Furthermore, since there are now virtually no truly large automobiles being manufactured, this category will be of decreasing significance in forecast years.

[32]Although one value of B used in Equation 8.14 and also used in several subsequent equations derived from Equation 8.14, has been modified, some more complex equations presented by TRDF that were apparently derived using the original value of B have not been modified; these are the four-tire truck equations for the minimum speed of a speed-change cycle and for excess operating costs due to speed-change cycles.

[33]As observed above, the equation for four-tire trucks in Exhibit 8.7 was derived by TRDF using a value of 0.08/sec. for B (rather than the 0.07/sec. value shown in Exhibit 8.6).

[34]Some of the equations in Exhibit 8-3 have a tendency to produce unreasonably small (and even negative) values for AES - CSMIN when CSMAX - AES becomes small. TRDF simply states that the equations in the exhibit are not valid when CSMAX - AES < 2.5 mph, but they do not provide an alternate procedure for this situation.

$$CSMIN = AES - \frac{(CSMAX - AES)}{2} \quad \text{whenever} \quad CSMIN > AES - \frac{(CSMAX - AES)}{2} \tag{8.15}$$

If the above procedure produces a negative value for CSMIN, it is replaced by zero and idling time occurs. The HERS procedure does not require the calculation of idling time, although it could be readily derived if needed.

8.1.2.1.3 Number of Speed-Change Cycles

For unrestricted-flow facilities with speed-change cycles with low to moderate amplitude, HERS 2.0 assumes a cycle duration, CTIME, of one minute. The distance traveled during such a cycle, TDIST, is obtained by multiplying the average effective speed over the cycle by the duration of the cycle:

$$TDIST = CTIME \times AES \tag{8.16}$$

It should be noted that, for cycles with low to moderate amplitude, a cycle duration of one minute allows for acceleration and deceleration at rates that are much lower than those used for strong acceleration and strong deceleration in the preceding subsection.[35] For cycles with amplitudes that are high in relation to maximum speed, however, completion of a cycle within one minute by trucks with six or more tires (vehicle types 4-7) requires acceleration and deceleration rates greater than those used in thepreceding subsection. For such cycles, HERS estimates TDIST using a formula derived by assuming that vehicles are always accelerating or decelerating at the rates presented in the preceding subsection. This equation is:

$$TDIST = -\frac{1}{B}(CSMAX - CSMIN) + D1 \times CSMAX^2 - D2 \times CSMIN^2 - D3 - \frac{A}{B^2}\ln\frac{A - B \times CSMAX}{A - B \times CSMIN} \tag{8.17}$$

where D1, D2 and D3 are parameters whose values depend upon the relationship between the maximum and minimum speeds over the cycle and the assumed 30 mph breakpoint in the rate of deceleration. The values of these parameters are given in Exhibit 8-5.

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[35]For fluctuations between 58 mph and 60 mph, the assumption that an automobile is always either accelerating or decelerating at the rates presented in the preceding section leads to a cycle duration of two seconds. For smaller fluctuations, the cycle duration is proportionately smaller.

Exhibit 8-4. Equations for Estimating the Minimum Speed of a Speed-Change Cycle for Unrestricted-flow Facilities

Small Autos:

$CSMIN = 0.1386 + 2.480\ AES - 1.301\ CSMAX - 0.00233\ CSMAX^2$

$R^2 = 0.996$ $S_y = 1.38$

Medium Autos:

$CSMIN = -0.05708 + 2.533\ AES - 1..287\ CSMAX - 0.00339\ CSMAX^2$

$R^2 = 0.994$ $S_y = 1.75$

Four-Tire Trucks:

$CSMIN = 0.3493 + 2.463\ AES - 1.300\ CSMAX - 0.00265\ CSMAX^2$

$R^2 = 0.995$ $S_y = 1.31$

Two-Axle Six-Tire Trucks:

$CSMIN = -0.0447 + 2.496\ AES - 1.297\ CSMAX - 0.00319\ CSMAX^2$

$R^2 = 0.994$ $S_y = 1.38$

Larger Trucks:

$CSMIN = -0.1226 + 2.463\ AES - 1..272\ CSMAX - 0.00302\ CSMAX^2$

$R^2 = 0.995$ $S_y = 1.28$

NOTES:

CSMIN	=	Minimum speed of speed change cycle (mph)
CSMAX	=	Maximum speed of speed change cycle (mph)
AES	=	Average effective speed (mph)

Source:

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, Table 30 (p.189).

For cycles with high amplitudes, the duration of the cycle, CTIME, is obtained by dividing the distance traveled by the average effective speed over the cycle:

$$CTIME = \frac{TDIST}{AES} \tag{8.18}$$

More precisely, for vehicle types 4-7, HERS evaluates Equations 8.17 and 8.18 for all speed-change cycles. When Equation 8.18 produces a cycle duration of more than one minute, the cycle is considered to have high amplitude (for that vehicle type), and the results of those two equations are used for CTIME and TDIST. For vehicle types 1-3 (four-tire vehicles), and for other vehicle types when Equation 8.18 produces a cycle duration of less than one minute, CTIME is set to one minute and TDIST is obtained from Equation 8.16.

Exhibit 8-5. Parameter Values for Use in Equations for TTIME and TDIST

Parameter	Max. Speed > 30mph Min. Speed >30mph	Max. Speed > 30mph Min. Speed < 30mph	Max. Speed < 30mph Min. Speed < 30mph
D1	4.2×10^{-5}	4.2×10^{-5}	2.53×10^{-5}
D2	4.2×10^{-5}	2.53×10^{-5}	2.53×10^{-5}
D3	0	0.0152	0
T1	8.4×10^{-5}	8.4×10^{-5}	5.05×10^{-5}
T2	8.4×10^{-5}	5.05×10^{-5}	5.05×10^{-5}
T3	0	0.00101	0

The expected number of speed-change cycles occuring while a given section is traversed, NSCC, is obtained by dividing the section length by the distance covered in one cycle:

$$NSCC = \frac{SLEN}{TDIST} \tag{8.19}$$

8.1.2.2 Restricted-Flow Facilities

The estimates of unconstrained speed produced by the APLVM procedure do not reflect the effects of stop signs or traffic signals. For a facility with stop signs and/or traffic signals, maximum speed (CSMAX)[36] is set to the estimate of unconstrained speed or, if the stop signs are too closely spaced for this speed to be attained, maximum speed is derived from the stop-sign spacing and the acceleration and deceleration formulas. For all restricted-flow facilities, the minimum speed (CSMIN) is set to zero. Estimates of the average effective speed (AES) over a section of a restricted-flow facility and the average number of stop cycles occurring are obtained by analyzing the effects of the stop signs and traffic signals on distance traveled in a given time period.[37] The analysis first addresses the effects of stop signs and then those of traffic signals.

8.1.2.2.1 Estimating the Effect of Stop Signs

Each stop sign is assumed to result in deceleration from the maximum speed (CSMAX) to a full stop followed immediately by acceleration back to CSMAX. Deceleration and acceleration rates are assumed to be the same as on unrestricted-flow facilities. For each vehicle type, the distance traveled during such a stop cycle, TDIST, is derived from CSMAX and the assumed deceleration and acceleration rates. This distance is given by:

$$TDIST = -\frac{1}{B}\,CSMAX \times D1 \times CSMAX^2 - D3 - \frac{A}{B^2}\ln\left(1 - \frac{B}{A}\,CSMAX\right) \qquad (8.20)$$

An initial estimate of TDIST is obtained by assuming CSMAX equals USPD. The average distance between stop signs (ADSS) is then obtained by dividing the section length (SLEN) by the number of stop signs (NSTOP). If the initial estimate of TDIST is no greater than ADSS, the section is said to have "widely spaced" stop signs. For such sections, CSMAX is set to USPD and the initial estimate of TDIST is used.

If the initial estimate of TDIST is greater than ADSS, the section is said to have "closely spaced" stop signs. For such sections, CSMAX is set to the maximum speed that can be attained between a pair of stop signs ADSS miles apart by a vehicle accelerating from rest at the first stop sign and coming to a full stop at the second sign, where acceleration is specified by Equation 8.14 and deceleration is determined by the TRDF procedure

[36]It should be noted that, for restricted-flow facilities, unconstrained speed is at least equal to maximum speed, while, for unrestricted-flow facilities, unconstrained speed is used as an estimate for average effective speed.

[37]These assumptions differ from those used by TRDF. TRDF uses the speed estimates produced by the APLVM procedure as estimates of AES (which they call ATS) and they then derive higher estimates of maximum speed. The latter estimates are 40 to 70 percent(!) higher than the speed estimates produced by the APLVM procedure and appear to be independent of the number of stop cycles required to traverse the section.

presented immediately above Equation 8.14. For each vehicle type, the resulting formula for CSMAX is:[38]

$$CSMAX(vt) = MAXSPC(1,vt) \times ADSS + MAXSPC(2,vt) \times ADSS^2 + MAXSPC(3,vt) \times ADSS^4 + MAXSPC(4,vt) \times ADSS^{1/2} + MAXSPC(5,vt) \times ADSS^{2/3} + MAXSPC(6,vt) \times ADSS^{3/2} \quad (8.21)$$

where MAXSPC(i,vt) is a set of maximum speed coefficients whose values are shown in Exhibit 8-6. The resulting values of CSMAX are then used in Equation 8.20 to obtain new values of TDIST.

The duration of the stop cycle, TTIME, is then derived:

$$TTIME = T1 \times CSMAX - T3 - \frac{1}{B}\ln(1 - \frac{B}{A}CSMAX) \quad (8.22)$$

The delay caused by each such cycle, SDELAY, is given by:

$$SDELAY = TTIME - \frac{TDIST}{CSMAX} \quad (8.23)$$

Finally, the average speed adjusted for stop-sign cycles (SSCSPD) is obtained:

$$SSCSPD = \frac{SLEN}{\frac{SLEN}{CSMAX} + NSTOP \times SDELAY} \quad (8.24)$$

where:

SLEN	=	the length of the section and
NSTOP	=	the number of stop signs on the section.

For restricted-flow sections without stop signs, SSCSPD is set to USPD for use in the traffic signal analysis that follows.

[38]Equation 8.21 was derived in two steps. First, for each vehicle type, Equation 8.20 was used to obtain the distance traveled for 63 values of maximum speed (1, 1.5, 2. 2.5, ..., 8.5, 9, 10, 11, ..., 55). For each vehicle type, regressions were then performed using maximum speed as the dependent variable. For each vehicle type, Equation 8.21 produced an R^2 of 1.0.

Exhibit 8-6. Coefficients for Calculating Maximum Speeds on Sections with Closely Spaced Stop Signs

Vehicle Type	MAXSPC(i,vt)					
	i=1	i =2	i=3	i=4	i=5	I=6
1. Small Autos	443.892	1508.579	-1730.031	171.864	-154.805	-1361.147
2. Medium Autos	421.878	1731.147	-2342.358	166.929	-125.943	-1471.421
3. Four-Tire Trucks	442.101	1589.452	-1927.134	174.004	-151.585	-1408.247
4. Two-Axle, Six-Tire Trucks	57.499	155.001	-41.822	109.922	-35.680	-193.464
5. Three+Axle Single-Unit Trucks	24.422	59.029	-8.174	90.890	-22.111	-86.654
6. Three & Four-Axle Combinations	24.422	59.029	-8.174	90.890	-22.111	-86.654
7. Five+Axle Combinations	24.422	59.029	-8.174	90.890	-22.111	-86.654

8.1.2.2.2 Estimating the Effect of Traffic Signals

The HERS 2.0 procedure for analyzing the effects of traffic signals presumes that all signals are synchronized but not staggered. For sections on which signals are staggered, the procedure thus tends to overestimate the effects on travel time and costs. A separate capability for analyzing the effects of staggered signals would be a desirable future improvement for HERS.

The procedure distinguishes between sections with "closely spaced" traffic signals and those with "widely spaced" signals.[39] The two types of sections are distinguished on the basis of whether or not the average spacing between signals is greater than the distance that a vehicle can travel (at its average effective speed before adjustment for signals) during the red period of a signal cycle; i.e., a section has "widely spaced" signals if:

$$\frac{SLEN}{NSIG} > SSCSPD \times RTIME \tag{8.25}$$

where:

SLEN	=	section length;
NSIG	=	number of signals on the section;
RTIME	=	red time; and
SSCSPD	=	average speed after adjustment for stop signs.

SSCSPD is obtained from Equation 8.23 or, for sections without stop signs, set equal to USPD. SLEN and NSIG are obtained from the HPMS database. RTIME is derived from an assumed average signal cycle of 90 seconds (0.025 hours) and the typical peak-hour percentage green time. For urban sections, this last quantity is contained in the HPMS database; for rural sections HERS assumes the percentage of green time is equal to: 65% for principal arterials, 50% for minor arterials, and 35% for collectors.

8.1.2.2.2.1 Estimating the Effect of Closely Spaced Signals

For closely spaced traffic signals it is assumed that all vehicles stop once every signal cycle. The distance traveled over any cycle consists of the distance traveled during the red period plus that traveled during the green period. For such sections, the average distance traveled during the red period, RDIST, is estimated as being half the average spacing between signals:

$$RDIST = \frac{SLEN}{2 \times NSIG} \tag{8.26}$$

For sections with closely spaced signals, the average distance traveled during the green period is estimated as the sum of the distance traveled while accelerating from rest to the average speed that would be attained in the absence of signals, plus the distance traveled at this speed over any remaining green time in the cycle. In the absence of

[39] The procedure presented by TRDF does not provide for separate analysis of sections with closely spaced traffic signals, and so it overestimates the number of stop cycles encountered on such sections.

signals, the average speed obtained would be SSCSPD. From Equation 8.14 it can be determined that the time (in seconds) required to accelerate to this speed, ACTIME, is:

$$ACTIME = -\frac{1}{B}\ln\left(1 - \frac{B \times SSCSPD}{A}\right) \tag{8.27}$$

and the distance traveled during this time, ACDIST, is:

$$ACDIST = \frac{1}{B}\left(A \times ACTIME - SSCSPD\right) \tag{8.28}$$

If GDIST is the distance traveled during the green time, GTIME, then:[40]

$$\begin{aligned} GDIST = &\frac{1}{B}\left(A \times ACTIME - SSCSPD\right) \\ &+ SSCSPD \times \max\left(GTIME - ACTIME, 0\right) \end{aligned} \tag{8.29}$$

Overall, for sections with closely spaced signals, we get an estimate of the average distance traveled during a signal cycle, SCDIST:

$$SCDIST = GDIST + \frac{SLEN}{2 \times NSIG} \tag{8.30}$$

where GDIST is given by Equation 8.28.

On sections with closely spaced signals, vehicles are assumed to stop for a signal once per signal cycle. Hence, for such sections, the number of stops for traffic signals, NTSS, is estimated by dividing the section length by the average distance traveled during the cycle:

$$NTSS = \frac{SLEN}{SCDIST} \tag{8.31}$$

8.1.2.2.2.2 Estimating the Effect of Widely Spaced Signals

For sections with widely spaced signals, the probability of being stopped during a given cycle, PSTOP, is estimated by dividing the distance traveled during the red portion of the cycle by the average spacing between signals:

$$PSTOP = \frac{SSCPD \times RTIME}{SLEN / NSIG} \tag{8.32}$$

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[40]The equation ignores a correction that would be required in the rare instance in which GTIME is not long enough to enable vehicles to accelerate to SSCSPD.

For a cycle during which a vehicle stops, the distance traveled during the green period is given by Equation 8.28 above and the average distance traveled during the red period can be estimated as:

$$RDIST = \tfrac{1}{2}\, SSCSPD \times RTIME \qquad (8.33)$$

Taking the typical signal cycle to be 90 seconds (or 0.025 hours), the average distance traveled in the course of a cycle during which a vehicle does not stop is SSCSPD/0.025. Combining this result with Equation 8.31 produces an estimate of the average distance traveled on sections with widely spaced signals:

$$\begin{aligned} SCDIST = {} & PSTOP \times \left(\tfrac{1}{2}\, SSCSPD \times RTIME + GDIST\right) \\ & + (1 - PSTOP)\ \ (0.025 \times SSCSPD) \end{aligned} \qquad (8.34)$$

where PSTOP and GDIST are given by Equations 8.31 and 8.28, respectively.

The average number of stops for traffic signals on a section with widely spaced signals is obtained by multiplying the number of signal cycles required to traverse the section by the probability of being stopped during any cycle:

$$NTSS = PSTOP \frac{SLEN}{SCDIST} \qquad (8.35)$$

8.1.2.2.3 Average Effective Speed and the Number of Speed-Change Cycles

The average effective speed (AES) on a restricted-flow facility is obtained:

$$AES = \begin{cases} SSCSPD & \text{if } NSIG = 0 \\ \frac{SCDIST}{0.025} & \text{otherwise} \end{cases} \qquad (8.36)$$

where SCDIST is given by Equation 8.30 for sections with closely spaced signals and by Equation 8.34 for sections with widely spaced signals, and 0.025 is the assumed average length of a signal cycle (in hours).

The total number of speed-change cycles on the section, NSCC, is estimated as the sum of the number of stop signs and the expected number of stops for traffic signals:

$$NSCC = NSTOP + NTSS \qquad (8.37)$$

8.2 The Value of Travel Time

The value of travel time differs between trips drivers take as part of their work (on-the-clock trips) and other trips. Time savings during on-the-clock trips conventionally are valued on the basis of savings to the employer. The savings include wages, fringe benefits, and, for some types of trucks, vehicle cost and the inventory carrying costs of the cargo. Off-the-clock time savings can be valued by asking people about the value of travel time or by examining choice situations (e.g., toll versus free route, speed, or housing location) that require choosing to save time versus money or safety.

Exhibit 8-7 presents a summary of the major components of estimates of the value of travel time for each of the seven vehicle types distinguished by HERS[41]. For each vehicle type, these values are used by HERS to develop estimates of travel time costs on each section from the equation:

$$TTCST(vt) = \frac{1000}{AES(vt)} \times TTVAL(vt) \qquad (8.38)$$

where:

TTCST(vt)	=	average travel-time cost (in 1988 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 1988 dollars) for occupants and cargo of vehicles of type vt (as shown on the bottom line of Exhibit 8-7).

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 2.0 the weights used are those obtained by the HPMS Vehicle Classification Study.[42] In HERS 2.0, these weights are scaled to add to 100 percent.[43] Separate weights are used for each functional system. HERS 2.0 does not adjust these weights to reflect variations in the percentage of trucks on each section.

The remainder of this section documents the development of the Exhibit 8-7 estimates of the value of an hour of travel time.

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[41] The values in Exhibit 8-7 are in 1988 dollars. For the 1995 C&P Report, the values were to converted to 1993 dollars by applying a factor of 1.16.

[42] HPMS Technical Manual, Table IV-20.

[43] The original weights only add to slightly more than 99 percent, because they exclude motorcycles and buses.

Exhibit 8-7. Value of One Hour Travel Time by Benefit Category and Vehicle Type (1988 dollars)

Category	Vehicle Class					
	Auto	4-Tire Truck	6-Tire Truck	3-4 Axle Truck	4-Axle Comb.	5-Axle Comb.
On-the-Clock						
Labor/Fringe	$ 14.49	$12.59	$ 17.80	$ 14.88	$ 19.52	$ 19.52
Vehicle	0.71	0.89	2.62	8.46	5.92	6.07
Inventory	0.00	0.00	0.00	0.00	0.50	0.50
Total	$ 15.20	$13.48	$ 20.42	$ 23.34	$ 25.94	$ 26.09
Other Trips						
Percentage of Miles	89.7%	57.5%	0%	0%	0%	0%
Value	$ 8.94	$ 8.94	NA	NA	NA	NA
Weighted Average	$ 9.59	$ 10.87	$ 20.42	$ 23.34	$ 25.94	$26.09

8.2.1 On-the-Clock Trips

Travel time for on-the-clock trips is valued on the basis of costs to the employer, including the wages and fringe benefits paid, costs related to vehicle productivity, inventory carrying costs, and spoilage costs. In these computations, no adjustment was made to reflect the tax deductibility of wage, fringe, vehicle, and spoilage costs, or the taxation of inventory cost savings. Because government obtains a lower return on investment than the private sector, a small percentage decrease in the value of on-the-clock travel time to reflect taxation probably would be appropriate, but substantial theoretical research would be required to determine the percentage.

8.2.1.1 Labor Costs

For autos, the hourly wage per vehicle occupant for on-the-clock trips in 1988 was assumed equal to the U.S. average for non-agricultural workers of $9.30,[44] plus fringe

[44] Economic Report of the President, U.S. Government Printing Office, Washington, D.C., February 1989.

benefits that were set to the U.S. average of 19.73 percent.[45] Average wages for drivers of four-tire (light) trucks were $8.08 per hour in 1988,[46] plus fringe benefits which again were valued at the U.S. average. For larger trucks, wages again were obtained from the U.S. Bureau of Labor Statistics,[47] and the fringe rate of 36 percent was taken from the Teamster's Union contract for the Central States area.[48]

Wages and fringe benefits per vehicle occupant were multiplied by average vehicle occupancy to compute employee costs per hour of work travel time. Average vehicle occupancy for on-the-clock trips in autos and light trucks is 1.3 in urban areas and 1.4 in rural areas.[49] Six-tire trucks, which include pick-up and delivery vehicles that sometimes carry a helper, were assumed to have an average occupancy of 1.1. Heavier single-unit trucks were assumed to carry only one worker. Data from Hertz[50] about the frequency of two-driver teams in crash-involved trucks (about 25 percent of all trucks) suggest combination trucks have an average of 1.12 occupants. The first row in Exhibit 8-7 shows the labor and fringe benefit costs per hour by type of vehicle.

8.2.1.2 Vehicle Costs

For autos in commercial motor pools and four-tire trucks, the cost 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 Motor Vehicle Manufacturers Association[51]) divided by 2000 hours per year of sign-out time (essentially the day shift or other shift when maximal vehicle use occurs). Fewer (more) vehicles would be required if travel time were lower (higher). Personal auto use costs employers mileage

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[45]U.S. Bureau of the Census, Statistical Abstract of the United States: 1989, U.S. Government Printing Office, Washington, D.C., 1989.

[46]U.S. Bureau of Labor Statistics, "Occupational Earnings in All Metropolitan Areas, July 1986," Washington, D.C., July 1987.

[47]Ibid.

[48]Bruce Orange, Trucking Management, Inc., Washington, D.C., personal communication, June 1988.

[49]U.S. Department of Transportation, 1983-1984 Nationwide Personal Transportation Study, Volume I, "Personal Travel in the U.S.," National Technical Information Service, Springfield, Virginia, August 1986.

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

[51]Motor Vehicle Manufacturers Association, Motor Vehicle Facts and Figures, 1989, Washington, D.C., 1989.

reimbursement, but no capital investment, so no equipment cost is associated with travel time changes for these vehicles. If the number of employees assigned to jobs requiring personal vehicles rose, labor costs would rise, but mileage reimbursed would change minimally.

For heavier trucks, the cost per hour was computed as the average vehicle cost per year[52] divided by the number of hours in service per year. Six-tire trucks and four-axle combination trucks were assumed to be in service 2000 hours per year. Loading and unloading times for four- and five-axle combination trucks were assumed to be equal. Data from the 1982 Truck Inventory and Use Survey[53] indicate five-axle combinations travel an average of 61,500 miles per year, while four-axle combinations average 37,700 miles per year. Since these trucks travel an average of 41.4 miles per driver hour (derived from Orange[54]), to cover these extra miles, five-axle combinations must be in service an average of 575 more hours per year than four-axle combinations. 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 in use only 1600 hours per year. (Increasing assumed annual use to 1800 hours would lower the estimated value of travel time for these vehicles by about $0.80 per hour.) The second row of Exhibit 8-7 shows the vehicle costs per hour by type of vehicle.

8.2.1.3 Inventory and Spoilage 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 from 1985-1987 plus 1 percent. With this annual rate, the discount rate per hour is 0.0011 percent. The average payload of a five-axle combination is 30,000 pounds. Truck Inventory and Use Survey data indicate that 23 percent of loaded combination truck vehicle-miles are for low-value natural resources and agricultural products. Since shipments of these commodities generally weigh appreciably more than shipments of higher valued commodities, they probably account for close to 35 percent of all combination truck ton-miles. The remaining 65 percent of ton-miles is accounted for by manufactured products, including goods of medium to high value, processed foods,

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[52]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.

[53]U.S. Bureau of the Census, Statistical Abstract of the United States: 1989, U.S. Government Printing Office, Washington, D.C., 1989.

[54]Bruce Orange, Trucking Management, Inc., Washington, D.C., personal communication, June 1988.

building materials, wood, and paper products. In 1988 dollars, the median value per pound of manufactured commodities is roughly $2.29 (value from Commodity Transportation Survey data in the 1977 Census of Transportation, inflated with the manufactured goods GDP inflator[55]). Data from the Statistical Abstract (1989) on the value of coal, corn, wheat, and soybeans, weighted by the tonnage produced, suggest nonmanufactured goods have an average value of $0.04 per pound. With these values, the average payload is valued at roughly $45,000, yielding a time value of $0.505 per hour. This estimate is not sensitive to the value of the nonmanufactured payload; if it were valued at $0.40 per pound rather than $0.04, the inventory value per hour would rise by $0.045.

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.

The inventory cost for three- and four-axle single-unit trucks was assumed negligible because dump trucks dominate this category and rarely haul goods that are critically needed. The inventory cost of delay for six-tire trucks was assumed to be negligible because these trucks are used primarily for local pick-ups and deliveries that are sensitive to day but not hour. Finally, autos and four-tire trucks (pick-ups and small vans) were assumed not to transport significant volumes of goods where inventory carrying costs or spoilage costs would be incurred or saved if travel time per local trip changed modestly.

The third row of Exhibit 8-7 shows the inventory costs per hour by type of vehicle. The fourth row shows the total travel time cost per hour of on-the-clock work travel.

8.2.1.4 Comparison with Prior Estimates

Exhibit 8-8 compares the HERS estimates of travel time for five-axle combination trucks and for all trucks with more than four tires to values obtained from two previous studies and adjusted to 1988 dollars. It can be seen that the HERS values lie between those obtained from the other two sources.

[55]U.S. Bureau of the Census, 1977 Census of Transportation, Commodity Transportation Survey, U.S. Government Printing Office, Washington, D.C., 1980.

Exhibit 8-8. Comparison of Values of Truck Travel Time

(1988 dollars)

Study	5-Axle Comb. Trucks	All Medium & Heavy Trucks
HERS	$26.09	$23.99
Buffington & McFarland[56]	$24.04	$21.74
Kamerud[57]	$29.24	$24.56

8.2.2 Other Trips

Off-the-clock trips include trips for commuting to and from work, personal business, and leisure activity. Miller[58] finds no convincing evidence that the average value of travel time differs between these purposes. The evidence suggests the value of travel time is higher for drivers than passengers. Nineteen studies published since 1970 in which value of driver travel time was related to wage rate were reviewed.[59] These studies estimated this relationship using route-choice models, surveys, speed-choice models, or models of housing-location choice. Additional estimates based on choice of travel mode were not considered because they include only out-of-pocket cost per trip, omitting purchase and insurance costs required to travel by personal vehicle. Thirteen of the 19 studies reviewed include a value between 55 percent and 60 percent of the wage rate, five include only higher values, and one only lower values. Accordingly, HERS values drivers' off-the-clock travel time at 60 percent of the wage rate.

After reviewing the literature, Miller[60] and Garder[61] independently conclude that the value of travel time used in transportation modelling should not vary by trip length.

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[56]Jesse L. Buffington and William F. McFarland, "Benefit-Cost Analyis: Updated Unit Costs and Procedures," Research Report No. 202-2, Texas Transportation Institute, Texas A&M University, College Station, Tex., August 1975.

[57]Dana B. Kamerud, "Benefits and Costs of the 55 MPH Speed Limit: New Estimates and Their Implications," Journal of Policy Analysis and Management, Vol. 7, pp. 341-352, 1988.

[58]Ted R. Miller, "The Value of Time and the Benefit of Time Saving," The Urban Intitute, Washington, D.C., 1989.

[59]See Jack Faucett Associates, "Value of Travel Time," study memorandum submitted to U.S. Department of Transportation, Federal Highway Administration, September 18, 1989; or Ted R. Miller, op. cit.

[60]Ted R. Miller, op. cit.

Based on the ratio of the values of driver and passenger time obtained in a survey by Hensher[62], HERS values the travel time of auto passengers (other than the driver) at 45 percent of the wage rate. Miller[63] recommends this same value for the travel time of bus passengers.

According to the 1983-84 National Personal Transportation Survey, average vehicle occupancy per vehicle mile for off-the-clock trips is 1.6 in urban areas and 2.0 in rural areas.

8.2.3 Values for Use in HERS

To develop travel time values for use in HERS, heavy trucks were assumed to be used only for work, so the value of heavy truck travel time equals the on-the-clock value. Lighter vehicles were assumed to be used both for work and for other purposes. The value of travel time in lighter vehicles equals the sum of the percentage of travel by drivers as part of their work (on-the-clock travel) multiplied by the value of work travel time, plus the percentage of off-the-clock travel multiplied by the value of non-work travel time.

For autos, the percentage of vehicle miles of travel that are on-the-clock was computed by summing the 4.2 percent of personal auto mileage that is for on-the-clock travel[64] plus all trips in the 6.4 percent of autos that are in commercial fleets of four or more.[65] Vehicle miles of travel per auto were assumed equal for commercial and personal autos.

For four-tire trucks, 42.5 percent of vehicle miles were on-the-clock in 1982[66], and it was assumed that the same percentage still applies. In actuality, the percentage probably dropped by an unknown amount between 1982 and 1989. The value of travel time for

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[61]Per Garder, "Value of Short Time Periods," Draft Report, University of North Carolina, Highway Safety Research Center, Chapel Hill, NC, May 1989.

[62]David A. Hensher, "Behavioral and Resource Values of Travel Time Savings: A Bicentennial Update," Macquarie University School of Economic and Financial Studies, New South Wales, Australia, June 1988.

[63]Ted R. Miller, op. cit.

[64]U.S. Department of Transportation, 1983-1984 Nationwide Personal Transportation Study, Volume I, "Personal Travel in the U.S.," National Technical Information Service, Springfield, Virginia, August 1986.

[65]Motor Vehicle Manufacturers Association, Motor Vehicle Facts and Figures, 1989, Washington, D.C., 1989.

[66]U.S. Bureau of the Census, 1982 Census of Transportation, Truck Inventory and Use Survey, U.S. Government Printing Office, Washington, D.C., 1984.

four-tire trucks only would be roughly $0.25 lower per hour if the percentage fell to 40 percent. The fifth row of

Exhibit 8-7 shows the off-the-clock costs per hour by type of vehicle, and the sixth row shows the percentage of miles that are off-the-clock. The seventh row shows the average travel time cost per hour that is used in HERS.

Travel delay probably is valued at about 1.5 times free-flow travel. The literature on modal choice clearly establishes that people value waiting time 1.5 to 2 times as much as travel time.[67] Car drivers are no different, as evidenced by how often people go through yellow and red lights. Bates et al.[68] found the value of travel time in congested traffic was 30 percent to 50 percent higher than in free flow. A survey by Hensher[69] indicates drivers prefer a more reliable arrival time than they do travel time savings. Deacon and Sonstelie[70] interviewed consumers who were waiting an average of 15 minutes in line to save roughly $0.185 per gallon on gasoline and consumers who paid the higher price and avoided the line. The study yielded values for 15 minutes of pre-planned in-vehicle waiting time of about 110 percent of the wage rate for drivers by themselves and 160 percent for drivers with a passenger, roughly 1.5 to 1.8 times the value of travel time. However, HERS does not distinguish travel delay time from travel time.

The value of time for four-tire vehicles may be indexed from 1988 dollars to dollars of any other year by using the Bureau of Labor Statistics (BLS) data on average hourly earnings of nonsupervisory workers on private nonfarm payrolls.[71] For trucks, a somewhat better index for this purpose can be obtained from BLS data on changes in employment costs (including the costs of benefits) for transportation and material

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[67]David A. Hensher, "Review of Studies Leading to Existing Values of Travel Time," Transportation Research Record 587, Transportation Research Board, Washington, D.C., 1976.

[68]John J. Bates, Mick Roberts, Ken Gwilliam, and Phil Goodwin, "The Value of Travel Time Savings," Policy Journals, Newbury, Berks, U.K., 1987.

[69]David A. Hensher, "Behavioral and Resource Values of Travel Time Savings: A Bicentennial Update," Macquarie University School of Economic and Financial Studies, New South Wales, Australia, June 1988.

[70]Deacon, Robert T., and Jon Sonstelie. "Rationing by Waiting and the Value of Time: Results from a Natural Experiment," Journal of Political Economy, Volume 93, Number 4, 1985, pp. 627-647.

[71]U.S. Department of Labor, Bureau of Labor Statistics, Employment and Earnings, U.S. Government Printing Office, Washington, D.C., monthly, Table C-1. Also published in U.S. Department of Commerce, Bureau of Economic Analysis, Survey of Current Business, U.S. Government Printing Office, Washington, D.C., monthly.

moving occupations.[72] A factor of 1.16 was applied to the values in Exhibit 8-7 to produce the 1993 dollar values shown in Exhibit 8-9 and used for the 1995 Conditions and Performance Report.

Exhibit 8-9. Value of One Hour Travel Time by Benefit Category and Vehicle Type (1993 dollars)

Category	Vehicle Class					
	Auto	4-Tire Truck	6-Tire Truck	3-4 Axle Truck	4-Axle Comb.	5-Axle Comb.
Weighted Average	$ 11.12	$ 12.61	$ 23.69	$ 27.07	$ 30.09	$30.26

8.3 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.[73]

Operating costs are estimated using a three-step procedure:[74]

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.

These three steps are described in the following sections.

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[72]Employment Cost Indexes and Levels, U.S. Department of Labor, Bureau of Labor Statistics, U.S. Government Printing Office, Washington, D.C., quarterly.

[73]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.

[74]The same general procedure (with different equations and parameters) can also be used to develop separate estimates of fuel consumption. These estimates, however, are not essential to HERS, since the estimates of operating costs include fuel costs. Accordingly, separate estimates of fuel consumption are not developed in HERS 2.0.

8.3.1 Constant-Speed Operating Costs

For positive and zero grades, constant-speed operating costs per thousand vehicle-miles in 1988 dollars (OPCST1) are estimated by vehicle type using the equation:

$$OPCST1 = OCXR(vt) \times (AES)^{OC1U(1,vt)} \times \exp\begin{bmatrix} OC1U(2,vt) + OC1U(3,vt) \times PSR \\ + OC1U(4,vt) \times AES + OC1U(5,vt) \times GR \end{bmatrix} \quad (8.39)$$

where:

AES	=	average effective speed (mph);
PSR	=	present serviceability rating (for pavements);
GR	=	grade (percent);
vt	=	vehicle type;
OC1U(i,vt)	=	a set of operating-cost coefficients; and
OCXR(vt)	=	a set of ratios of values of operating-cost indexes used for converting the operating-cost estimates to 1988 dollars.

Values for OCXR and OC1U are shown in Exhibit 8-10. Equation 8.39, with the OCXR(vt) set to 1, was fit by Elkins, et al.,[75] to the operating-cost tables originally developed by Zaniewski, et al.[76] These cost estimates reflect the sum of use-related costs for fuel, oil, tires, maintenance and repair, and depreciation. The equations obtained by Elkins produce estimates of operating costs in 1980 dollars. The operating-cost index ratios, OCXR(vt), are used to convert these cost estimates to 1988 dollars. Values for OCXR(vt) were obtained from updated figures for five-vehicle operating-cost indexes originally developed by JFA for use in estimating the FHWA/Faucett VMT Forecasting Model.[77] The R^2 values obtained by Elkins are shown in Exhibit 8-10 along with all the OC1U coefficients and OCXR ratios.

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[75]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, Table 32, pp. 226-229.

[76]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, Appendix A, Tables A.1-A.64.

[77]Jack Faucett Associates, The FHWA/Faucett VMT Forecasting Model, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August, 1988. The indexes used in Exhibit 8-0 reflect a weighted average of fuel and maintenance costs and are derived from data presented in the referenced report (pp. 12-16 and 54-59). Separate

For negative grades, constant-speed operating costs per thousand vehicle-miles are estimated from equations presented in Exhibit 8-11. With three exceptions,[78] these equations, like Equation 8.39, were estimated by Elkins using the Zaniewski operating-cost tables, with the results converted to 1988 dollars by multiplying by OCXR(vt), whose values are shown in Exhibit 8-10.

The equations in Exhibit 8-11 were fit using up to eight regressors and a variety of equation forms. The complexity of these equations was necessitated by the complex behavior of the operating-cost tables that these equations represent. Despite their complexity, it is appreciably more efficient computationally to use these equations than to estimate constant-speed operating costs as a continuous function of AES, PSR and grade using three-dimensional interpolation between values obtained from the Zaniewski operating-cost tables.

To obtain acceptable fits for combination trucks (vehicle types 6 and 7), it was necessary to use more than one equation for each of the two vehicle types. The general form of the equation used for these two vehicle types is shown in Exhibit 8-11 and the

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indexes were used for all four-tire vehicles and for each of the four categories of medium and heavy truck distinguished by HERS.

[78]The exceptions are the equation for four-tire trucks and two of the equations used for three and four-axle combinations (the equations corresponding to j = 3 and 4 in Exhibit 8-13). In two of these cases, extra terms were added in order to produce qualitatively more satisfactory fits. In the third case (j = 3 in Exhibit 8-0), a single equation was found to provide a satisfactory fit for a situation in which TRDF used two equations.

Exhibit 8-10. Coefficients for Uphill and Zero-Grade Constant-Speed Operating-Cost Equation

Vehicle Type	OCXR(vt)	OC1U(i,vt)					R^2
		i=1	i=2	i=3	i=4	i=5	
1. Small Autos	0.837	-0.5212	6.558	-0.1080	0.01190	0.0402	0.956
2. Medium Autos	0.837	-0.431	6.272	-0.1052	0.01400	0.0548	0.965
3. Four-Tire Trucks	0.837	-0.443	6.142	-0.1084	0.01870	0.0674	0.955
4. Two-Axle, Six-Tire Trucks	0.999	-0.434	6.831	-0.0731	0.01450	0.0889	0.951
5. Three+Axle Single-Unit Trucks	1.034	-0.4084	7.389	-0.0868	0.01229	0.1050	0.964
6. Three & Four-Axle Combinations	1.042	-0.415	7.311	-0.1122	0.01313	0.1170	0.930
7. Five+ Axle Combinations	1.048	-0.319	7.190	-0.1140	0.01096	0.1440	0.952

Exhibit 8-11. Downhill Constant-Speed Operating-Cost Equations

1. Small Autos:

$$OPCST1 = OCXR(1) \times [351.02 + 6.426 \times PSR - 44.59\,LN(PSR) + 4.585 \times GR + 0.0375 \times GR \times AES \times PSR + 1.647 \times GR^2 - 70.78 \times \ln(AES) + 1.325 \times AES]$$

$R^2 = 0.91$

2. Medium Autos:

$$OPCST1 = OCXR(2) \times PSR^{-0.221} \times AES^{-0.433} \times \exp[6.19 - 0.0394 \times PSR - 0.0075 \times GR + 0.0119 \times GR^2 + 0.00197 \times GR \times AES + 0.0156 \times AES]$$

$R^2 = 0.930$

3. Four-Tire Trucks:

$$OPCST1 = OCXR(3) \times PSR^{-0.248} \times AES^{-0.09346} \times \exp[5.422 - 0.024 \times GR + 0.017 \times GR^2 - 0.012 \times AES + 0.000275 \times AES^2 + 0.0026 \times GR \times AES + 0.011 \times GR \times PSR]$$

$R^2 = 0.929$

4. Two-Axle, Six-Tire Trucks:

$$OPCST1 = OCXR(4) \times [502.33 + 8.035 \times PSR - 73.44 \ln(PSR) + 5.02 \times GR + 4.807\,GR^2 + 0.6567 \times GR \times AES + 5.519 \times AES - 121 \times \ln(AES)] \times$$

$R^2 = 0.901$

5. Single-Unit Trucks with Three or More Axles:

$$OPCST1 = OCXR(5) \times AES^{-0.389} \times \exp[7.423 - 0.1197 \times PSR + 0.0947 \times R + 0.01967 \times GR^2 + 0.003008 \times AES]$$

$R^2 = 0.925$

6&7. Combination Trucks:

$$OPCST1 = OCXR(vt) \times \exp[OC1D(1,j) + OC1D(2,j) \times PSR + OC1D(3,j) \times AES + OCID(4,j) \times GR + OC1D(5,j) \times PSR^2 + OC1D(6,j) \times AES^2 + OC1D(7,j) \times GR^2]$$

where the OC1D coefficients are given in Exhibit 8-12.

Exhibit 8-12. Coefficients for Downhill Constant-Speed Operating-Cost Equations for Combination Trucks

	j	Grade	AES	OCID(i,j)							R^2
				i=1	i=2	i=3	i=4	i=5	i=6	i=7	
Three- & Four-Axle Combinations	1	≥ -1%	≤ 20 mph	6.624	-0.1412	-0.03780	---	0.01490	-0.000860	---	0.998
	2	≥ -1%	≥ 25 mph	6.398	-0.3490	-0.01820	---	0.03730	0.000281	---	0.986
	3	-2%	any	7.040	-0.3541	-0.08720	---	0.03640	0.001130	---	0.912
	4	≤ -3%	any	5.722	-0.4470	-0.01860	-0.256	0.04450	0.000104	-0.00382	0.968
Five- & More Axle Combinations	5	≥ -1%	≤ 25 mph	6.076	-0.2963	-0.05380	---	0.02930	0.000819	---	0.995
	6	≥ -1%	≥ 30 mph	5.333	-0.3861	0.02429	---	0.04067	-0.000120	---	0.993
	7	-2%	≤ 55 mph	6.364	-0.3860	-0.03155	---	0.03890	0.000280	---	0.991
	8	-2%	≥ 60 mph	-33.200	-0.4480	1.14300	---	0.04550	-0.008300	---	0.999
	9	≤ -3%	any	5.480	-0.4320	-0.01630	-0.393	0.04361	0.000086	-0.01350	0.993

coefficients for each of the equations, along with the corresponding range of validity,[79] are shown in Exhibit 8-12. In the latter exhibit, the index j is used to distinguish the nine equations used. As can be seen, for each of the two vehicle types, the equation to be used depends upon average grade and, in some cases, on average effective speed.

8.3.2 The Effect of Speed-Change Cycles

Excess operating costs due to speed-change cycles are estimated by vehicle type from the equation:

$$OPCST2 = OCXR(vt) \times \begin{bmatrix} OC2(1,vt,CSMAX) \\ + \quad OC2(2,vt,CSMAX) \times CSMAX \\ + \quad OC2(3,vt,CSMAX) \times CSMAX^2 \\ + \quad OC2(4,vt,CSMAX) \times CSMIN \\ + \quad OC2(5,vt,CSMAX) \times CSMIN^2 \\ + \quad OC2(6,vt,CSMAX) \times CSMAX \times CSMIN \\ + \quad OC2(7,vt,CSMAX) \times CSMAX^2 \times CSMIN^2 \end{bmatrix} \tag{8.40}$$

where:

OPCST2	=	excess operating costs due to speed-change cycles per thousand cycles (1988 dollars);
CSMAX	=	maximum speed of speed-change cycle (mph);
CSMIN	=	minimum speed of speed-change cycle (mph);
vt	=	vehicle type;
OC2(i,vt,CSMAX)	=	a set of operating-cost coefficients given in Exhibit 8-13; and
OCXR(vt)	=	a set of ratios (shown in Exhibit 8-10) of values of operating-cost indexes used for converting operating-cost estimates to 1988 dollars.

[79]It may be observed that, there are gaps in the range of validity of these questions (between -1 and -2 percent, and between -2 and -3 percent). Since vertical alignment improvements normally do not decrease grades to less than three percent, and HERS is not intended to analyze any improvements that do, grades in these ranges never enter into a benefit/cost analysis of a vertical alignment improvement. Use of the equations in the discontinuous form specified in the exhibit thus does not bias any of the benefit/cost analyses.

The operating-cost coefficients shown in Exhibit 8-13 were obtained by JFA using ordinary least-squares regression to fit Equation 8.40 to updated operating-cost tables developed by Elkins, et al.,[80] from the tables originally developed by Zaniewski, et al.[81]

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[80]Elkins, et al., op. cit., Table 36, p. 238. The Elkins tables provide estimates of excess operating costs due to speed-change cycles beyond the costs for constant-speed operation at the average effective speed. These tables reflect Elkins' analysis of the characteristics of speed-change cycles rather than the HERS analysis presented above. Also, as observed in Footnote 33, the excess-operating-cost equations were derived by Elkins using a value of 0.08/sec. for the variable B in Exhibit 8.6 (rather than the 0.07/sec. value shown in the exhibit).

[81]Zaniewski, et al., op. cit., Appendix A, Tables A.65-A.72. Equation 8.39 was also used by TRDF (Table 36) to obtain a single set of coefficients for each vehicle type, independent of CSMAX (instead of two sets dependent on CSMAX, as shown in Exhibit 8-12). The TRDF equations, however, produced negative estimates of OPCST2 for some values of the independent variables and large relative errors for other values.

Exhibit 8-13. Coefficients for Equation for Excess Operating Costs Due to Speed-Change Cycles

Vehicle Type	CSMAX	OC2(i,vt,CSMAX)							R^2
		i=1	i=2	i=3	i=4	i=5	i=6	i=7	
1. Small Autos	≤ 40	1.180	-0.0499	0.00526	-0.0928	-0.003590	0.003120	-1.145×10^{-6}	0.997
	≥ 45	63.300	-2.6000	0.03170	—	-0.002430	0.000217	-1.067×10^{-6}	0.998
2. Medium Autos	≤ 40	0.770	0.1249	0.00598	-0.2080	-0.006130	0.002080	—	0.999
	≥ 45	110.100	-4.5500	0.05630	—	-0.001148	0.003190	-1.987×10^{-6}	0.997
3. 4 Tire Trucks	≤ 40	1.075	0.0787	0.00930	-0.1781	-0.007320	—	—	0.999
	≥ 45	163.500	-6.7300	0.08160	—	—	-0.006220	-2.48×10^{-6}	0.997
4. Two Axle, Six Tire Trucks	≤ 35	3.320	—	0.04410	-0.5990	0.033400	0.014710	-8.45×10^{-6}	0.999
	≥ 40	45.400	-4.0700	0.11910	2.9700	-0.045600	-0.070500	—	0.999
5. Three+ Axle Single-Unit Trucks	≤ 50	27.390	-2.6800	0.13300	1.0180	-0.082600	-0.030000	—	0.993
	≥ 55	3401.000	-134.1000	1.42100	13.5700	—	-0.271000	-2.81×10^{-5}	0.999
6. Three & Four Axle Combinations	≤ 55	43.940	-3.8600	0.16700	1.5150	-0.082500	-0.059400	—	0.991
	≥ 60	4896.000	-182.0000	1.81000	18.5700	—	-0.354000	-2.64×10^{-5}	0.999
7. Five+ Axle Combinations	≤ 50	18.770	-0.8060	0.147200	—	-0.114800	-0.028800	—	0.997
	≥ 55	3498.000	-135.3000	1.45700	10.1600	—	-0.237000	-3.26×10^{-5}	0.999

8.3.3 The Effect of Curves

For each vehicle type, HPMS estimates excess operating costs due to curves as a function of average effective speed and degrees of curvature using tables originally developed by Zaniewski, et al.[82]

Elkins, et al., fit a set of equations[83] to these tables. However, these equations involve raising side friction to a noninteger power and so cannot be used for negative values of side friction.[84] Indeed the irregular relationships represented in these tables cannot be represented in a regression equation without using an excessive number of independent variables. Accordingly, HERS obtains excess operating costs due to curves, OPCST3, by multiplying values from the Zaniewski tables by OCXR(vt) to convert these costs to 1988 dollars and using linear interpolation where necessary.

8.3.4 Total Operating Costs

For each vehicle type, total operating costs, OPCOST, per thousand vehicle-miles are obtained by combining the three components of operating costs:[85]

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[82]Zaniewski, et al., op. cit., Appendix A, Tables A.73-A.80.

[83]Elkins, et al., op. cit., Table 33, pp. 230-231.

[84]Side friction, SF, is obtained:

$$SF = \frac{AES^2}{15 \times RC} - SP$$

where:

RC	=	radius of curvature in feet (= 5729.578 divided by degrees of curvature); and
SP	=	superelevation (fraction)

Positive values of side friction correspond to superelevations that do not fully overcome the centrifugal force of the vehicle. Negative values correspond to superelevations that more than overcome this force. The latter case occurs when increasing congestion results in reducing operating speeds on facilities originally designed for relatively high speeds.

[85]The resulting estimates of operating costs represent the sum of costs for fuel, oil, tires, maintenance and repair, and mileage-related depreciation.

$$OPCOST = OPCST1 + \frac{OPCST2}{SLEN/NSCC} + OPCST3 \qquad (8.41)$$

where:

OPCST1	=	constant-speed operating costs per thousand vehicle-miles;
OPCST2	=	excess operating costs due to speed-change cycles per thousand cycles; and
OPCST3	=	excess operating costs due to curves per thousand vehicle-miles

For each section, total operating costs per thousand vehicle-miles are obtained by taking a weighted average of the corresponding costs for each vehicle type. In HERS 2.0, the weights used are the HPMS weights[86] that are also used in the procedure for obtaining average travel-time costs.

In HERS 2.0, all costs are in 1988 dollars. Vehicle operating costs can be indexed from 1988 dollars to dollars of any other year using the Consumer Price Index (CPI) for private transportation.[87] A somewhat better index can be obtained as a weighted average of the CPI components for motor fuel, for automobile maintenance and repair,and for other private transportation[88], thus excluding the influence of the prices of new and used vehicles. For the 1995 Conditions and Performance Report, a factor of 1.18 was applied to obtain operating costs in 1993 dollars.

8.4 Estimating Safety Costs

Annual safety costs of a highway section are estimated in two steps. First, the expected annual numbers of crashes[89], injuries, and fatalites on the section are obtained by multiplying annual VMT by crash, injury and fatality rates per million vehicle-miles.

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[86] HPMS Technical Manual, Table IV-20.

[87] U.S. Department of Labor, Bureau of Labor Statistics, CPI Detailed Report, U.S. Government Printing Office, Washington, D.C., monthly. Also published in U.S. Department of Commerce, Bureau of Economic Analysis, Survey of Current Business, U.S. Government Printing Office, Washington, D.C., monthly.

[88] Values for the CPI components are published in CPI Detailed Report, op. cit. (but not in Survey of Current Business). Weights for these components can be obtained from U.S. Department of Labor, Bureau of Labor Statistics, Relative Importance of Components in the Consumer Price Indexes, U.S. Government Printing Office, Washington, D.C., annual.

[89] In recent years, motor-vehicle safety professionals have adopted the term "crash" to replace the word "accident."

These results are then multiplied by estimates of cost per crash, per injury, and per fatality.

The crash, injury and fatality rates are referred to as "incident rates" and vary by facility type and traffic volume. The estimated safety effects of any HERS improvement result from changes in a section's facility type.[90]

The following subsections present the incident rates and crash cost values used by HERS.

8.4.1 Crash, Injury, and Fatality Rates

At one time, HPMS data included state-reported crash, injury, and fatality incidence by sample section. The HPMS model uses tables of crash, injury, and fatality incident rates per million vehicle-miles by facility type and traffic volume that were developed from these data for the Highway User Investment Study. The HPMS tables provide mean values from the reported data, without trimming of outliers (which may be data-entry errors) or consideration of the number of observations reflected in the resulting means.

For HERS, the HPMS incident rates were adjusted in four ways. First, very large or small values at the extremes of the volume distribution, which generally are based on data for a minimal number of sections, were adjusted to be more consistent with values from larger samples, including both rates from the middle volume categories on the same facility type and rates for the same volume on related facility types. Second, rates were adjusted when the ratios of fatalities per injury, fatalities per crash, or injuries per crash were radically different from values for other volumes within a facility type and counter to the trend by volume. Third, rates were changed when the pattern across facility types was obviously illogical. For example, for a given traffic volume, four-lane roads with full access control should be at least as safe as four-lane roads with partial access control. Fourth, all rates were scaled so that overall rates would match recent national rates by facility type.

The HERS incident rates are presented in Exhibit 8-14, 8-15, and 8-16. Exhibit 8-17 compares the numbers of crashes, fatalities and injuries implicit in the HERS incident rates with those implicit in the HPMS rates.

To adjust to recent national incident rates, 1984 HPMS estimates of VMT by facility type and VMT class were multiplied by the smoothed incident rates to compute estimated total incidents in HPMS for 1984. To obtain the rates used in HERS, the adjusted HPMS rates were multiplied by the ratio of the estimated actual incidents in 1984 to the

[90] Although most changes in facility type result in improving safety, adding lanes frequently results in reducing safety. Thus, the safety benefits of improvements may be either positive or negative.

estimated incidents in HPMS. Separate adjustments were made for rural versus urban roads and for fatalities on roads with fully controlled access versus other roads.

National fatality rates by facility type and urban/rural location were taken from 1984 Federal Accident Reporting Sytem (FARS) data, which provide a virtually complete enumeration. Injury and crash rates are averages of 1982-1984 estimated data from special tabulations of data from the National Highway Traffic Safety Administration's National Accident Sampling System (NASS). NASS is the best available source for aggregate information on police-reported crashes. However, uncertainty of NASS estimates is sufficiently large that use of data averaged across three years generally is preferable to reliance on data from a single year. The years 1982-1984 were chosen because of the consistency of sampling procedures and data forms across those years.

Rural Interstate fatalities, injuries, and crashes were increased by the percentages suggested by Miller[91] to reflect the impact of increasing the speed limit on these roads to 65 mph in 38 states during 1987. Crashes, injuries, and fatalities on local roads and streets were excluded from the national incidence estimates since these facilities are similarly excluded from the HPMS database used by HERS.

HERS 2.0 estimates safety benefits only for adding lanes, restricting access, or adding a median. For two-lane rural roads, data also exist[92] on the significant safety benefits of straightening hazardous horizontal curves, stabilizing or paving deficient shoulders, and widening lanes or shoulders. However, corresponding data do not exist for other facility types. Including these safety benefits in HERS only for two-lane rural roads would bias the selection procedure toward selecting improvements for this type of section. On the other hand, since these safety benefits undoubtedly contribute a larger share of improvement benefits (in both relative and absolute terms) on two-lane rural roads than on other facility types, the HERS 2.0 approach of excluding these benefits biases the procedure against improving two-lane rural sections.

8.4.2 Crash Costs

The HERS estimates of the value of reducing injuries and fatalities are based on the "willingness-to-pay" approach. Thus, the HERS values reflect estimates of how much people have been observed to pay, in time or dollars, for small safety improvements.

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[91]Ted R. Miller, 65 MPH: Winners and Losers, The Urban Institute, Washington, D.C., 1989

[92]Charles V., Zegeer, Donald W. Reinfurt, Joseph Hummer, Lynn Herf, and William W. Hunter, "Safety Effects of Cross Section Design for Rural Two-Lane Roads," Transportation Research Record, Washington, D.C., September 1989.

This approach has been accepted in recent years by the National Safety Council[93], the Office of Management and Budget[94], and the Regulation Council of the U.S. Department

[93] National Safety Council, Accident Facts, Chicago, Illinois, 1988.

[94] Office of Management and Budget, Regulatory Program of the United States, U.S. Government Printing Office, Washington, D.C., 1989.

Exhibit 8-14. Fatality Rates

(per 100 million vehicle miles)

Urban

No. of Lanes: Access Control:	6+ Full	4 Full	6+ Partial	4 Partial	4+ None Divided	4+ None Undivided	2-3
AADT							
< 2,000	1.5	2.0	2.5	3.0	4.0	6.5	2.5
2,000-3,999	1.5	2.0	2.5	3.0	4.0	6.5	4.0
4,000-7,999	1.5	2.0	2.5	3.0	3.5	4.0	3.0
8,000-15,999	1.5	2.0	2.5	2.5	3.0	3.5	2.5
16,000-23,999	1.5	1.5	2.5	2.0	2.5	2.5	2.0
24,000-35,999	1.5	1.0	2.0	2.0	2.0	2.0	2.0
36,000-57,999	1.5	1.0	2.0	2.0	2.0	2.0	2.0
58,000-75,999	1.5	1.0	2.0	2.0	2.0	2.0	2.0
≥ 76,000	1.5	1.0	2.0	2.0	2.0	2.0	2.0

Rural

No. of Lanes: Access Control:	4+ Full	4+ Partial	4+ None Divided	4+ None Undivided	2-3
AADT					
< 2,000	2.0	2.5	3.5	5.0	5.0
2,000-3,999	2.0	2.5	3.5	5.0	5.0
4,000-7,999	2.0	2.5	3.5	5.0	5.0
8,000-15,999	1.5	2.0	2.5	3.0	3.5
16,000-23,999	1.5	2.0	2.5	3.0	3.5
24,000-35,999	1.5	2.5	3.0	3.0	3.5
36,000-57,999	1.5	2.5	3.0	3.0	3.5
58,000-75,999	1.5	2.5	3.0	3.0	3.5
≥ 76,000	1.5	2.5	3.0	3.0	3.5

Exhibit 8-15. Injury Rates

(per 100 million vehicle miles)

Urban

No. of Lanes: Access Control:	6+ Full	4 Full	6+ Partial	4 Partial	4+ None Divided	4+ None Undivided	2-3
AADT							
< 2,000	65	40	365	185	275	580	195
2,000-3,999	65	40	365	185	275	580	195
4,000-7,999	65	35	365	185	275	365	270
8,000-15,999	65	35	365	200	325	365	330
16,000-23,999	70	35	365	220	335	365	395
24,000-35,999	40	40	225	220	335	335	395
36,000-57,999	45	60	225	220	335	335	395
58,000-75,999	55	60	225	220	335	335	395
≥ 76,000	70	60	225	220	335	335	395

Rural

No. of Lanes: Access Control:	4+ Full	4+ Partial	4+ None Divided	4+ None Undivided	2-3
AADT					
< 2,000	45	120	150	150	150
2,000-3,999	45	120	150	170	150
4,000-7,999	45	120	150	200	165
8,000-15,999	45	120	175	205	195
16,000-23,999	45	150	210	230	195
24,000-35,999	45	150	225	230	195
36,000-57,999	45	150	225	230	195
58,000-75,999	45	150	225	230	195
≥ 76,000	45	150	225	230	195

Exhibit 8-16. Crash Rates

(per 100 million vehicle miles)

Urban

No. of Lanes: Access Control:	6+ Full	4 Full	6+ Partial	4 Partial	4+ None Divided	4+ None Undivided	2-3
AADT							
< 2,000	140	70	515	275	415	785	345
2,000-3,999	140	70	515	275	415	785	345
4,000-7,999	140	65	515	275	415	685	490
8,000-15,999	140	65	515	300	490	685	590
16,000-23,999	125	65	515	350	590	685	660
24,000-35,999	90	80	375	375	590	590	660
36,000-57,999	90	120	375	375	590	590	660
58,000-75,999	100	140	375	375	590	590	660
≥ 76,000	120	140	375	375	590	590	660

Rural

No. of Lanes: Access Control:	4+ Full	4+ Partial	4+ None Divided	4+ None Undivided	2-3
AADT					
< 2,000	65	130	175	175	185
2,000-3,999	65	130	175	195	185
4,000-7,999	65	130	175	220	195
8,000-15,999	65	130	200	230	240
16,000-23,999	65	150	220	230	240
24,000-35,999	65	150	220	230	240
36,000-57,999	65	150	220	230	240
58,000-75,999	65	150	220	230	240
≥76,000	65	150	220	230	240

Exhibit 8-17. Implied Annual Numbers of Crashes, Injuries, and Fatalities in HPMS and HERS

	HPMS		HERS	
	Urban	Rural	Urban	Rural
Interstate System				
Fatalities	6,795	5,229	3,753	2,600
Injuries	316,098	96,179	162,376	71,320
Crashes	592,220	154,886	293,986	110,325
Other Nonlocal Roads				
Fatalities	18,575	33,513	13,574	20,565
Injuries	1,392,973	611,957	1,707,010	732,627
Crashes	2,962,880	846,567	3,025,701	966,221

of Transportation[95]; and it is required for the evaluation of safety improvements by a June 30, 1988, Technical Advisory of the Federal Highway Administration.

Methods for quantifying the value people place on mortality reductions include surveying people about their willingness to invest money to increase their health and safety as well as estimating:

- The wage differentials paid to induce people to take risky jobs.
- The values implied by product demand and price in markets for safety-related products such as safer automobiles, smoke detectors, houses in areas with little air pollution, or cigarettes as more has become known about their health effects.
- The trade-offs people make between time, money, comfort, and safety through their speed choice, use of pedestrian tunnels, safety belt use, and purchase and use of child safety seats and motorcycle helmets.

The estimate of societal benefit per death averted used in HERS 2.0 is $2.5 million in 1993 dollars.

Estimated costs for nonfatal injuries were derived from data in Miller, Brinkman and Luchter.[96] This source provides willingness-to-pay estimates of injury costs by injury

[95] J. Marquez, Memorandum from the General Counsel, Office of the Secretary, to the Regulation Council, U.S. Department of Transportation, Washington, D.C., April 10, 1986.

severity on the Accident Injury Severity (AIS) threat-to-life severity scale. For each highway functional system, a weighted average of these costs was obtained using weights from 1982-1984 National Accident Sampling System (NASS) data on the distribution of nonfatal injuries across the AIS scale. The resulting estimates of cost per nonfatal injury are shown in Exhibit 8-18 in 1988 dollars. Also shown in Exhibit 8-18 are estimates of property damage costs per crash. The 1988 estimates were derived from NASS data on the number of vehicles per crash by functional system and crash severity, Insurance Information Institute estimates of damage per vehicle by severity[97] and National Highway Traffic Safety Administration estimates of proportion of damage by severity.[98] The injury and property damage costs can be indexed from 1988 dollars to dollars of another year using the CPI components for medical care and for automobile body work, respectively.[99] Exhibit 8-18 also shows the crash costs in 1993 dollars.[100]

[96]Ted R. Miller, Philip C. Brinkman, and Stephen Luchter, "Crash Costs and Safety Policy," Accident Analysis and Prevention, Volume 21, Number 3, June 1989.

[97]Insurance Information Institute, 1987-88 Property/Casualty Fact Book, New York City, 1987.

[98]U.S. Department of Transportation, National Highway Traffic Safety Administration, The Economic Cost to Society of Motor Vehicle Accidents, Washington, D.C., 1983.

[99]U.S. Department of Labor, Bureau of Labor Statistics, CPI Detailed Report, U.S. Government Printing Office, Washington, D.C., monthly.

[100] Factors of 1.45 and 1.20 were used to convert the 1988 dollars to 1993 dollars for cost per nonfatal injury and property damage cost per crash, respectively.

Exhibit 8-18. Crash Costs

Functional System	Cost per Nonfatal Injury		Property Damage Cost per Crash	
(Dollar Year)	1988	1993	1988	1993
Urban				
Interstate	$ 18,000	$ 26,100	$ 5,000	$ 6,000
Other Freeway	15,000	21,750	6,000	7,200
Other Principal Arterial	16,000	23,200	6,000	7,200
Minor Arterial	13,000	18,850	6,000	7,200
Collector	10,000	14,500	5,000	6,000
Rural				
Interstate	17,000	24,650	4,000	4,800
Other Principal Arterial	22,000	31,900	5,000	6,000
Minor Arterial	18,000	26,100	5,000	6,000
Major Collector	25,000	36,250	5,000	6,000
Minor Collector	20,000	29,000	4,000	4,800

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 2.0. This output consists of the following:

- One page of output summarizing the state of the system at the start of the run;
- For each funding period, one page of output summarizing the state of the system at the end of the funding period;
- 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
- For each funding period and for the overall analysis period, up to twenty pages of additional output providing information on the costs and benefits associated with the selected improvements.

The first page of output provides a summary of initial conditions for:

1. Miles of road;
2. Average PSR;
3. Average speed;
4. Total VMT;
5. Travel-time costs per thousand vehicle-miles;
6. Operating costs per thousand vehicle-miles (for all vehicles combined and separately for four-tire vehicles and for trucks);
7. Crash costs per thousand vehicle miles;
8. Total user costs per thousand vehicle-miles;
9. Crashes per 100 million vehicle miles;
10. Injuries per 100 million vehicle miles;
11. Fatalities per 100 million vehicle miles ;
12. Annual maintenance costs per mile; and
13. Percent of total VMT on roads not meeting minimum tolerable conditions for:

- pavement condition;
- volume/capacity ratio;
- lane width;
- right-shoulder width;
- shoulder type;
- surface type;
- horizontal alignment;
- vertical alignment.

This information is produced for each of the ten functional systems in the HPMS database, with individually produced summary forecasts for the rural system, the urban system, and for the complete system.

For each funding period, one page of output is produced providing a corresponding summary of conditions at the end of the period; and, for each funding period and for the overall analysis period, a similar summary of the change in conditions during the period is produced. For each funding period, the 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 shows how much of these funds were spent; while, if a performance goal was specified, it shows a comparison of the actual performance with the specified goal. Users should be aware that the forecasts of safety statistics may be biased upwards due to the exclusion from HERS 2.0 of non-highway related factors that are causing a secular decline in crash and fatality rates.

In addition to the above output, for each funding period, up to twenty pages of optional output can be requested by the user to provide summaries of:

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;

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[1]In HERS 2.0, 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.

6. The average benefit/cost ratio of selected improvements;
7. Lane-Miles added to the system through widening improvements;
8. Miles improved;
9. Miles of mandatory improvements selected on a priority basis to address unacceptable conditions;
10. Miles of non-mandatory improvements not selected on a priority basis;
11. Total benefits in the last year of the period;
12. Maintenance costs savings in the last year of the period;
13. User benefits in the last year of the period;
14. Travel time savings in the last year of the period;
15. Operating cost savings in the last year of the period;
16. Safety benefits in the last year of the period;
17. Crashes avoided in the last year of the period;
18. Injuries avoided in the last year of the period;
19. Lives saved in the last year of the period;
20. VMT for improved sections in the last year of the period.

Also, any of the first seven of the optional output pages can be requested for the overall analysis period.

Each page of optional output provides values for one of the above measures by improvement type and functional system. Summary values are also produced 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.[2] If estimates of annual effects are printed for the last year of the funding period, a separate set of these pages is not printed for the overall analysis period, since the two sets of output would be identical

The HERS user has the ability to specify which of the twenty pages of optional output should be printed for the funding periods and, separately, which of the first six pages should be printed for the overall analysis period. For a run with four funding periods,

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[2]See preceding footnote.

producing all optional pages would result in 97 pages of output (one page summarizing the initial state of the system, 22 pages for each funding period, plus another eight pages for the overall analysis period).

Appendix A: TEMPERATURE DIFFERENTIALS

Exhibit A - 1 of this appendix contains a listing of the temperature differentials, by state and county, used by HERS to determine the thickness of flexible overlays of rigid pavements as described in Chapter 6. The temperature differentials are defined as the difference between the mean high temperature for the warmest month of the year and the mean low for the coldest month. The values used were obtained from National Oceanographic and Atmospheric Administration data for selected observation points.[1] For states without individual county listings, the listed temperature differential is used throughout the state.

Exhibit A - 1. Temperature Differentials by State and County

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
AL		1		
	Autauga		1	52
	Baldwin		3	49
	Barbour		5	52
	Bibb		7	52
	Blount		9	52
	Bullock		11	52
	Butler		13	52
	Calhoun		15	52
	Chambers		17	52
	Cherokee		19	52
	Chilton		21	52
	Choctaw		23	52
	Clarke		25	52
	Clay		27	52
	Cleburne		29	52
	Coffee		31	52
	Colbert		33	52
	Conecuh		35	52
	Coosa		37	52
	Covington		39	52
	Crenshaw		41	52
	Cullman		43	52
	Dale		45	52
	Dallas		47	52
	De Kalb		49	52
	Elmore		51	52

[1]National Oceanographic and Atmospheric Administration, Local Climatological Data: Annual Summary with Comparative Data, Asheville, N.C., 1987

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Escambia		53	49
	Etowah		55	52
	Fayette		57	52
	Franklin		59	52
	Geneva		61	52
	Greeene		63	52
	Hale		65	52
	Henry		67	52
	Houston		69	52
	Jackson		71	52
	Jefferson		73	52
	Lamar		75	52
	Lauderdale		77	52
	Lawrence		79	52
	Lee		81	52
	Limestone		83	52
	Lowndes		85	52
	Macon		87	52
	Madison		89	52
	Marengo		91	52
	Marion		93	52
	Marshall		95	52
	Mobile		97	49
	Monroe		99	52
	Montgomery		101	52
	Morgan		103	52
	Perry		105	52
	Pickens		107	52
	Pike		109	52
	Randolph		111	52
	Russell		113	52
	St Clair		115	52
	Shelby		117	52
	Sumter		119	52
	Talladega		121	52
	Tallapoosa		123	52
	Tuscaloosa		125	52
	Walker		127	52
	Washington		129	49
	Wilcox		131	52
	Winston		133	52
AK		2		
	Aleutian Is.		10	55
	Anchorage		20	55
	Angoon		30	46
	Barrow-N. Slope		40	64
	Bethel		50	55
	Bristol Bay Borough		60	55
	Bristal Bay		70	55

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Cordova-Mcarthy		80	55
	Fairbanks		90	64
	Haines		100	46
	Juneau		110	46
	Kenai-Cook Inlet		120	55
	Ketchikan		130	46
	Kobuk		140	64
	Kodiak		150	55
	Kuskokwim		160	55
	Mananuska-Susitna		170	55
	Nome		180	64
	Outer Ketchikan		190	46
	Prince Of Wales		200	46
	Seward		210	55
	Sitka		220	46
	Skagway-Yukatat		230	46
	Southeast Fairbanks		240	55
	Upper Yukon		250	64
	Valdez-Chitna-Whittier		260	55
	Wade Hampton		270	55
	Wrangell-Petersburg		280	46
	Yukon-Koyukuk		290	64
AZ		4		
	Apache		1	65
	Cochise		3	62
	Coconino		5	65
	Gila		7	67
	Graham		9	65
	Greenlee		11	65
	La Paz		12	65
	Maricopa		13	67
	Mohave		15	65
	Navajo		17	65
	Pima		19	62
	Pinal		21	65
	Santa Cruz		23	62
	Yavapai		25	67
	Yuma		27	65
AR		5		61
CA		6		
	Alameda		1	32
	Alpine		3	55
	Amador		5	55
	Butte		7	55
	Calaveras		9	55
	Colusa		11	55
	Contra Costa		13	32
	Del Norte		15	32
	El Dorado		17	55

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Fresno		19	61
	Glenn		21	55
	Humboldt		23	32
	Imperial		25	61
	Inyo		27	61
	Kern		29	62
	Kings		31	61
	Lake		33	55
	Lassen		35	55
	Los Angeles		37	30
	Madera		39	61
	Marin		41	32
	Mariposa		43	55
	Mendocino		45	32
	Merced		47	55
	Modoc		49	55
	Mono		51	55
	Monterey		53	32
	Napa		55	55
	Nevada		57	55
	Orange		59	30
	Placer		61	55
	Plumas		63	55
	Riverside		65	61
	Sacramento		67	55
	San Benito		69	61
	San Bernardino		71	62
	San Diego		73	30
	San Francisco		75	32
	San Joaquin		77	55
	San Luis Obispo		79	32
	San Mateo		81	32
	Santa Barbara		83	32
	Santa Clara		85	32
	Santa Cruz		87	32
	Shasta		89	55
	Sierra		91	55
	Siskiyou		93	55
	Solano		95	55
	Sonoma		97	32
	Stanislaus		99	55
	Sutter		101	55
	Tehama		103	55
	Trinity		105	55
	Tulare		107	61
	Tuolumne		109	55
	Ventura		111	30
	Yolo		113	55
	Yuba		115	55

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
CO		8		
	Adams		1	69
	Alamosa		3	69
	Arapahoe		5	69
	Archuleta		7	69
	Baca		9	69
	Bent		11	75
	Boulder		13	69
	Chaffee		15	69
	Cheyenne		17	75
	Clear Creek		19	69
	Conejos		21	69
	Costilla		23	69
	Crowley		25	75
	Custer		27	69
	Delta		29	69
	Denver		31	69
	Dolores		33	69
	Douglas		35	69
	Eagle		37	69
	Elbert		39	69
	El Paso		41	69
	Fremont		43	69
	Garfield		45	69
	Gilpin		47	69
	Grand		49	69
	Gunnison		51	69
	Hinsdale		53	69
	Huerfano		55	69
	Jackson		57	69
	Jefferson		59	69
	Kiowa		61	75
	Kit Carson		63	75
	Lake		65	69
	La Plata		67	69
	Larimer		69	69
	Las Animas		71	69
	Lincoln		73	75
	Logan		75	75
	Mesa		77	69
	Mineral		79	69
	Moffat		81	69
	Montezuma		83	69
	Montrose		85	69
	Morgan		87	69
	Otero		89	75
	Ouray		91	69
	Park		93	69
	Phillips		95	75

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Pitkin		97	69
	Prowers		99	75
	Pueblo		101	75
	Rio Blanco		103	69
	Rio Grande		105	69
	Routt		107	69
	Saquache		109	69
	San Juan		111	69
	San Miguel		113	69
	Sedgwick		115	75
	Summit		117	69
	Teller		119	69
	Washington		121	75
	Weld		123	69
	Yuma		125	75
CT		9		68
DE		10		62
DC		11		66
FL		12		
	Alachua		1	44
	Baker		3	44
	Bay		5	43
	Bradford		7	44
	Brevard		9	44
	Broward		11	31
	Calhoun		13	43
	Charlotte		15	31
	Citrus		17	44
	Clay		19	44
	Collier		21	31
	Columbia		23	48
	Dade		25	31
	De Soto		27	44
	Dixie		29	44
	Duval		31	44
	Escambia		33	43
	Flagler		35	44
	Franklin		37	48
	Gadsden		39	48
	Gilchrist		41	44
	Glades		43	44
	Gulf		45	43
	Hamilton		47	48
	Hardee		49	44
	Hendry		51	43
	Hernando		53	44
	Highlands		55	44
	Hillsborough		57	44
	Holmes		59	43

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Indian River		61	44
	Jackson		63	43
	Jefferson		65	48
	Lafeyette		67	48
	Lake		69	44
	Lee		71	31
	Leon		73	48
	Levy		75	44
	Liberty		77	48
	Madison		79	48
	Manatee		81	44
	Marion		83	44
	Martin		85	44
	Monroe		87	31
	Nassau		89	44
	Okaloosa		91	43
	Okeechobee		93	44
	Orange		95	44
	Osceola		97	44
	Palm Beach		99	31
	Pasco		101	44
	Pinellas		103	43
	Polk		105	44
	Putnam		107	44
	St Johns		109	44
	St Lucie		111	44
	Santa Rosa		113	43
	Sarasota		115	31
	Seminole		117	43
	Sumter		119	44
	Suwannee		121	48
	Taylor		123	48
	Union		125	44
	Volusia		127	44
	Wakulla		129	48
	Walton		131	43
	Washington		133	43
GA		13		54
HI		15		
	Hawaii		1	13
	Honolulu		3	22
	Kauai		7	22
	Maui		9	22
ID		16		69
IL		17		69
IN		18		66
IA		19		74
KS		20		71
KY		21		63

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
LA		22		
	Acadia		1	48
	Allen		3	48
	Ascension		5	48
	Assumption		7	48
	Avoyelles		9	48
	Beauregard		11	48
	Bienville		13	48
	Bossier		15	48
	Caddo		17	48
	Calcasieu		19	41
	Caldwell		21	48
	Cameron		23	41
	Catahoula		25	48
	Claiborne		27	48
	Concordia		29	48
	De Soto		31	48
	East Baton Rouge		33	48
	East Carroll		35	48
	East Feliciana		37	48
	Evangeline		39	48
	Franklin		41	48
	Grant		43	48
	Iberia		45	48
	Iberville		47	48
	Jackson		49	48
	Jefferson		51	48
	Jefferson Davis		53	41
	Lafayette		55	48
	Lafourche		57	48
	Lasalle		59	48
	Lincoln		61	48
	Livingston		63	48
	Madison		65	48
	Morehouse		67	48
	Natchitoches		69	48
	Orleans		71	48
	Ouachita		73	48
	Plaquemines		75	48
	Pointe Coupee		77	48
	Rapides		79	48
	Redriver		81	48
	Richland		83	48
	Sabine		85	48
	St Bernard		87	48
	St Charles		89	48
	St Helena		91	48
	St James		93	48
	St John The Babtist		95	48

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	St Landry		97	48
	St Martin		99	48
	St Mary		101	48
	St Tammany		103	48
	Tangipahoa		105	48
	Tensas		107	48
	Terrebonne		109	48
	Union		111	48
	Vermillion		113	41
	Vernon		115	48
	Washington		117	48
	Webster		119	48
	West Baton Rouge		121	48
	West Carroll		123	48
	West Feliciana		125	48
	Winn		127	48
ME		23		67
MD		24		63
MA		25		59
MI		26		
	Alcona		1	64
	Alger		3	69
	Allegan		5	64
	Alpena		7	64
	Antrim		9	64
	Arenac		11	64
	Baraga		13	69
	Barry		15	64
	Bay		17	64
	Benzie		19	64
	Berrien		21	64
	Branch		23	64
	Calhoun		25	64
	Cass		27	64
	Charlevoix		29	64
	Cheboygan		31	64
	Chippewa		33	69
	Clare		35	64
	Clinton		37	64
	Crawford		39	64
	Delta		41	69
	Dickinson		43	69
	Eaton		45	64
	Emmet		47	64
	Genesee		49	64
	Gladwin		51	64
	Gogebic		53	69
	Grand Traverse		55	64
	Gratiot		57	64

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Hillsdale		59	64
	Houghton		61	69
	Huron		63	64
	Ingham		65	64
	Ionia		67	64
	Iosco		69	64
	Iron		71	69
	Isabella		73	64
	Jackson		75	64
	Kalamazoo		77	64
	Kalkaska		79	64
	Kent		81	64
	Keweenaw		83	69
	Lake		85	64
	Lapeer		87	64
	Leelanau		89	64
	Lenawee		91	64
	Livinston		93	64
	Luce		95	69
	Mackinac		97	69
	Macomb		99	64
	Manistee		101	64
	Marquette		103	69
	Mason		105	64
	Mecosta		107	64
	Menominee		109	69
	Midland		111	64
	Missaukee		113	64
	Monroe		115	64
	Montcalm		117	64
	Montmorency		119	64
	Muskegon		121	64
	Newaygo		123	64
	Oakland		125	64
	Oceana		127	64
	Ogemaw		129	64
	Ontonagon		131	64
	Osceola		133	64
	Oscoda		135	64
	Otsego		137	64
	Ottawa		139	64
	Presque Ile		141	64
	Roscommon		143	64
	Saginaw		145	64
	St Clair		147	64
	St Joseph		149	64
	Sanilac		151	64
	Schoolcraft		153	69
	Shiawassee		155	64

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Tuscola		157	64
	Van Buren		159	64
	Washtenaw		161	64
	Wayne		163	64
	Wexford		165	64
MN		27		78
MS		28		57
MO		29		67
MT		30		72
NE		31		76
NV		32		
	Carson City		510	69
	Churchill		1	69
	Clark		3	72
	Douglas		5	69
	Elko		7	80
	Esmeralda		9	72
	Eureka		11	80
	Humboldt		13	69
	Lander		15	69
	Lincoln		17	72
	Lyon		19	69
	Mineral		21	72
	Nye		23	72
	Pershing		27	69
	Storey		29	69
	Washoe		31	69
	White Pine		33	80
NH		33		73
NJ		34		61
NM		35		69
NY		36		
	Albany		1	69
	Allegany		3	64
	Bronx		5	59
	Broome		7	64
	Cattaraugus		9	64
	Cayuga		11	64
	Chautauqua		13	64
	Chemung		15	64
	Chenango		17	64
	Clinton		19	69
	Columbia		21	69
	Cortland		23	64
	Delaware		25	64
	Dutchess		27	59
	Erie		29	64
	Essex		31	69
	Franklin		33	69

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Fulton		35	69
	Genesee		37	64
	Greene		39	69
	Hamilton		41	69
	Herkimer		43	64
	Jefferson		45	64
	Kings		47	59
	Lewis		49	64
	Livingston		51	64
	Madison		53	64
	Monroe		55	64
	Montgomery		57	64
	Nassau		59	59
	New York		61	59
	Niagra		63	64
	Oneida		65	64
	Onondaga		67	64
	Ontario		69	64
	Orange		71	64
	Orleans		73	64
	Oswego		75	64
	Otsego		77	64
	Putnam		79	59
	Queens		81	59
	Rensselaer		83	64
	Richmond		85	64
	Rockland		87	64
	St Lawrence		89	69
	Saratoga		91	69
	Schenectady		93	69
	Schoharie		95	69
	Schuyler		97	64
	Seneca		99	64
	Steuben		101	64
	Suffolk		103	59
	Sullivan		105	59
	Tioga		107	64
	Tompkins		109	64
	Ulster		111	64
	Warren		113	69
	Washington		115	69
	Wayne		117	64
	Westchester		119	59
	Wyoming		121	64
	Yates		123	64
NC		37		
	Alamance		1	58
	Alexander		3	58
	Alleghany		5	58

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Anson		7	58
	Ashe		9	58
	Avery		11	58
	Beaufort		13	58
	Bertie		15	58
	Bladen		17	50
	Brunswick		19	50
	Buncombe		21	58
	Burke		23	58
	Cabarrus		25	58
	Caldwell		27	58
	Camden		29	58
	Carteret		31	50
	Caswell		33	58
	Catawba		35	58
	Chatham		37	58
	Cherokee		39	58
	Chowan		41	58
	Clay		43	58
	Cleveland		45	58
	Columbus		47	58
	Craven		49	58
	Cumberland		51	58
	Carrituck		53	58
	Dare		55	50
	Davidson		57	58
	Davoe		59	58
	Duplin		61	58
	Durham		63	58
	Edgecombe		65	58
	Forsyth		67	58
	Franklin		69	58
	Gaston		71	58
	Gates		73	58
	Graham		75	58
	Granville		77	58
	Greene		79	58
	Guilford		81	58
	Halifax		83	58
	Harnett		85	58
	Haywood		87	58
	Henderson		89	58
	Hertford		91	58
	Hoke		93	58
	Hyde		95	50
	Iredell		97	58
	Jackson		99	58
	Johnston		101	58
	Jones		103	58

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Lee		105	58
	Lenoir		107	58
	Lincoln		109	58
	Mcdowell		111	58
	Macon		113	58
	Madison		115	58
	Martin		117	58
	Mecklinberg		119	58
	Mitchell		121	58
	Montgomery		123	58
	Moore		125	58
	Nash		127	58
	New Hanover		129	50
	Northampton		131	58
	Onslow		133	50
	Orange		135	58
	Pamlico		137	50
	Posquotank		139	58
	Pender		141	50
	Perquimans		143	58
	Person		145	58
	Pitt		147	58
	Polk		149	58
	Randolph		151	58
	Richmond		153	58
	Robeson		155	50
	Rockingham		157	58
	Rowan		159	58
	Rutherford		161	58
	Sampson		163	58
	Scotland		165	58
	Stanly		167	58
	Stokes		169	58
	Surry		171	58
	Swain		173	58
	Transylvania		175	58
	Tyrrell		177	58
	Union		179	58
	Vance		181	58
	Wake		183	58
	Warren		185	58
	Washington		187	58
	Watauga		189	58
	Wayne		191	58
	Wilkes		193	58
	Wilson		195	58
	Yadkin		197	58
	Yancey		199	58
ND		38		87

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
OH		39		64
OK		40		67
OR		41		
	Baker		1	60
	Benton		3	45
	Clackamas		5	45
	Clatsop		7	45
	Columbia		9	45
	Coos		11	45
	Crppl		13	60
	Curry		15	45
	Deschutes		17	60
	Douglas		19	45
	Gilliam		21	60
	Grant		23	60
	Harney		25	60
	Hood River		27	60
	Jackson		29	60
	Jefferson		31	60
	Josephine		33	60
	Klamath		35	60
	Lake		37	60
	Lane		39	45
	Lincoln		41	45
	Linn		43	60
	Malheur		45	60
	Marion		47	45
	Morrow		49	60
	Multnomah		51	45
	Polk		53	45
	Sherman		55	60
	Tillamook		57	60
	Umatilla		59	60
	Union		61	60
	Wallowa		63	60
	Wasco		65	60
	Washington		67	45
	Wheeler		69	60
	Yamhill		71	45
PA		42		
	Adams		1	69
	Allegheny		3	62
	Armstrong		5	62
	Beaver		7	62
	Bedford		9	69
	Berks		11	60
	Blair		13	69
	Bradford		15	69
	Bucks		17	60

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Butler		19	62
	Cambria		21	69
	Cameron		23	69
	Carbon		25	69
	Centre		27	69
	Chester		29	60
	Clarion		31	62
	Clearfield		33	69
	Clinton		35	69
	Columbia		37	69
	Crawford		39	62
	Cumberland		41	69
	Dauphin		43	69
	Delaware		45	60
	Elk		47	69
	Erie		49	62
	Fayette		51	62
	Forest		53	62
	Franklin		55	69
	Fulton		57	69
	Greene		59	62
	Huntington		61	69
	Indiana		63	62
	Jefferson		65	62
	Juniata		67	69
	Luckawanna		69	69
	Lancaster		71	60
	Lawrence		73	69
	Lebanon		75	69
	Lehigh		77	60
	Luzerne		79	69
	Lycoming		81	69
	Mckean		83	69
	Mercer		85	62
	Miffin		87	69
	Monroe		89	69
	Montgomery		91	60
	Montour		93	69
	Northhampton		95	69
	Northumberland		97	69
	Perry		99	69
	Philidelphia		101	69
	Pike		103	69
	Potter		105	69
	Schuykill		107	69
	Snyder		109	69
	Somerset		111	69
	Sullivan		113	69
	Susquehanna		115	69

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Tioga		117	69
	Union		119	69
	Venango		121	62
	Warren		123	62
	Washington		125	69
	Wayne		127	69
	Westmoreland		129	62
	Wyoming		131	69
	York		133	69
RI		44		61
SC		45		58
SD		46		81
TN		47		61
TX		48		
	Anderson		1	61
	Andrews		3	67
	Angelina		5	53
	Aransas		7	43
	Archer		9	61
	Armstrong		11	67
	Atascosa		13	61
	Austin		15	53
	Bailey		17	67
	Bandera		19	61
	Bastrop		21	61
	Baylor		23	61
	Bee		25	43
	Bell		27	61
	Bexar		29	61
	Bianco		31	61
	Borden		33	67
	Bosque		35	61
	Bowie		37	61
	Brazoria		39	43
	Brazos		41	61
	Brewster		43	67
	Briscoe		45	67
	Brooks		47	43
	Brown		49	61
	Burleson		51	61
	Burnet		53	61
	Caldwell		55	61
	Calhoun		57	43
	Callahan		59	61
	Cameron		61	43
	Camp		63	61
	Carson		65	67
	Cass		67	61
	Castro		69	67

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Chambers		71	43
	Cherokee		73	61
	Childress		75	67
	Clay		77	61
	Cochran		79	67
	Coke		81	67
	Coleman		83	61
	Collin		85	61
	Collingsworth		87	67
	Colorado		89	53
	Comal		91	61
	Comanche		93	61
	Concho		95	61
	Cooke		97	61
	Coryell		99	61
	Cottle		101	67
	Crane		103	67
	Crockett		105	61
	Crosby		107	67
	Culberson		109	67
	Dallam		111	67
	Dallas		113	61
	Dawson		115	67
	Deaf Smith		117	67
	Delta		119	61
	Denton		121	61
	De Witt		123	61
	Dickens		125	67
	Dimmit		127	43
	Donley		129	67
	Duval		131	43
	Eastland		133	61
	Ector		135	67
	Edwards		137	61
	Ellis		139	61
	El Paso		141	67
	Erath		143	61
	Falls		145	61
	Fannin		147	61
	Fayette		149	61
	Fisher		151	67
	Floyd		153	67
	Foard		155	67
	Fort Bend		157	53
	Franklin		159	61
	Freestone		161	61
	Frio		163	61
	Gaines		165	67
	Galveston		167	43

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Garza		169	67
	Gillespie		171	61
	Glasscock		173	67
	Goliad		175	43
	Gonzales		177	61
	Gray		179	67
	Grayson		181	61
	Gregg		183	61
	Grimes		185	53
	Guadalupe		187	61
	Hale		189	67
	Hall		191	67
	Hamilton		193	61
	Hansford		195	67
	Hardeman		197	67
	Hardin		199	53
	Harris		201	53
	Harrison		203	61
	Hartley		205	67
	Haskell		207	67
	Hays		209	61
	Hemphill		211	67
	Henderson		213	61
	Hidalgo		215	43
	Hill		217	61
	Hockley		219	67
	Hood		221	61
	Hopkins		223	61
	Houston		225	53
	Howard		227	67
	Hudspeth		229	67
	Hunt		231	61
	Hutchinson		233	67
	Irion		235	67
	Jack		237	61
	Jackson		239	43
	Jasper		241	53
	Jeff Davis		243	67
	Jefferson		245	43
	Jim Hogg		247	43
	Jim Wells		249	43
	Johnson		251	61
	Jones		253	67
	Karnes		255	61
	Kaufman		257	61
	Kendall		259	61
	Kenedy		261	43
	Kent		263	67
	Kerr		265	61

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Kimble		267	61
	King		269	67
	Kinney		271	61
	Kleberg		273	61
	Knox		275	67
	Lamar		277	61
	Lamb		279	67
	Lampass		281	61
	La Salle		283	43
	Lavaca		285	61
	Lee		287	61
	Leon		289	61
	Liberty		291	53
	Limestone		293	61
	Lipscomb		295	67
	Live Oak		297	43
	Llano		299	61
	Loving		301	67
	Lubbock		303	67
	Lynn		305	67
	Mcculloch		307	61
	Mclennan		309	61
	Mcmullen		311	43
	Madison		313	53
	Marion		315	61
	Martin		317	67
	Mason		319	61
	Matagorda		321	43
	Maverick		323	61
	Medina		325	61
	Menard		327	61
	Midland		329	67
	Milam		331	61
	Mills		333	61
	Mitchell		335	67
	Montague		337	61
	Montgomery		339	53
	Moore		341	67
	Morris		343	61
	Motley		345	67
	Nacogdoches		347	61
	Navarro		349	61
	Newton		351	53
	Nolan		353	67
	Nueces		355	43
	Ochiltree		357	67
	Oldham		359	67
	Orange		361	43
	Palo Pinto		363	61

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Panola		365	61
	Parker		367	61
	Parmer		369	67
	Pecos		371	67
	Polk		373	53
	Potter		375	67
	Presidio		377	67
	Rains		379	61
	Randall		381	67
	Reagan		383	67
	Real		385	61
	Red River		387	61
	Reeves		389	67
	Refugio		391	43
	Roberts		393	67
	Robertson		395	61
	Rockwall		397	61
	Runnels		399	61
	Rusk		401	61
	Sabine		403	61
	San Augustine		405	61
	San Jacinto		407	53
	San Patricio		409	43
	San Saba		411	61
	Schleicher		413	61
	Scurry		415	67
	Shackelford		417	61
	Shelby		419	61
	Sherman		421	67
	Smith		423	61
	Somerville		425	61
	Starr		427	43
	Stephens		429	61
	Sterling		431	67
	Stonewall		433	67
	Sutton		435	61
	Swisher		437	67
	Tarrant		439	61
	Taylor		441	67
	Terrell		443	67
	Terry		445	67
	Throckmorton		447	61
	Titus		449	61
	Tom Green		451	67
	Travis		453	61
	Trinity		455	53
	Tyler		457	53
	Upshur		459	61
	Upton		461	67

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Uvalde		463	61
	Val Verde		465	61
	Van Zandt		467	61
	Victoria		469	43
	Walker		471	53
	Waller		473	53
	Ward		475	67
	Washington		477	53
	Webb		479	43
	Wharton		481	53
	Wheeler		483	67
	Wichita		485	61
	Wilbarger		487	61
	Willacy		489	43
	Williamson		491	61
	Wilson		493	61
	Winkler		495	67
	Wise		497	61
	Wood		499	61
	Yoakum		501	67
	Young		503	61
	Zapata		505	43
	Zavala		507	61
UT		49		74
VT		50		73
VA		51		
	Accomack		1	54
	Albemarle		3	61
	Alleghany		5	61
	Amelia		7	61
	Amherst		9	61
	Appomattox		11	61
	Arlington		13	61
	Augusta		15	61
	Bath		17	61
	Bedford		19	61
	Bland		21	61
	Botetourt		23	61
	Brunswick		25	61
	Buchanan		27	61
	Buckingham		29	61
	Campell		31	61
	Caroline		33	61
	Carroll		35	61
	Charles City		37	61
	Charolotte		39	61
	Chesterfield		41	61
	Clarke		43	66
	Craig		45	61

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Culpeper		47	61
	Cumberland		49	61
	Dickenson		51	61
	Dinwiddle		53	61
	Essex		57	61
	Fairfax		59	61
	Fauquier		61	66
	Floyd		63	61
	Fluvanna		65	61
	Franklin		67	61
	Frederick		69	66
	Giles		71	61
	Gloucester		73	54
	Goochland		75	61
	Grayson		77	61
	Greene		79	61
	Greensville		81	61
	Halifax		83	61
	Hanover		85	61
	Henrico		87	61
	Henry		89	61
	Highland		91	61
	Isle Of Wright/Wir		93	61
	James City		95	61
	King And Queen		97	61
	King George		99	61
	King William		101	61
	Lancaster		103	54
	Lee		105	61
	Loudoun		107	66
	Louisa		109	61
	Lunenburg		111	61
	Madison		113	61
	Mathews		115	54
	Mecklenburg		117	61
	Middlesex		119	54
	Montgomery		121	61
	Nelson		125	61
	New Kent		127	61
	Northhampton		131	54
	Northumberland		133	54
	Nottoway		135	61
	Orange		137	61
	Page		139	61
	Patrick		141	61
	Pittsylvania		143	61
	Powhatan		145	61
	Prince Edward		147	61
	Prince George		151	61

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Prince William		153	66
	Pulaski		155	61
	Rappahannock		157	61
	Richmond		159	61
	Roanoke		161	61
	Rockbridge		163	61
	Rockingham		165	61
	Russell		167	61
	Scott		169	61
	Shenandoah		171	61
	Smyth		173	61
	Southampton		175	61
	Spotsylvania		177	61
	Stafford		179	66
	Surry		181	61
	Sussex		183	61
	Tazewell		185	61
	Warren		187	66
	Washington		191	61
	Westmoreland		193	61
	Wise		195	61
	Wythe		197	61
	York		199	54
	Abingdon		501	61
	Alexandria		510	66
	Bedford		515	61
	Bristol		520	61
	Buena Vista		530	61
	Charlottesville		540	61
	Chesapeake		550	54
	Clifton Forge		560	61
	Colonial Heights		570	61
	Covington		580	61
	Danville		590	61
	Emporia		595	61
	Fairfax		600	66
	Falls Church		610	66
	Franklin		620	66
	Fredericksburg		630	61
	Galax		640	61
	Hampton		650	54
	Harrisonburg		660	61
	Hopewell		670	61
	Lexington		678	61
	Lynchburg		680	61
	Martinsville		690	61
	Newport News		700	54
	Norfolk		710	54
	Norton		720	61

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Pertersburg		730	61
	Portsmouth		740	54
	Radford		750	61
	Richmond		760	61
	Roanoke		770	61
	Salem		775	61
	South Boston		780	61
	Staunton		790	61
	Suffolk		800	54
	Virginia Beach		810	54
	Waynesboro		820	61
	Williamsburg		830	54
	Winchester		840	66
WA		53		
	Adams		1	63
	Asotin		3	63
	Benton		5	63
	Chelan		7	63
	Clallam		9	38
	Clark		11	38
	Columbia		13	63
	Cowitz		15	38
	Douglas		17	63
	Ferry		19	63
	Franklin		21	63
	Garfield		23	63
	Grant		25	63
	Grays Harbor		27	38
	Island		29	38
	Jefferson		31	38
	King		33	38
	Kitsap		35	38
	Kittitas		37	63
	Klickitat		39	63
	Lewis		41	38
	Lincoln		43	63
	Mason		45	38
	Okanogan		47	63
	Pacific		49	38
	Pend Oreille		51	63
	Pierce		53	38
	San Juan		55	38
	Skagit		57	38
	Skamania		59	63
	Snohomish		61	38
	Spokane		63	63
	Stevens		65	63
	Thurston		67	38
	Wankiakum		69	38

STATE	County	STATE FIPS	COUNTY FIPS	TEMP
	Walla Walla		71	63
	Whatcom		73	63
	Whitman		75	63
	Yakima		77	63
WV		54		60
WI		55		69
WY		56		69
PR		72		19

Appendix B: BENEFIT COST ANALYSIS

This appendix presents a detailed description of the benefit/cost analysis procedure used by HERS 2.0. It is divided into two major sections. The first describes the analysis of potential improvements to a section for which no improvements have yet been selected fot the current funding period. The second section 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.

B.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.

B.1.1 The Normal Case

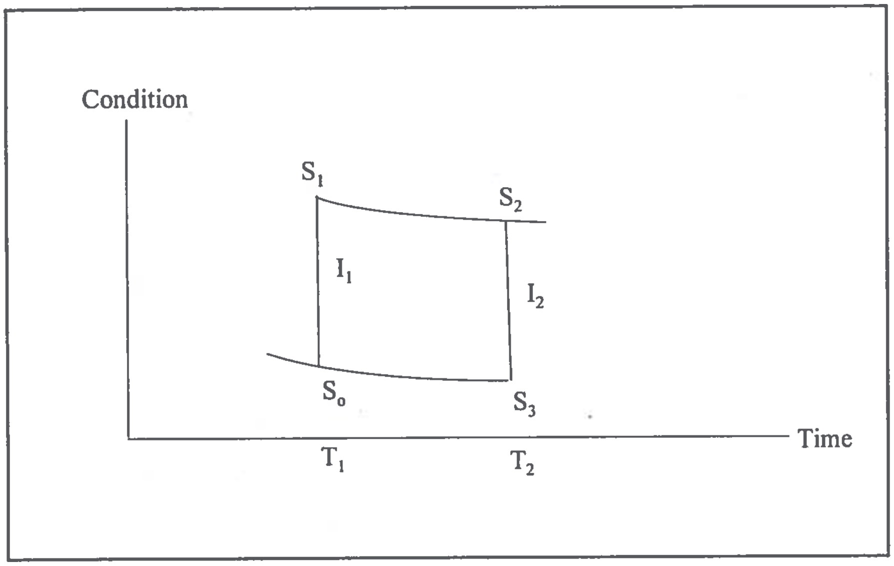
The normal situation described above is shown schematically in Exhibit B - 1. In the exhibit, S_0 represents the condition or state of section H (PSR, capacity, alignment characteristics, etc.) prior to improvement at time T_1; S_1 represents the condition at time T_1 after improvement I_1 is implemented; 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 B - 1) that would improve H's condition from S_3 to S_2. Under most conditions, the cost of 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.

Exhibit B - 1. The Effect of Improvements on Highway Conditions



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.

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]

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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

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 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 $C(I_2)$ is appreciably less than $C(I_1)$. In HERS 2.0, 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 H appreciably above S_2, and the residual value at time T_2 of reconstruction at time T_1 will be appreciably less than the normal cost of reconstruction. The result is that the procedure will be biased against selecting

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be desirable to implement improvements on sections with growing traffic volumes somewhat earlier than indicated by HERS.

[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.

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 prereconstruction PSR (represented by S_0 in Exhibit B - 1) results in a relatively low PSR improvement, and, accordingly, a relatively low residual value. The extent of the bias against reconstruction thus varies with prereconstruction PSR. This bias against reconstruction, and particularly against early reconstruction, appears to be reasonable, though it may be somewhat overstated -- particularly since HERS 2.0 does not have any way of representing the non-economic factors that result in early reconstruction.

B.1.2 Sections with Declining Traffic Volumes

Consider now a section on which traffic is forecasted 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.

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 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 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 the current 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.

B.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 during 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 end of the next funding period. In this case, if resurfacing is not performed at T_1 (in Exhibit B - 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.

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

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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.

to use for analyzing I_1 extends until the section's PSR becomes unacceptable if no improvements are made to the section.

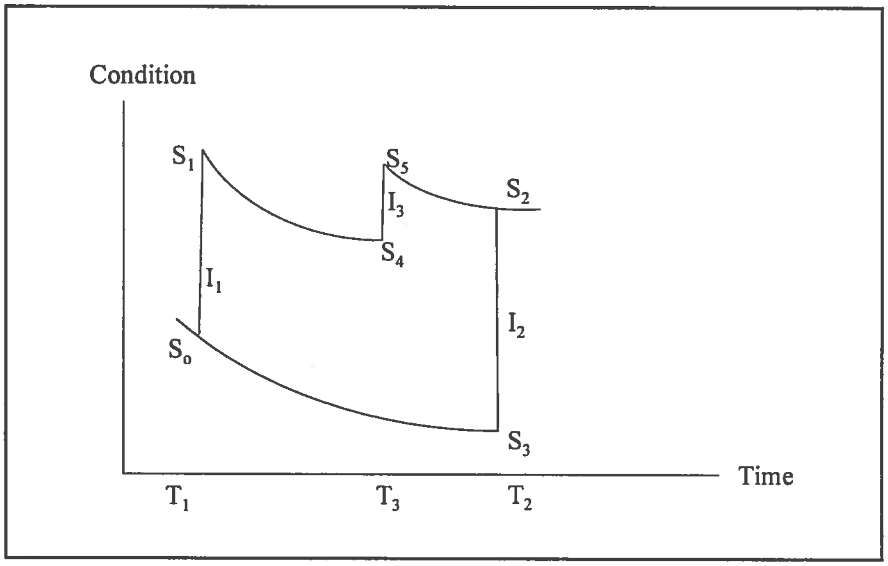
If the BCA period used is only a single-funding period long, the residual value of I_1 will be particularly high (due to high cost of reconstruction) and an inappropriate bias toward selecting I_1 will be created. Use of the longer BCA period avoids this bias, but it is likely that I_1 would still be 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 2.0 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 B - 2. 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 B - 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.

Exhibit B - 2. Effects of an Improvement Over Several Funding Periods



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 B - 2. HERS 2.0 does not contain code for handling this case, though such code may be incorporated into a subsequent version of HERS.

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 B - 1.

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 any 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

$$C\left(Recon\left(I_2\right)\right) \;=\; \frac{PSR\left(S_2\right) - PSR\left(S_3\right)}{PSRRecon - PSR\left(S_3\right)} \; C\left(Recon\right) \qquad \text{(B.1)}$$

where RRecon 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.

B.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 2.0, I_4 may differ from I_1 in one or more of the following ways[5]:

(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 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.
2. Only (b) exists.
3. (c) exists either alone or in conjunction with (a) or (b).

(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.

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[5]A fourth type of difference occurs 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, as discussed in Chapter 3, the current HPMS database does not contain information that could be used as the basis for such an analysis.

B.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 2.0, 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 2.0, 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 is 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 period that is below that level is used instead; and (2) if the PSR in 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 2.0 assumptions about minimum pavement deterioration rates effectively limit the length of the analysis period to a maximum of 21 years for resurfacing and a typical maximum of about 35 years for reconstruction.

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.

B.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 2.0 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 2.0 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 necessarily 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.

B.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.

U.S. GOVERNMENT PRINTING OFFICE: 1997-500-498