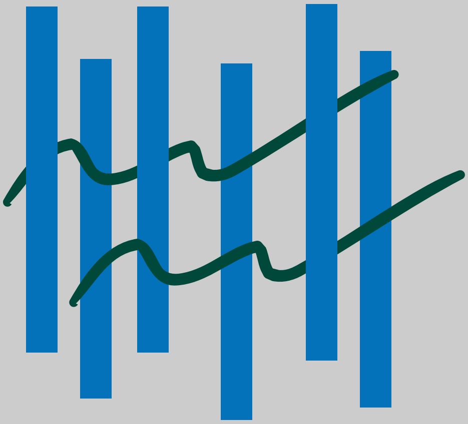

HERS-ST 2.0

Highway Economic Requirements System-State Version

OVERVIEW

U.S. Department of Transportation
Federal Highway Administration

2002

Highway Economic Requirements System State Version

Overview

U.S. Department
of Transportation
**Federal Highway
Administration**

September 2002

Contents

Chapter 5. ESTIMATION OF IMPACTS 5-1

Acronyms used in this report

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ANB	Annualized net benefits
APLVM	Aggregate Probabilistic Limiting Velocity Model
BCA	benefit-cost analysis
BCR	benefit-cost ratio
BIAS	Bridge Investment Analysis System
BLS	U.S. Bureau of Labor Statistics
BNIP	Bridge Needs Investment Process
C&P	Conditions and Performance report to Congress
DL	deficiency level
DOT	U.S. Department of Transportation
DS	design standard
EPA	Environmental Protection Agency
ESAL	equivalent single axle load
FAA	U.S. Federal Aviation Administration
FHWA	U.S. Federal Highway Administration
FP	funding period
FTA	U.S. Federal Transit Administration
GAO	U.S. Government Accounting Office
GIS-T	Geographic Information System - Transportation
HCM	Highway Capacity Manual
HDM	Highway Design Model
HERS	Highway Economic Requirements System
HPMS	Highway Performance Monitoring System
IBCR	incremental benefit-cost ratio
IRI	International Roughness Index
LCCA	life-cycle cost analysis
LOS	level of service
LRE	long-run elasticity
LRS	long-run share/supplement/shift (part of LRE)
MCS	minimum condition standard
MTC	minimum tolerable condition

Acronyms used in this report

NCHRP	National Cooperative Highway Research Program
NOB	Net Operating Benefits (excluding fixed costs)
NPV	net present value
OAP	overall analysis period
OMB	U.S. Office of Management and Budget
OST	Office of the Secretary of Transportation
PCE	passenger-car equivalent space on a highway (for trucks)
PSR	Present Serviceability Rating
RL	reconstruction level
ROW	right-of-way
RSL	remaining service life (of an asset)
SDL	serious deficiency level
SRE	short-run elasticity
TCD	traffic control device (signal or stop sign)
TRDF	Texas Research and Development Foundation
UL	unacceptable deficiency level
V/C	volume-to-capacity ratio
VMT	vehicle miles of travel

References

Federal Highway Administration, *Highway Economic Requirements System State Version (HERS-ST)*: *User's Guide*, Washington, DC: US DOT/FHWA, September 2002.

short citation: *HERS-ST User’s Guide* (2002).

Federal Highway Administration, *Highway Economic Requirements System State Version (HERS-ST)*: *Technical Report (Draft)*, Washington, DC: US DOT/FHWA, September 2002.

short citation: *HERS-ST Technical Report* (2002).

Lee, Douglass B., Jr., “Induced Demand and Elasticity,” *Highway Economic Requirements System State Version (HERS-ST)*, Washington, DC: US DOT/FHWA, September 2002.

short citation: Lee, “Induced Demand and Elasticity” *HERS-ST* (2002)

CHAPTER 1

INTRODUCTION

This document introduces the reader to the Highway Economic Requirements System-State Version (HERS-ST). The Overview Report is meant to be a complement to other technical documentation, notably the “HERS-ST Technical Report,” and the “HERS-ST User's Guide.”

The Overview offers a description of the conceptual structure of the model, organized in a way that allows major components to be disassembled into subcomponents, and further into equations and procedures. To go beyond this level, the reader is referred to specific sections of the aforementioned reports. Unique among the available documentation materials, this Report provides tutorials for some of the more difficult concepts.

The HERS-ST model is a highway investment/ performance model that considers engineering and economic concepts and principles in reviewing the impact of alternative highway investment levels and program structures on highway condition, performance, and user impacts. Specifically, the HERS-ST model simulates highway condition and performance levels and identifies deficiencies through the use of engineering principles. However, when it simulates the selection of improvements for implementation, it relies on economic criteria. In general, HERS-ST is designed to select only those projects where benefits will exceed initial costs. Its benefits consist of reductions in user costs, agency maintenance costs, and externalities over the life of the improvement. Costs consist of the initial capital costs of the improvement. HERS-ST attempts to optimize the relationship between public highway investment and user costs.

The HERS-ST is an enhanced version of the HERS model which has been used by the Federal Highway Administration since 1995 to provide estimates of the investment required to either maintain or improve the Nation's highway system. This information is submitted to Congress biennially via the “Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance (C&P) Report to Congress.” The reader should note that the logical structure of HERS-ST is identical to the national version of HERS. As such, the model is referred to simply as “HERS” throughout this document. It is primarily a user-friendly Graphical User Interface and certain input/output features that distinguishes HERS-ST from HERS-National.

It is very important that the user of the HERS-ST model not treat it as an inscrutable “black box.” HERS-ST cannot make decisions based on information which it lacks or on relationships that are not in the model. The user is expected to be knowledgeable about highway construction, traffic engineering, and benefit-cost, and to understand how HERS-ST derives its results. This understanding allows the user to provide sound input data and parameters, to interpret the results with insight and to modify the output to account for HERS-ST limitations.

CHAPTER 2

HERS LOGICAL STRUCTURE

Engineering and Economics

The HERS model is a synthesis of engineering knowledge and applied microeconomics. The relationships among traffic volumes, capacity, pavement deterioration, speeds, crashes, travel time, curves and grades, and other highway attributes are based on engineering relationships. Evaluation of improvement projects is conducted using a benefit-cost framework, which is an application of microeconomic theory. The framework guides the choice of engineering relationships to use for estimating the relevant measures of benefit, such as travel time savings, pollution reduction, and operating cost reductions. Discounting and life-cycle cost analysis are incorporated.

Although demand forecasts are supplied externally, HERS adjusts these forecasts to take account of improvements that make travel easier, and therefore attract more users, or conversely, deter travel by increasing congestion and worsening pavement condition. Thus there are many points in the model at which economic and engineering principles interact and find a resolution. This integration is an important and perhaps unique strength of the HERS model.

HERS Model Objectives

The HERS model estimates the level of expenditure on highway capital investment that would be justified on benefit-cost grounds, subject to various assumptions and constraints. It does this by taking a representative sample of highway sections, designing alternative improvements for each section, selecting the best improvement (if any), and extrapolating the results to the national highway network. Benefits are the reductions in user costs, agency maintenance costs, and externalities, over the life of the improvement; costs are the initial capital costs of the improvement.

The HERS model estimates the total highway investment required to implement all improvements whose benefits exceed their costs, or, alternatively, to achieve a specified user cost level, or the model will provide the user cost level resulting from a given level of highway capital expenditure.

HERS is not intended as a project evaluation tool. The reason for this is that the model's knowledge of the conditions on, and characteristics of, a given section is far from complete, so the estimated benefits and costs of improvements may be significantly inaccurate. Correspondingly, the analytic relationships are somewhat simplified.

(1) At the state level, the model may be used to find worthwhile improvements on representative prototype sections, and provide—in the aggregate—good estimates of warranted capital spending for the nation as a whole.

(2) The model might also be used to screen candidate projects for further study, refining specific quantitative measures while using the benefit-cost framework offered by the model.

(3) HERS could apply a consistent objective evaluation standard to a variety of projects proposed by different agencies for different purposes, with differing levels and styles of supporting documentation.

(4) Depending upon the projects selected for evaluation, HERS might be able to suggest funding priorities, such as among functional classes, geographic areas, or types of improvements.

Model Applicability

Inherent in the HERS analysis are the following characteristics:

- Only highways are considered explicitly (other transportation modes such as transit or other public good areas such as education are considered indirectly through the discount rate);
- No interdependencies (such as network impacts) among highway sections are addressed in the model;
- New construction on new alignment is not explicitly included;
- Initial improvement costs include typical capital expenditures (the cost of delay associated with implementing improvement options is not considered); and
- The only user charges included are fuel taxes (tolls are excluded).

While the HERS model does not perform all types of analyses that might be desirable, it does represent a significant advancement in the development of highway investment/performance analytical techniques over previous tools. Some of the types of questions that HERS is designed to address are found in Table 2-1.

TABLE 2-1. **Kinds of information that can be produced by the HERS model**

What level of capital expenditure is justified on benefit-cost grounds?
What user cost level will result from a given stream of investment?
What investment level is required to maintain user cost levels?
What are the user cost and fiscal impacts of varying the investment stream (e.g., postponing improvement of backlog deficiencies)?
What are the tradeoffs between capital investment and the performance of the highway system? If total investment is less than the economically efficient level, how much is lost in lower benefits?
What is the cost, over 20 years, of correcting all existing and accruing highway deficiencies?
Given a certain investment scenario, what percentage of the vehicle miles traveled will be on roads with conditions below a minimum tolerable standard?
Given a stream of investment, what is the most effective mix of highway improvements on existing facilities? Will performance increase or decrease relative to the base year?
What would be the effect of higher or lower fuel excise tax rates on VMT and capital needs?

Historical Antecedents

Benefit-Cost analysis is a framework for evaluating public expenditure decisions. It directs attention to estimating the impacts of a proposal and assigning values to those impacts. The HERS model simulates the evaluation and selection of potential improvement projects according to benefit-cost criteria, using prototype highway sections. The scope of benefit-cost analysis is intended to be exhaustive with respect to benefits in the current version of HERS, including externalities, but pricing is not necessarily optimal and hence the efficiency achieved is “second-best.”

Benefit-cost concepts first formally appeared in the writings of 19th century French economist Jules Dupuit, though in the realm of public works its use has been widespread only since World War II. The procedure was institutionalized by the Federal government with the Flood Control Act of 1936. Establishment of the Interagency Water Resources Council, in 1966, further promoted the application of benefit-cost techniques by Federal water resource agencies. Government evaluation of water resource projects continues to be based primarily on BCA.

Beyond Federal agencies and water projects, state and local highway planning agencies have been encouraged to use BCA. The AASHTO describes the technique in its 1977 publication, *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements*.[1] The NCHRP, of the Transportation Research Board, recently developed a computerized version of this approach.[2]

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[1] American Association of State Highway and Transportation Officials, A *Manual on User Benefit Analysis of Highway and Bus-Transit Improvements,* Washington, DC, 1977.

Interest has been expressed by both the Executive and Legislative branches of government to advance the application of BCA in the evaluation of infrastructure projects. Executive Order No. 12893, *Principles for Federal Infrastructure Investments*, "requires that select programs (including the Federal-aid highway program) of the Federal government systematically analyze expected benefits and costs, both quantitatively and qualitatively before making infrastructure investments."[3]

Conceptual Structure

The HERS model designs and evaluates possible improvements (including doing nothing) on individual sections of highway. It performs this project evaluation on each section in the database, for a single funding period (FP), and then repeats the process for the next funding period.

Project Evaluation

Project evaluation, in this context, refers to the process from identifying deficiencies on a section to selecting an improvement to implement. Once all funding periods in the overall analysis period have gone through the project evaluation process, the results are tabulated and printed. This overall process is represented in Figure 2-1.

Project evaluation is at the core of HERS. Engineering criteria are used to find the most likely improvements; economic criteria are used to evaluate which improvements are most worthwhile from society's perspective.

Highway improvements analyzed by HERS consist of various combinations of three improvement types: pavement, widening, and alignment. HERS starts by determining that a section deficiency should be considered for correction in the current funding period. A list of alternative improvements for the section is generated, and each is evaluated for implementation. Benefits and costs are estimated and the best improvement is selected for implementation, given funding constraints or performance objectives indicated by the analyst. Total improvement costs are then the sum of all beneficial improvements on all improved sections.

The framework for project evaluation, in its simplest form, can be represented by the diagram in Figure 2-2. The highway itself is described in the section data (HPMS sample data or equivalent), including degrees of curvature and grades, surface quality, lane and shoulder widths, pavement strength, and a travel forecast. Highways are normally broken up into sections that are fairly homogeneous (same pavement condition, lane

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[2] Texas Transportation Institute, *MicroBENCOST. User's Manual,* prepared for the National Cooperative Highway Research Program, Project 7-12, College Station, Texas, October 1993, currently under revision.

[3] Executive Order 12893, *Principles for Federal Infrastructure Investments,* Federal Register, Volume 59, No. 20, Washington, DC, January 31, 1994.

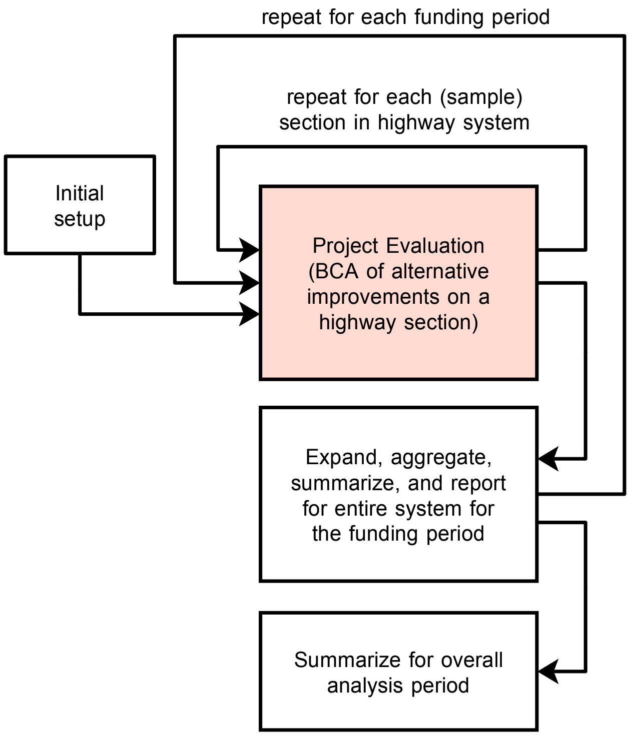

FIGURE 2-1. **Overall HERS process.**

widths, and traffic volume). Current traffic (vehicles per day, share of trucks) and forecast future traffic are also provided.

> **Design:** HERS can identify deficiencies and, if any are found, propose one or more improvement alternatives to consider (e.g., resurfacing, additional lanes); alternatively, the user can specify an improvement for a given section (e.g. grade separation).
>
> **Impacts:** Impacts of each alternative on the highway, user costs, agency costs, and the environment are estimated.
>
> **Evaluation:** Differences relative to the base case are valued and synthesized into estimates of incremental benefits and costs.

These three steps—design of alternatives, estimation of impacts, and project evaluation—represent the primary logical structure of HERS. The process is repeated for each highway section, and the results summarized at the system level.

Each of the steps presented in Figure 2-2 are described in the remainder of this chapter.

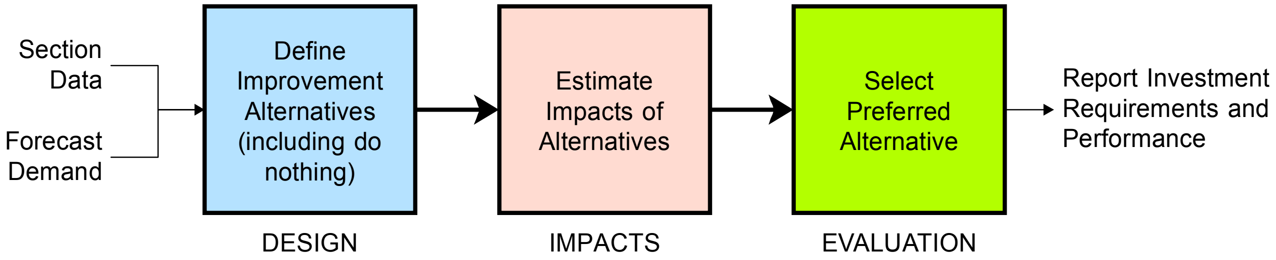

FIGURE 2-2. **Major steps in project evaluation.**

Inputs

The HERS model consists of two programs: the PreProcessor and the main program, both of which can be operated from a single graphical user interface (GUI). The PreProcessor requires as input: tables containing design standards; deficiency levels for highway sections by functional system; a set of run specifications; and section data. The PreProcessor reads the section data file, and produces a corresponding HERS data file.

The main HERS program requires as input: a set of run specifications; tables containing design standards; deficiency levels for highways by functional system; specifications of the costs of highway improvements considered by HERS; emissions cost factors; other parameters; and the HERS data file (output by the preprocessor). The main program uses these inputs to forecast changes to the highway system and analyze potential improvements for each of several FPs. All programs run on a personal computer.

The HERS National Model Sample Sections

HERS-ST is preceded by and derived from the HERS national model. The national model utilizes the HPMS sample section database as its primary source of highway information. The HPMS database was developed in the late 1970s to monitor national-level program effectiveness and to project future investment requirements. Today, the database consists of information describing over 100,000 highway section's samples to represent the national system. HPMS data are used by FHWA for a variety of strategic planning and highway investment evaluation purposes.

In the national model, each HPMS sample section represents a larger number of actual highway sections. The total mileage represented by any given section is obtained by multiplying the length of the section by its expansion factor. All HERS national estimates of capital expenditures are obtained by analyzing individual sample sections and multiplying the results by the section's expansion factor. Expansion factors are determined with respect to the types of highways found in the state. The expansion factor is the ratio of the total highway segment length in the AADT volume group to the total sampled highway length for the volume group and is calculated by software.

The HERS-ST Model

The HERS-ST model is an adaptation and extension of the HERS national model, intended to be useful for state-level highway capital programming and other investment decision analysis.[4] Several important features have been added in the development of HERS-ST. One modification has been to add a separate input file for section data on user-specified improvements that will occur on specific sections, including the date at which the improvement will occur. A second modification is that the state version outputs the condition of each section at the end of each funding period. Additionally, the GUI is provided to facilitate input preparation and operation of the model for state users.

States are not constrained to use only HPMS data, but the data items used by HERS-ST are primarily a subset of those defined for HPMS purposes in the HPMS Field Manual. It is up to each state to describe the highway sections it wants to evaluate in terms of HPMS data items and format, whether the sections are already HPMS sample sections (in which case the input preparation is easy) or otherwise in the states' highway databases.[5] Expansion factors can be used in conjunction with the state's HPMS sample sections, or different expansion factors can be calculated for a different set of sample sections, or the expansion factors can be set equal to one, in which case each section represents only itself.

Design of Improvements

The term "design" is used here in a broad sense to encompass the identification of deficiencies and generation of improvements candidates. HERS-ST accomplishes the first of the three major steps in Figure 2-2 in one of two ways: the user can specify an improvement for each section that must be considered, or the user can let HERS generate the improvement alternatives.

User-Specified Improvements

In HERS-ST, the user can, for any given section, specify an improvement that will take place, along with several attributes such as the date of the improvement and its impact on the capacity of the section.

These user-specified improvements can be used to plug in improvements that are already planned or programmed (approved), or to ensure that all sections on a route, or contiguous sections, are improved to the same extent or at the same time.

HERS-Generated Improvements

HERS starts the internal design process by searching for conditions that indicate deficiencies. Moreover, HERS considers both present conditions and forecasted future con-

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[4] This document—the Overview Report—uses the acronym HERS to refer to both the national model and the HERS-ST version, unless it is necessary to make a distinction between the two.

[5] In the remainder of this report, the term "HPMS data" or "section data" refer to either the FHWA-maintained sample section database, or a state dataset having the same variables and format.

ditions in searching for potential deficiencies. The steps in designing alternative improvements are shown in simplified form in Figure 2-3.

Deficiencies

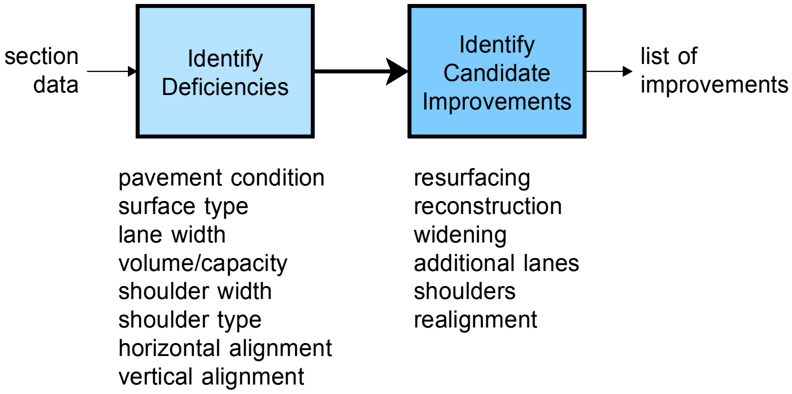


FIGURE 2-3. **Steps in the design of improvement alternatives.**

Each section may exhibit "deficiencies" at the beginning of an analysis period, meaning that some conditions or performance are bad enough that an improvement could be considered for correcting the conditions. If the section has no deficiencies, no improvement options are proposed or evaluated. For HERS to begin generating alternatives, a section must have either a pavement or a capacity deficiency, even if the section has other kinds of deficiencies.

The thresholds for these deficiencies can be set so as to cause most sections to be evaluated, if that is desired. The thresholds for identifying a section as deficient are referred to as deficiency criteria, of which there are several levels, described below (See "Deficiency Criteria" on page 4-4). The deficiency categories then suggest the types of improvements that will correct the deficiencies.

Improvement Types

If the user has not specified an improvement, the model chooses from a list of improvement types, ranging from resurfacing to reconstruction, including combinations of such improvements as realignment and lane widening. No proposed or recommended improvements are found in the HPMS sample data, but the HERS-ST model allows users to pre-identify improvements to be implemented. These improvements overrule the portions of HERS that identify deficiencies and choose improvements.

Impact Estimation

Impacts include changes in speed, accidents, emissions, traffic volume, and pavement condition. For each cycle in the analysis period, changes are made to the input record to simulate the changes expected to occur to the actual highway over time. The two items changed by this process are Annual Average Daily Traffic (AADT) and pavement condition (as expressed by either the Present Serviceability Rating (PSR) or the International Roughness Index (IRI)). The Volume/Capacity (V/C) ratio is also recalculated based on the updated AADT and capacity after improvement.

Traffic Forecasts

Current AADT is provided in the section record for both the base year and a specified future year. For each section, the annual growth factor for AADT is derived by interpolation between the base year and the state-specified future year. This growth factor is then applied to AADT for any year for which AADT is known, or has already been forecast, to obtain forecast AADT for any subsequent year of interest.

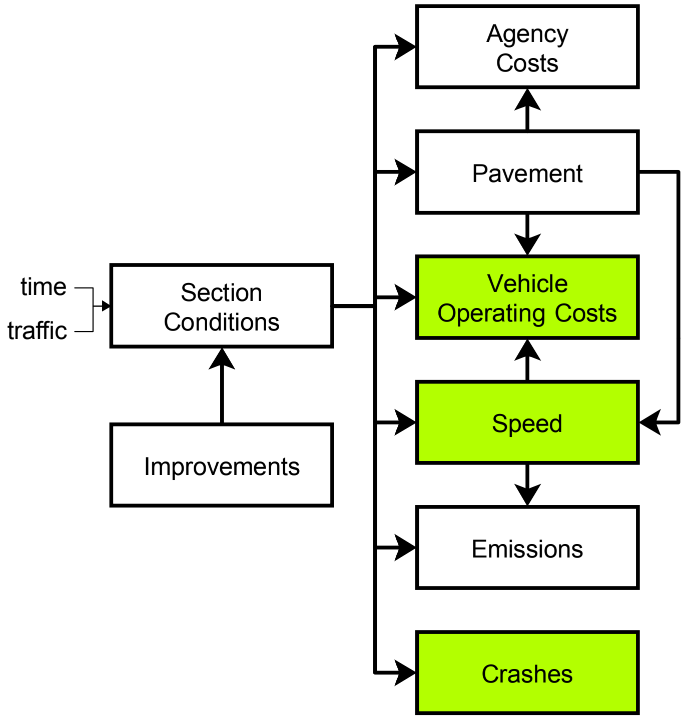
Thus HERS does not do any travel demand forecasting; the model accepts at face value whatever forecast is provided, and assumes that this embodies all the relevant exogenous demand factors, such as economic growth, land use and development patterns, demographic trends, alternative routes and modes, and a generally constant level of service. HERS can adjust the exogenous forecast based on what improvements are made or not made over the analysis period, and how those improvements affect the generalized price (cost of travel to the user, including time and operating costs) of travel.

Relationships Among Impact Submodels

Figure 2-4 shows the impacts estimation submodels within HERS, and their interrelationships. Initial conditions include the characteristics of the section and the volume and type of traffic. The critical performance measures that change from one period to the next are pavement and traffic volume.

Pavement is worn by the application of heavy axles and weather, and reduced pavement quality in turn both increases vehicle operating costs and lowers average speed. Vehicle operating costs are affected by speed and pavement surface quality. Agency costs are maintenance, which are affected by pavement deterioration. Emissions are affected by volume and speed, and crashes are determined by volume and the geometry of the highway.

- Traffic volume affects speed and crashes
- Pavement affects speed and maintenance
- Capacity, terrain, curves and grades, traffic control devices, and vehicle type affect speed
- Geometric design and other highway attributes affect crash rates
- Speed, pavement, and geometric characteristics affect operating costs
- Trucks (and weather) affect pavement
- Speed and vehicle type affect emissions rates



see Exhibit 2-5 in the *HERS-ST Technical Report* (2002).

FIGURE 2-4. Relationships among impact models.

- Improvements affect capacity and pavement

Outputs of three of these submodels—vehicle operating costs, speed, and crashes—have a feedback effect on traffic volumes (not shown in the diagram), through a supply-demand model.

Supply and Demand

A feature developed for the HERS national model and used for the 1995 *Conditions and Performance* report to Congress was the recognition that improvements to a highway result in more traffic on the section than would have been the case without the improvements. This is not simply a matter of redistributing traffic (although that is part of it); if all sections are improved, then traffic will be higher on all sections. Alternatively, if sections are not improved, pavement and congestion may worsen and traffic will correspondingly diminish.

How much traffic volumes change as a result of highway conditions is represented in HERS by a generalized price and a price elasticity. Elasticity quantifies the relationship between generalized price and traffic volume. The former includes travel time, operating costs, safety costs, and user taxes as these are felt by the user. Tolls are not currently represented in the model.

The section volume forecast provides a baseline point in each funding period through which the demand curve passes. HERS fits a constant-elasticity demand curve to this point, using the short-run elasticity (SRE) specified by the user. The “supply” side is a result of combining all user costs—travel time and delay, vehicle operating costs, crash risk—into a price to the user at each volume level. Each section generates a supply and demand curve for each improvement in each funding period, and the equilibrium volume is found that balances demand and supply price, as shown in Figure 2-5.

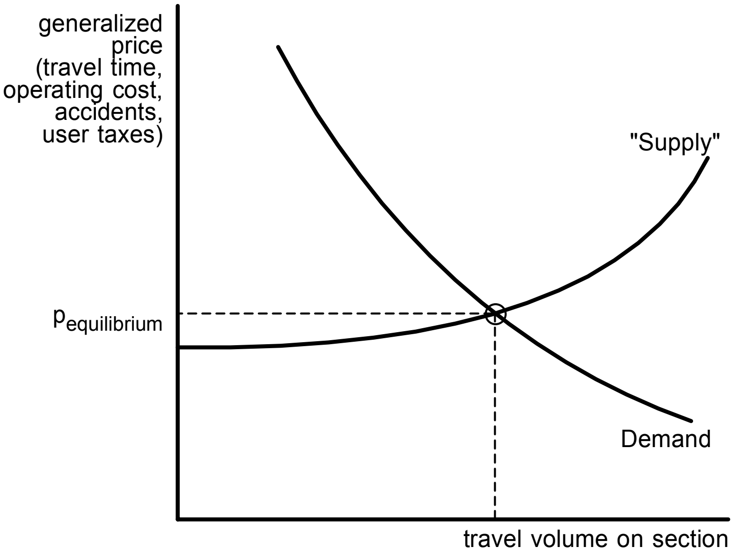


FIGURE 2-5. Equilibrium of supply and demand.

Evaluation of Improvements

Incremental Benefits and Costs

The benefit-cost analysis (BCA) technique compares the cost of implementing an improvement to the benefits expected over the life of the improvement. The objective is to maximize total net benefits, whether funding or performance are constrained or not. For alternative improvements on the same section (only one of which can be implemented in the same period), the one with the highest net benefits is preferred. In the presence of a funding constraint, however, a lesser improvement with a higher BCR may be selected in order to also implement an improvement with a higher BCR on another section. This procedure applies a methodology referred to as incremental benefit-cost ratios (IBCRs), that compare an improvement to a less aggressive improvement (explained more thoroughly in Chapter 7).

The major components of costs and benefits tabulated by HERS are shown in Table 2-2.

TABLE 2-2. **Components of HERS benefits and costs**

	User Benefit	Agency Cost	Exter-nality
BENEFITS			
VEHICLE OPERATING COST SAVINGS	X		
SAFETY COST SAVINGS	X		
TRAVEL TIME COST SAVINGS	X		
INCREMENTAL CONSUMER SURPLUS	X		
HIGHWAY MAINTENANCE COST SAVINGS		X	
RESIDUAL VALUE		X	
EMISSIONS REDUCTION			X
COSTS			
INITIAL IMPROVEMENT COST		X	

Improvement Selection and Constraints

If the analyst has requested that improvements achieving some minimum BCR be implemented, then, for each section, the best improvement—among those passing the BCR threshold—is selected for implementation. Otherwise, the most attractive improvements are selected, considering each section in sequence, until all available funds are exhausted or until a user specified minimum level of highway system performance is reached. User-specified improvements are included in this process.

The BCA evaluation as a basis for selecting improvements can be constrained or ignored to various degrees. Deficiencies whose correction is mandatory, and user-specified improvements are examples of actions that force some improvements to be undertaken whether or not they pass the BCR threshold.

Outputs

HERS-ST produces estimates of justifiable expenditures by functional class and improvement type, for each funding period, subject to the parameters the model is given and whatever constraints are imposed on the solution by the chosen scenario.

Performance Measures

The primary output of HERS is a set of tables describing:

- The state of the highway system at the start of the run and at the end of each FP;

- The changes occurring during each FP;
- The changes occurring during the overall analysis period;
- The benefits and costs of the improvements simulated during each FP; and
- The benefits and costs of the improvements during the overall analysis period.

This information is provided by functional class as well as system totals.[6] HERS-ST also prints section condition files that detail the conditions of each section at the end of each funding period, including information about the implemented improvements (see Table D-1 in the *HERS-ST User's Guide,* 2002). Every HERS run produces a set of standard outputs as well as optional output that may be specified by the analyst.

Standard Output

Each HERS run produces output summarizing the state of the highway system at the start of the run and at the end of each FP. Also provided is a summary of changes which occurred during each FP and during the entire analysis period. The major measures provided in the standard output are listed in Table 2-3.

TABLE 2-3. **Standard output**

Miles
Average PSR
Average Speed
VMT
User Costs
Average Annual Maintenance Costs
Percent VMT Below MTC

The *Initial state of the highway system* page, provided in the HERS output, describes the condition of the highway sections included in the HPMS input data. This page presents basic measures of highway extent, condition and usage. This is followed by a summary of estimated user costs, including safety statistics and estimated annual maintenance costs per mile.

The *Conditions at the end of a funding period* page is also produced as HERS output. This output contains all the information contained in the Initial State of the highway system output but the results represent the end of the FP.

The third set of HERS standard output, *Changes occurring during each funding period*, summarizes changes in the state of the highway system resulting from simulated condition and performance deterioration and/or implementation of improvements. This output is presented in the same format as the state of the system at the beginning of the FP, with the exception that the change in highway mileage is not presented, since there is no

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[6] See “Functional Class” on page 3-5 for a description of the functional class hierarchy.

change. The BCR of the last improvement selected for implementation during the period is also presented.

Output summarizing the *Changes occurring during each funding period* as well as the *Changes which occur during the overall analysis period* (but without the BCR information) is produced. The “Changes” page also reports, for performance constrained runs, the performance goals and the level of performance achieved.

Optional Output

Optional output pages can be produced presenting various statistics for sections improved during the period by highway functional system, by the type of improvement selected, and by IBCR range. Major optional output measures are indicated in Table 2-4.

TABLE 2-4. **Optional output**

Total Initial Cost of Selected Improvements
Lane-Miles Improved
Average BCR of Improvements
Benefits in Last Year
VMT for Improved Sections
Miles Improved
Travel Time Benefits
Number of Sections Improved

Other performance measures are available in the form of Deficiencies as % of VMT and Deficiencies as % of miles. When selected, these print for: beginning of FP1, and “Changes During” and “End of FP” for all FPs. The pages list percentages for nine deficiency categories by functional class. From three to five deficiency levels are listed for each category and include UL, DL, and user-specified thresholds (USTs). (see Appendix D of the *HERS-ST User’s Guide,* 2002).

Scenarios

The HERS model was designed to evaluate the implications of alternative programs and policies on the conditions, performance, and user cost levels associated with the a given highway system. HERS permits the analyst to establish any one of three objectives:

(1) Implement all improvements with incremental BCRs greater than a set threshold value;

(2) Maximize the net present value of improvements selected for implementation, given a funding constraint; or

(3) Minimize the cost of improvements necessary to achieve specific performance goals related to user costs, agency costs, and safety incident rates.

The default is economic efficiency, which utilizes the benefit-cost criterion to the greatest extent; other scenarios and input parameters may produce results that are, to varying degrees, determined by factors other than benefits.

Minimum BCR

If the minimum required BCR is set to 1.0, then the scenario is referred to as "economic efficiency," meaning that the best improvement on a given section is selected so as to maximize net benefits, and all sections having a worthwhile (net benefits > 0) improvement are included in the improvement program, i.e.,

- the "best" improvement for each section (maximum net benefit) is selected,
- all sections having a worthwhile project are accepted (NB>0 or BCR>1.0), and
- the best improvement (if any) for each section is chosen on consideration of benefits and costs, without constraints on performance or funding.

User-specified improvements are implemented regardless of BCR. The minimum BCR can also be set above or below 1.0. If the BCR is set to a large negative number, the result is a "full (engineering) needs" scenario in which improvements are made so as to correct all deficiencies, without respect to net benefits.

Constrained Funding

Funding constraints can be imposed overall or by functional class, with the result that not all worthwhile (economically efficient) projects may be implemented. HERS may substitute an improvement on one section while giving up a more "aggressive" (higher cost) improvement on another section, in order to maximize the total net benefits that can be achieved with the limited investment funds. In the HERS-National model, sections may be broken into two sections in order to use up all of the funds available. In HERS-ST this does not occur, so the funding constraints are only approximate in any given funding period.

Constrained Conditions or Performance

Performance requirements can be imposed on the sum of user costs, agency costs, or some combination. Depending upon how the constraints are set, the results can be counterintuitive.

The minimum BCR run with the threshold BCR set to 1.0 is the most straightforward application of HERS, and the most readily interpreted. Other scenarios have differing but greater degrees of difficulty in comprehension. The most difficult are those scenarios that require a given or historical performance level, such as pavement condition or user cost. A preferable way to test funding levels or performance targets is to make several minimum BCR runs, adjusting the BCR threshold until the target spending or performance results.

CHAPTER 3

INPUT DATA AND PARAMETERS

Highway Section Data

FHWA's Highway Performance Monitoring System (HPMS) defines and tabulates data that are collected and submitted by states. The number of items and their operational definitions have been reviewed and revised several times in the past, and the database provides consistent and high-quality descriptions of a large sample of U.S. highway sections.[1]

HERS has long been a major user of the HPMS data. The data elements used by the HERS model, for each section, are shown in Table 3-1. Not all HPMS data items are used by HERS. HERS drops some items and constructs others, in the PreProcessor, resulting in a modified set of data items being input to the main model. With the development of the HERS-ST model, states may be able to take advantage of the research and refinement effort that have gone into building the HPMS database.

Traffic Forecasts

Two of the HPMS data items are future AADT and the future AADT year, which together provide a point estimate of the volume of traffic at a given date. This forecast, matched with the volume for the initial data year, generates two demand points that contain all the information HERS receives pertaining to exogenous demand factors (regional economy, demographics). HERS has the option of fitting a straight line to the two points, fitting a geometric curve, or a logistic curve that could curve up, down, or have an S-shape. This fitting is done in the PreProcessor, yielding a traffic growth factor or growth amount for use in the HERS model.

Truck Share

An important component of the forecast is the share of traffic that is trucks, since it is trucks that generate ESALs (equivalent single axle loads, a standard measure of pavement stress), and ESALs that cause pavement deterioration (along with time and weather).

HERS also has a feature for changing the truck share of traffic over the forecast period, by increasing or decreasing the percent trucks at a constant rate.

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[1] Descriptions of the HPMS data items and how they are measured can be found in the December 2000 *HPMS Field Manual*, available at http://www.fhwa.dot.gov/ohim/hpmsmanl/hpms.htm.

TABLE 3-1. **HPMS sample section data elements used in HERS**

HPMS Data Item	Type	HPMS Data Item	Type
Reporting Units	identification	Vertical Alignment Adequacy	geometrics
Year	identification	Grades by Class (6 classes)	geometrics
State Code	identification	Percent Passing Sight Distance	geometrics
County Code	identification	Roughness (IRI)	pavement
Rural/Urban Designation	identification	Present Serviceability Rating (PSR)	pavement
Sample Number	identification	Surface/Pavement Type	pavement
Section Subdivision	identification	Structural Number (SN) or Slab Thickness (D)	pavement
Standard Expansion Factor	identification	AADT	traffic/capacity
Linear Referencing System beginning milepost	identification	Speed Limit	traffic/capacity
Linear Referencing System ending milepost	identification	Weighted Design Speed	traffic/capacity
Linear Referencing System Identification	identification	Percent Peak Single Unit Trucks	traffic/capacity
Functional System	system	Percent Average Daily Single Unit Trucks	traffic/capacity
Generated Functional System Code	system	Percent Peak Combination Trucks	traffic/capacity
Unbuilt Facility	description	Percent Average Daily Combination Trucks	traffic/capacity
Type of Facility	description	K-Factor	traffic/capacity
Section Length	description	Directional Factor	traffic/capacity
Number of Through Lanes	geometrics	Peak Capacity	traffic/capacity
Access Control	geometrics	Peak Lanes Peak Direction	traffic/capacity
Median Type	geometrics	Turning Lanes - Left	traffic/capacity
Median Width	geometrics	Turning Lanes - Right	traffic/capacity
Lane Width	geometrics	Percent Green Time	traffic/capacity
Shoulder Type	geometrics	Signalized Intersections	traffic/capacity
Right Shoulder Width	geometrics	Stop Sign Intersections	traffic/capacity
Left Shoulder Width	geometrics	Other/No Control Intersections	traffic/capacity
Peak Parking	geometrics	HOV Operations	traffic/capacity
Widening Feasibility	geometrics	Future AADT	forecast
Horizontal Alignment Adequacy	geometrics	Future AADT Year	forecast
Curves by Class (6 classes)	geometrics	Climate Zone	environment
Type of Terrain	geometrics	Year of Surface Improvement	improvements

source: *HERS-ST User's Guide* (2002) Table A-3.

Default Data

In general, each section record must be complete with all data items for HERS to perform a project evaluation on that section. For some data items, however, HERS will attempt to estimate the missing item using other data items in the same record and applicable models. The specific data items that HERS will try to estimate if they are missing are described in section 3.1.2 “Conversions, Limits, and Defaults” of the *HERS Users Guide* (December 2000), pp. 3-10 to 3-14.

HERS Time Frame

The HERS model operates in a simplified discrete time frame in which events occur at points in time that are determined by the length of the funding period (FP). Results are summarized and reported by funding periods, but the analysis itself is oriented to BCA periods, and subdivisions of the BCAP that are called demand periods. The length of a demand period is the same as a funding period, but goes from the midpoint of a FP to the midpoint of the next FP.

Funding Periods

The analyst determines the length of the overall analysis period and the length of the funding periods. Typically, a HERS-national evaluation is conducted over a 20-year horizon divided into four FPs of five years each. HERS will implement no more than one improvement per deficient highway section for each FP.

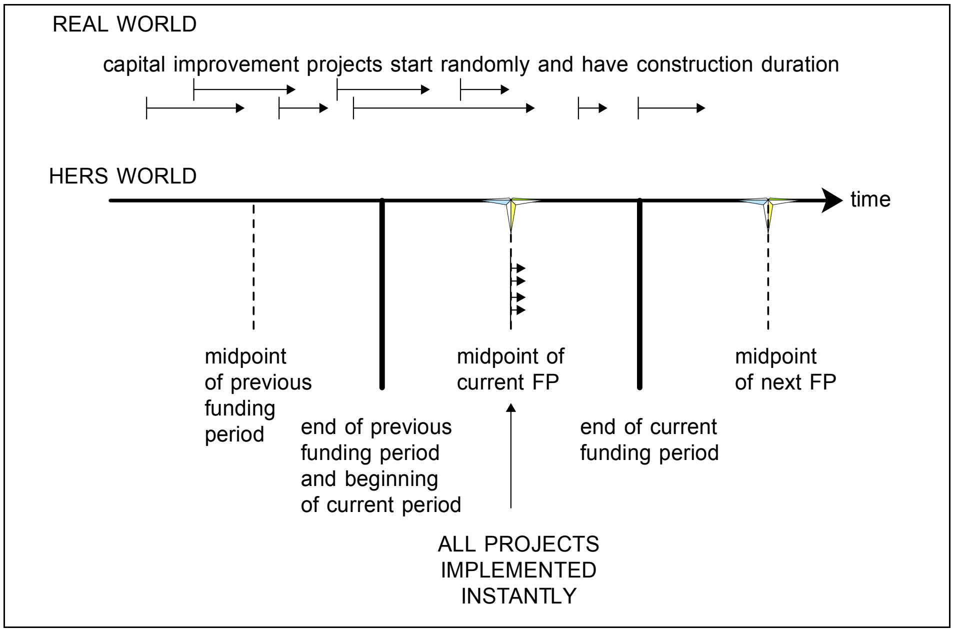


FIGURE 3-1. **HERS funding periods.**

The funding period is a simplification of the real world, in that decisions are assumed to occur once within an FP and all projects are implemented instantaneously. The contrast between HERS and actual practice is illustrated in Figure 3-1. The midpoint of the funding period represents the period as a single point in time. The FP length can be potentially varied between one and seven years, with shorter periods taking longer computational times; HERS national runs have used 5-year FPs.

BCA Analysis Period

All user and operating agency benefits are estimated for the lifetime of the least-aggressive project and discounted to the beginning of the BCA period (BCAP) by applying an analyst-specified discount rate. Whatever the length of the BCA period, it runs from mid-point of FP to mid-point of FP, as shown in Figure 3-2. A BCAP may consist of only one demand period, or a larger number, depending upon the lifetime of the least aggressive improvement.

Benefits are evaluated on the assumption that the improvement is implemented at the beginning of the BCA period, and the initial cost of the improvement is also assumed to be incurred at this time. Reductions in operating agency maintenance costs are estimated for the entire BCA period and the residual value of the improvement is calculated at the end of the period. Benefits, then, are averaged over the demand period and discounted from the midpoint, except residual value, which is discounted from the end of the BCAP.

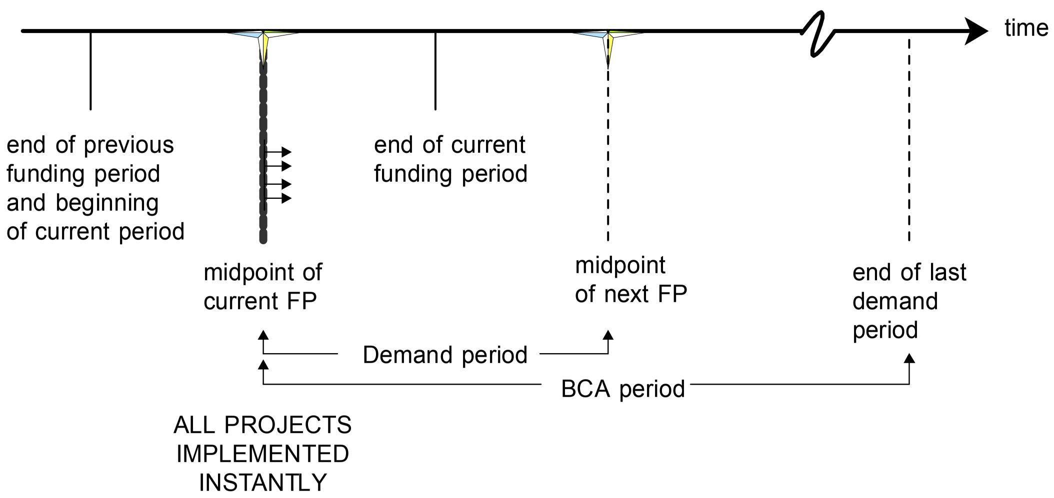


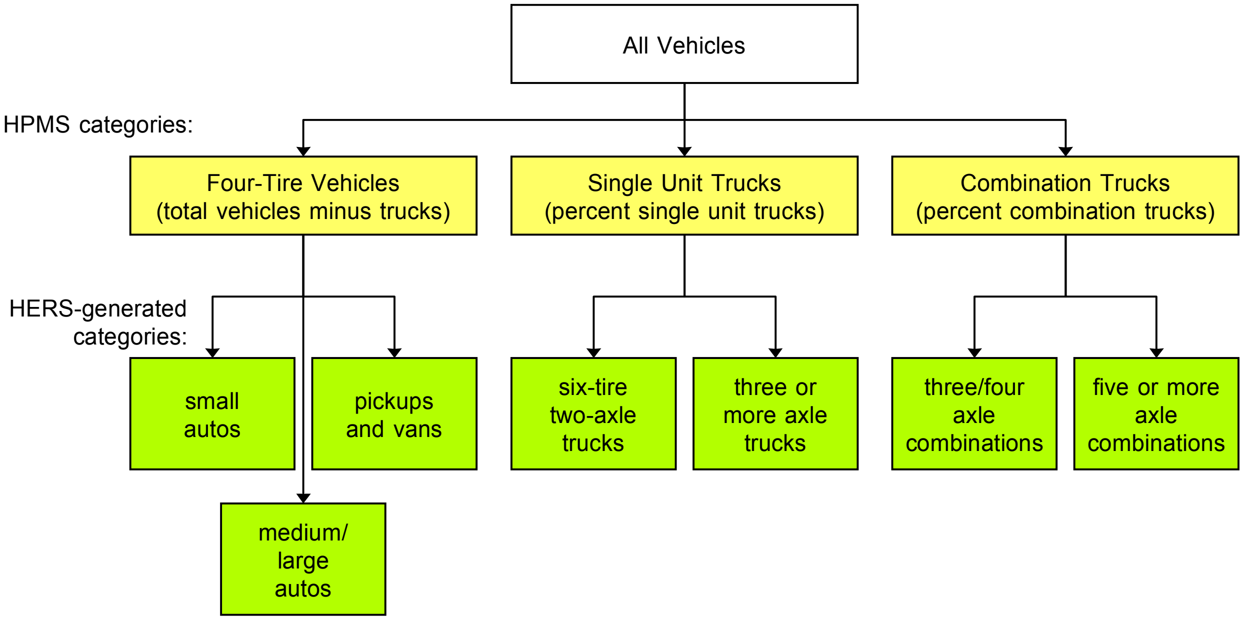
FIGURE 3-2. **Benefit-cost analysis period and demand periods.**

Disaggregation Categories

Vehicle Types

The HERS model divides vehicles into seven types, as shown in Figure 3-3. The full breakdown is not in the HPMS sample section data items; instead, the share of single unit and combination trucks in the traffic stream is reported. In this definition, a truck is anything with six tires or more, which could be a two-axle vehicle but not a standard pickup truck. HERS then applies aggregate national distributions derived from the *HPMS Vehicle Classification Study* to allocate single unit and combination trucks into the seven subclasses.

Thus the top row of three shaded vehicle types is obtained directly from the section data record, whereas the bottom row of seven types is expanded from the first three using average distributions by functional class. In this case, HERS contains procedures to utilize a finer level of detail than is currently available from the HPMS.



source: FHWA, *HERS-ST Technical Report* (2002).

FIGURE 3-3. **Composition of the vehicle fleet.**

Functional Class

All public roads and streets in the United States are functionally classified by type and use. HERS implements nine of the functional classes (those shaded in Figure 3-4) of the overall highway system functional classification hierarchy. Results are reported by funding period and by functional class. Within HERS, there are several groupings of highway types by functional class, sometimes also disaggregated by AADT range and other attributes

Section records in the three lower functional classes can be analyzed either as Rural Major Collectors (if rural) or Urban Collectors (if urban).

Facility Types

HERS relationships sometimes utilize physical characteristics of the road, such as

- two-lane roads
- three-lane
- multilane
    - divided, median or two-way left-turn lane
    - undivided
- freeway by design
- traffic control devices (presence or absence of stop signs or traffic signals)

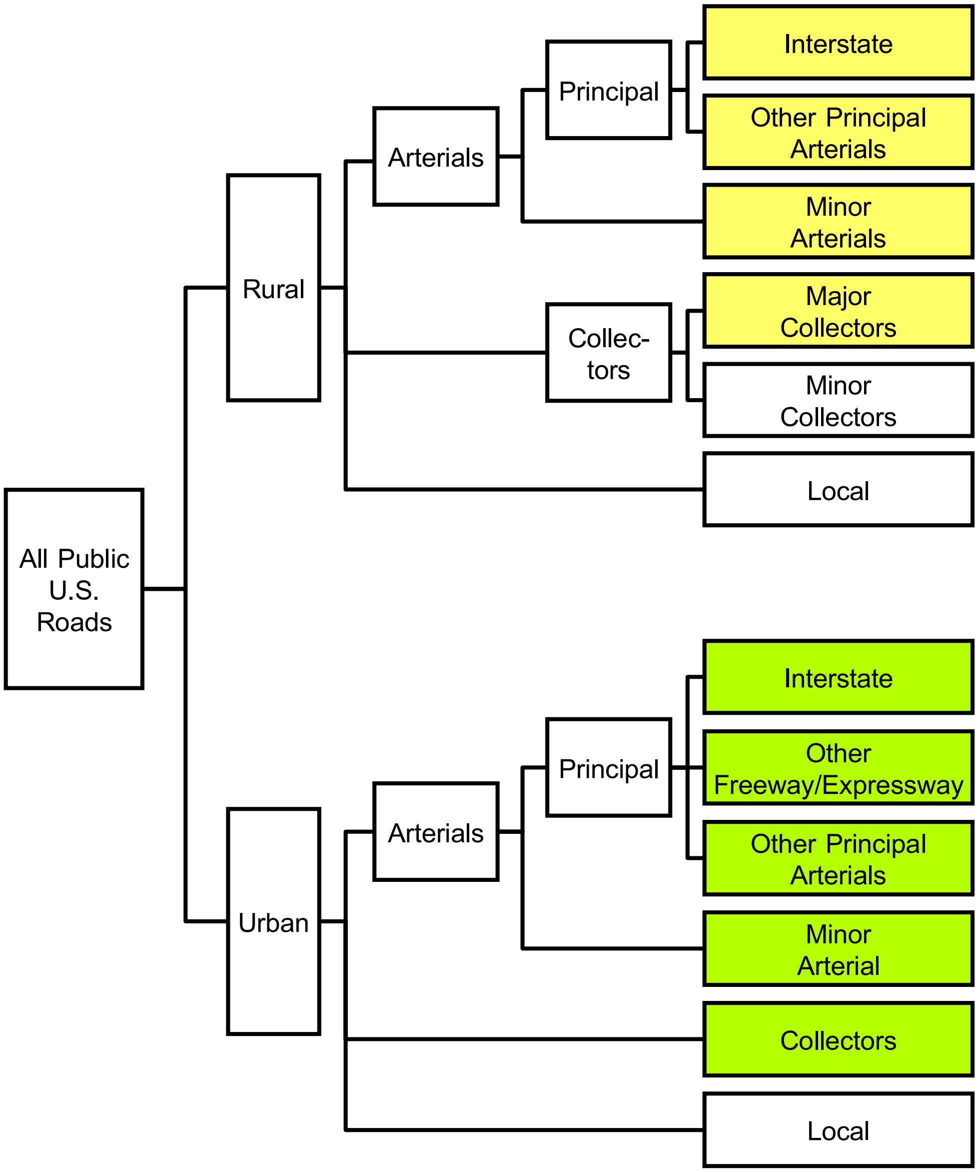


FIGURE 3-4. **U.S. highway system functional classification.**

Each of these characteristics is sometimes used, but never are all used at the same time. A typical classification by facility type would be two-lane roads, multi-lane other than expressways, and freeways.

Terrain Types

When terrain is explicitly considered, it is classed into one of three types:

- flat
- rolling
- mountainous

AADT Volume Groups

Highways may also be separated into AADT/c classes according to break points that are appropriate to the functional class.

Parameters

Default Values

A number of the input files can be edited by the analyst. A set of default values are provided for each input, making it possible to run the model using either default or analyst-specified values. The analyst may readily change deficiency levels, improvement cost values, and assumptions related to the value of user benefits such as travel time.

Listed below are some of the parameters used in HERS.

Deficiency Criteria and Design Standards

HERS incorporates several methods for identifying deficiencies and specifying improvements:

- Deficiency Levels
- Serious Deficiency Levels:
- Unacceptable Levels:
- Reconstruction Levels
- Design Standards
- User-specified Thresholds

Deficiency levels are entered in tables in the HERS inputs, and default values are shown in the *HERS Users' Guide* (Draft 2000). A brief description of their use is found below (See "Deficiency Criteria" on page 4-4).

Design Period

The last year of the design period, the design year, is used in evaluating the need for capacity improvements to sections that are considered for improvement. The default is 20 years.

Truck Growth Factor

The truck growth factor (by functional system) expresses the annual rate of growth (as a ratio) in the percentage of vehicles that are trucks (i.e., having six or more tires). 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 1.00 is used for the annual growth factors for percent trucks for all functional classes.

Indices

A set of deflator indices is used by HERS for adjusting costs from the year dollars in which they are specified to any other year dollars. The default 1997 indices are included in the Appendix C to the *HERS Users' Guide* and are based on the following series:

- Pavement and Widening Without Alignment Costs - Default values provided by FHWA;
- Other Improvement Costs - FHWA's Bid Price Index;[2]
- Highway Maintenance Costs - FHWA's Bid Price Index;
- Vehicle Operating Costs - CPI for private transportation;[3]
- Value of Time Costs - Total compensation of all civilian workers;[4]
- Value of Life - Default values provided by FHWA;[5]
- Injury Costs - Total compensation of all civilian workers;[6] and
- Property Damage Costs - CPI component for motor vehicle body work.[7]

Various Pavement Deterioration Factors

The analyst may specify (1) the PSR of newly constructed sections, (2) the increase in PSR due to resurfacing, and (3) the maximum PSR after resurfacing. In addition, the analyst may set the rate of pavement deterioration, making it possible to modify the pavement deterioration rate to reflect local conditions or alternative scenario assumptions.

The maximum pavement deterioration rate/year may be adjusted as well. This value is significant for sections for which the database contains low structural numbers that would otherwise result in excessive deterioration rates. The default value for this maximum rate is 0.3 per year.

Safety and Value of Time Parameters

The analyst may specify values for human life, average cost per nonfatal injury, average cost of property damage, and components of travel time. The default value of life is $3 million in 2000 dollars. Default values for nonfatal injuries and property damage are shown in Table 5-9 of the *HERS Technical Report* (2002). Travel time values are given in Table 5-2 of the present document.

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[2] U.S. Department of Transportation, Federal Highway Administration, Office of Engineering, *Price Trends for Federal-Aid Highway Construction,* Washington, DC, quarterly.

[3] U.S. Department of Labor, Bureau of Labor Statistics, CPI *Detailed Report,* U.S. Government Printing Office, Washington, DC, monthly.

[4] U.S. Department of Transportation.

[5] U.S. Department of Transportation.

[6] U.S. Department of Transportation.

[7] *Ibid.*

Policy Options

HERS can provide feedback on a number of choices that might be considered policy alternatives. Engineering design standards can be tightened or relaxed. Values of time and human life can be set at different levels. The BCR can be set at a level other than 1.0, and weights can be applied to benefits. Performance levels for maintaining pavement condition or maintaining user costs can be applied. In addition to these, two types of financial policies can be established: one is to constrain expenditures on capital spending, and the other is to set a fuel excise tax rate. Also, a “corridor constraint” can be imposed to limit the allowable total number of lanes.

Funding Constraint

As mentioned above under Scenarios (in Chapter 1), a HERS run can be constrained to invest no more than a given limit in dollars. The funding constraint can be imposed

- by funding period, and
- by funding period and any one of 5 groupings of functional classes.

Fuel Tax

The price to the user includes any excise taxes levied on fuel consumed, but changes in fuel taxes paid by users are not counted as costs or benefits. The level at which the fuel tax is set, therefore, will have a direct effect on traffic volumes and travel demand through the demand curve and the two elasticity parameters associated with demand. A higher fuel tax will “disinduce” some amount of traffic, compared to a lower tax rate. The tax rate thus has an indirect effect on benefits through the volume of travel. In principle, an increase in the fuel tax could obviate the need for some investment as determined by HERS, while generating increased revenues (depending upon demand elasticities) to fund improvements.

The fuel tax is input to HERS as two parameters: the amount per gallon to be applied in the first FP, and the rate of growth (or decline) in the tax for subsequent FPs.

Maximum Number of Lanes

The maximum number of lanes value establishes a policy constraint on the number of lanes allowed on any section, when there is a conflict. This value will override either the model default or the section-specific value of widening feasibility if the number of lanes is already at the maximum (See “Widening Feasibility” on page 4-9).

CHAPTER 4

DESIGN OF IMPROVEMENT ALTERNATIVES

Once the relevant data for a given section are assembled by HERS for evaluation, the three primary functions HERS must perform—as shown above in Figure 2-2—are

- design alternative improvements
- estimate the impacts of each relative to the base case, and
- translate those impacts into net benefits of the improvement.

As was shown in Figure 2-3, the design of improvements is broken into two major branches:

(1) HERS can identify improvements based on deficiencies calculated from section data and compared to deficiency levels, or;

(2) Improvements can be specified by the user for any or all sections.

If HERS designs the improvements, then the process consists of two steps:

- identify deficiencies
- propose improvements to correct the deficiencies

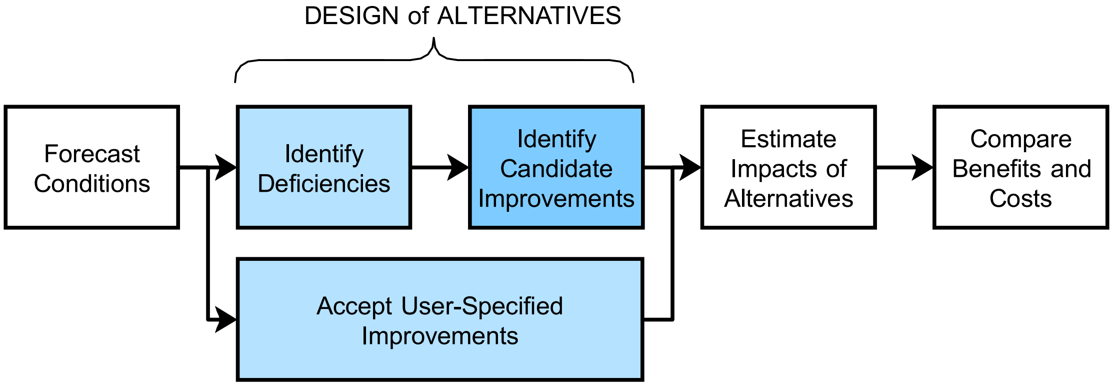

FIGURE 4-1. Design of alternatives within overall HERS flow.

These steps are shown in conjunction with each other in Figure 4-1. This chapter summarizes the design-of-alternatives functions in HERS.

User-Specified Improvements

The user may specify, in addition to the data describing the section and its conditions, an improvement that will take place on that section during each analysis period. The additional data (provided in a separate file) are listed in Table 4-1. User-specified improvements are also referred to as "state" improvements, and, when they are entered, HERS-ST is said to operating in "Override" mode (HERS internal improvement design and selection process is being bypassed).

Improvements can be chosen from the list HERS generates its alternatives from internally (referred to as "HERS-type" improvements), or from a list of user-specified improvement types, referred to as "special improvements." Specified improvements may be HERS-type, special, or a combination.

TABLE 4-1. **Input data for user-specified improvements**

Field	Data Item
1	number of improvements
2	county code
3	sample identifier
4	year of first improvement
5	type of improvement
6	override flag
7	cost of improvement
8	lanes added
9	increase in capacity
(repeat 4-9 for up to 10 improvements)	

The override flag can be set to several options, depending upon the type of improvement specified. An improvement may be required to be implemented as specified, or it can be the minimum improvement that will take place, allowing HERS to substitute more aggressive improvements if they are cost-beneficial. The flag can be used to ensure that the improvement is not implemented before a stated year (HERS is prevented from implementing it earlier even if it passes the BCR threshold), or it is possible to prevent a section from being improved at all during the overall analysis period.

For a user-specified improvement, given its cost and the impacts of the improvement on PSR and capacity, other impacts are calculated in HERS in the normal way and estimates of benefits are tabulated. These net benefits are added into the aggregate benefits from all projects, but any user-specified improvement is always implemented, whether or not it generates positive net benefits.

HERS-Designed Improvements

The first step in designing improvement alternatives is to identify deficiencies on the section. A deficiency can be defined as a highway condition or performance element that is below a specified acceptable level. HERS evaluates eight highway section characteristics for deficiencies, listed in Figure 2-3 under the box labeled “Identify Deficiencies.”

After HERS has forecast the conditions on the section that will occur at the midpoint of the first (or the next) funding period (the beginning of the BCA period), these conditions are checked against the deficiency criteria that apply to that functional class. If there are no deficiencies in either pavement or peak V/C at that time, the section will not be considered for improvement.[1] If the section is deficient in either or both of those, improvements that correct those deficiencies will be considered. If there are additional deficiencies as well, improvements that correct those deficiencies will also be considered.

Deficient Section Characteristics

Eight section characteristics may be flagged as deficient in some way, and these characteristics are described below.

Pavement Condition: Pavement conditions influence user costs, i.e., operating costs, safety and travel time. HERS accepts pavement condition measured either as PSR (Present Serviceability Rating) or IRI (International Roughness Index), but conducts its calculations internally in PSR. The scales are described in Table 4-2. Pavement with a PSR below 2.0 is generally not acceptable as a paved surface, and is considered to have failed. Measurement of PSR requires visual inspection of pavement, and has been replaced (or supplemented) in the HPMS database by the International Roughness Index (IRI), a method based on physical measurements. HERS accepts IRI measurements, but converts them to the PSR scale for internal processing.

Surface Type: There are five surface types: high flexible; high rigid; intermediate; low; and unpaved. The type of surface affects the PSR and therefore impacts vehicle operating costs such as fuel consumption.

Volume/Capacity: Levels of congestion are measured according to V/C ratios. Peak V/C is not included in the section data, so V/C is estimated from capacity, AADT, and the K-factor for the section. In the case of an unacceptable V/C ratio, the HERS pro-

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[1] If the surface type for the section is given as unpaved, but the deficiency level indicates paved. the section is considered deficient in pavement.

TABLE 4-2. **Present Serviceability Rating (PSR) and IRI**

PSR	IRI	Description
5	0	
		Very Good: Only new or nearly new pavements are likely to be smooth enough and sufficiently free of cracks and patches to quality for this category.
4	52	
		Good: Pavements in the category should give a first-class ride and exhibit few, if any, visible signs of surface deterioration.
3	119	
		Fair: The riding qualities of this category are noticeably inferior to those of new pavements, and may be barely tolerable for high-speed traffic.
2	213	
		Poor: Pavements that have deteriorated to such an extent that the speed of free-flow traffic is impacted.
1	374	
		Very Poor: Extremely deteriorated pavement; the facility is passable only at reduced speeds and with considerable ride discomfort.
0	999	

cedure chooses the most aggressive widening option warranted by the section's characteristics.

Lane Width and Right Shoulder Width: The lane width of a highway influences both capacity and safety. Substandard lane widths tend to reduce the capacity of a highway, and may affect safety. Lane widths are considered more important on the higher functional systems (See “Functional Class” on page 3-5 for more information on the highway functional system).

Shoulder Type: There are five shoulder types: surfaced; stabilized; combination; earth; and curbed. The shoulder type affects the capacity level of a highway which in turn impacts safety, travel time, and vehicle operating costs.

Horizontal and Vertical Alignment: The alignment of a highway affects the speed at which vehicles may safely travel. Both horizontal and vertical types of alignment contribute to the level of service and safety of a highway, and impact operating costs. Horizontal alignment affects speed and sight distance, while vertical alignment affects sight distance, operating costs and speed, primarily for trucks.

Deficiency Criteria

HERS incorporates several methods for identifying deficiencies and specifying improvements:

> **Deficiency Levels (DLs):** The basic set of deficiency criteria are contained in the DLs. An improvement made on the section may not correct all of the deficiencies on that section, but improvements that correct each or all of the deficiencies will be proposed and evaluated. The analyst sets DLs for each of the eight section attributes above. Relatively relaxed DLs (levels that few

sections fail) will limit the number of potential improvements analyzed by HERS and decrease computation time. More stringent DLs, however, will require HERS to analyze a larger number of potential improvements and may permit HERS to find a more cost-beneficial set of improvements to be implemented (see Chapter 3 of FHWA, *HERS-ST Technical Report* (2002) for more information on DLs).

Serious Deficiency Levels (SDLs): The SDLs are criteria for deficiencies that must be corrected if any improvement is made to the section, but they will not be corrected if no improvement is found to be worthwhile.

Unacceptable Levels (ULs): If requested by the user, ULs must be corrected, whether the best improvement is cost-beneficial or not, if the section is also deficient in pavement or capacity. This DL is voided if the section has an exogenous improvement specified by the user.

Reconstruction Levels (RLs): The RLs give the PSR for pavements below which the pavement must be reconstructed rather than resurfaced.

Design Standards: If a section is reconstructed, then all design standards must be satisfied.

User-Specified Thresholds: These performance levels are used only for generating output statistics summarizing specific characteristics of interest to the user (e.g., percentage of pavement below PSR = 2.0).

Improvement Options

Improvement Types

The improvement selection logic is based on a hierarchy of three major deficiency categories: pavement deficiencies; capacity-related deficiencies; and alignment deficiencies. Thus HERS identifies improvements based on improvement options selected from the three improvement categories of pavement, widening, and alignment. The list of pavement and widening improvement types is shown in Figure 4-2. For user-specified improvement types, refer to FHWA, *HERS-ST User’s Guide* (2002).

Alignment

In HERS, any of the pavement and widening improvements can be combined with an alignment improvement. An alignment improvement generally results in improving all of a section's substandard curves and/or grades to the design standard. The four alignment options are to improve curves, improve grades, improve both or improve neither.

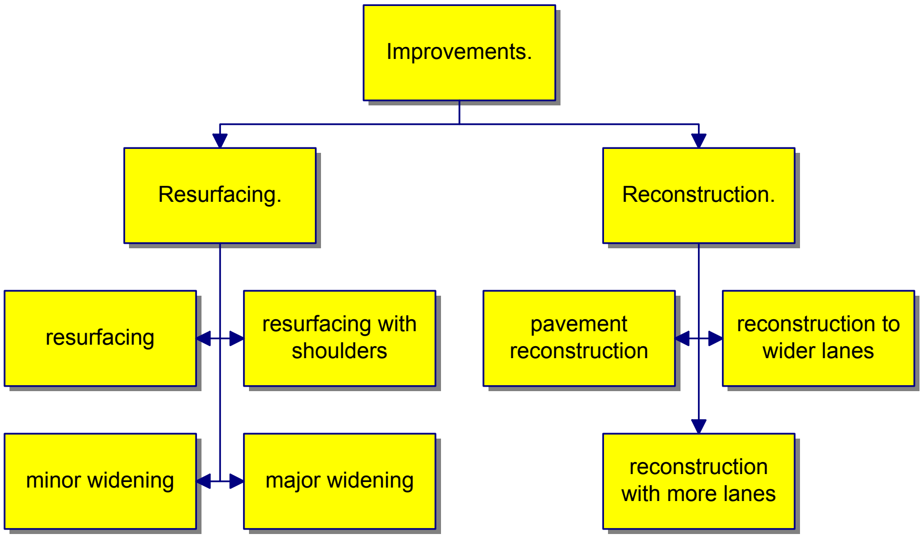

FIGURE 4-2. **HERS pavement and widening improvement types.**

Deficiencies and Improvements

For each of the eight types of deficiencies there is at least one improvement type that will correct the deficiency. Deficiencies and improvements map as shown in Figure 4-3. Although lane and shoulder widenings have some effect on capacity, additional lanes are required to correct a V/C deficiency. Shoulder width is corrected by most improvement types; lane width by adding lanes (See Table 6-1 in FHWA, *HERS-ST Technical Report*, 2002).

More Aggressive Alternatives

Improvements are ordered in HERS from least expensive to most expensive, in terms of initial capital outlay. An alternative is considered “more aggressive” if it is typically more expensive. The significance of a more aggressive worthwhile alternative is in selecting improvements under a funding constraint: HERS may prefer a less aggressive improvement on one section because it can use the funds for a project on another section that generates a higher IBCR (See “Selection of the Best Alternative Using IBCRs” on page 7-4).

Even though a particular improvement may correct a given deficiency, a more aggressive improvement may be cost-beneficial in that either the more aggressive improvement is worthwhile even though the less aggressive improvement is not, or the incremental benefit-cost ratio (IBCR) of the more aggressive improvement relative to the less aggressive improvement is positive.

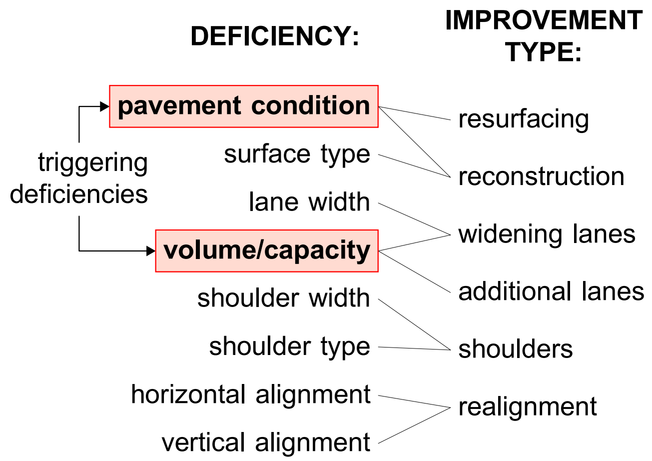

FIGURE 4-3. **Deficiencies matched to correcting improvements.**

For resurfacing options, the hierarchy of aggressiveness is shown in Figure 4-4. Options with alignment improvement are shown on the right-hand side. On the left, adding lanes is more aggressive than widening lanes, which is more aggressive than widening shoulders. If lanes are added, it is assumed that shoulder deficiencies and lane width deficiencies are corrected, and all lanes are resurfaced.

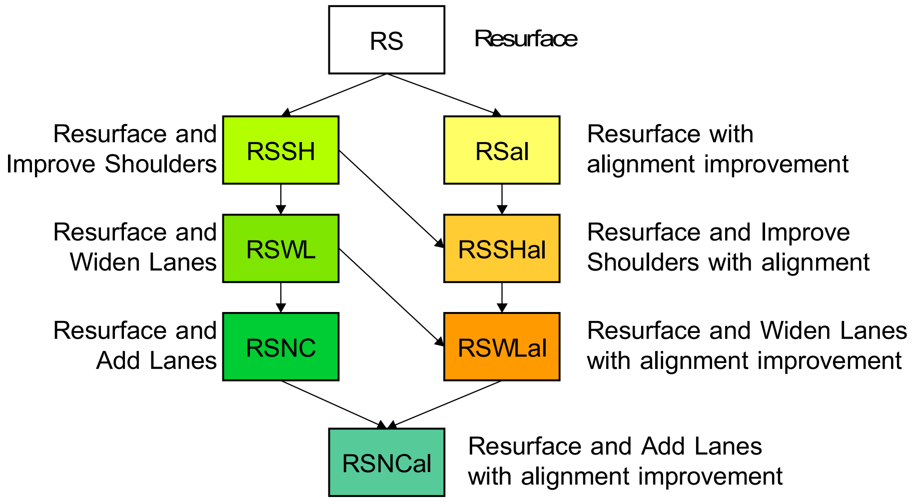

FIGURE 4-4. **Resurfacing improvement hierarchy.**

Candidate Improvements

The HERS-ST user can define new improvement types which are "non-native" to HERS (improvements that are different from those generated internally by HERS). These user-defined improvement types are only implemented on the sections specified by the user, and may only impact section conditions through adding lanes and increasing capacity; other section characteristics are unchanged. The user can also specify the cost of the improvement. The improvement may, at the user's option, be combined with native HERS improvements.

The procedure HERS uses internally (if no user-specified improvement has been declared for the section) for identifying an improvement type to address ordinary deficiencies consists of two components (see Figure 4-5):

(1) The identification of one (or a maximum of two) improvement types to correct all existing deficiencies. The improvement type is identified through the selection of:

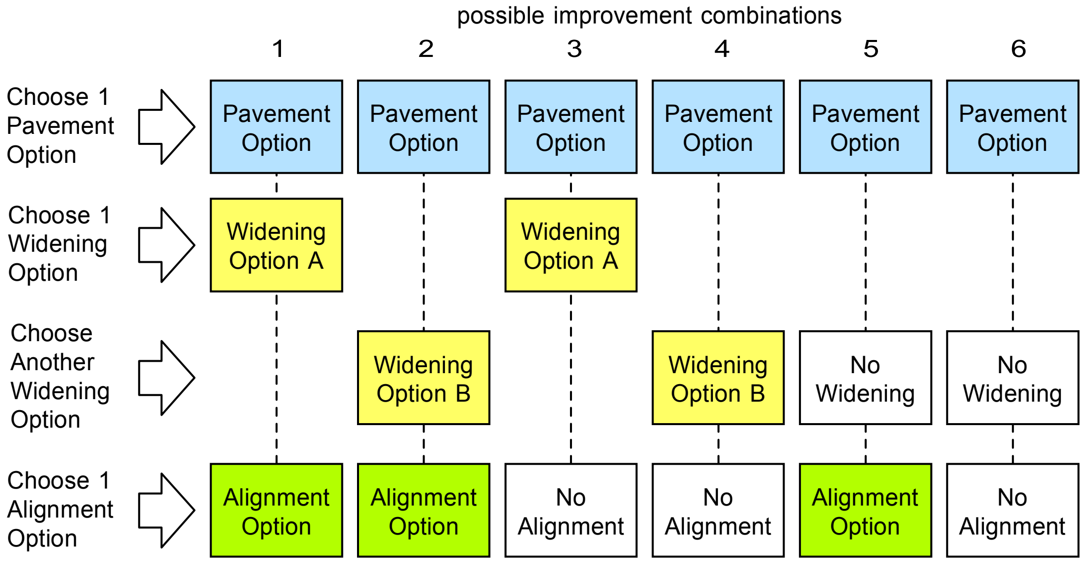

FIGURE 4-5. **HERS identification of six kinds of improvement for evaluation.**

- A maximum of one pavement improvement option,
- A maximum of two widening options, and
- A maximum of one alignment improvement option.

(2) The identification of any less costly improvement types warranting BCA as possible alternatives to the first improvement. Less aggressive improvements can be derived directly from the most aggressive improvement. The less aggressive improvements include:

- Replacing a widening option with no widening, and
- Replacing improved alignment with no change in alignment.

Thus it is possible for HERS to generate as many as six candidate improvements for a given section. For additional information on how HERS generates improvement options, see Chapter 3 “Identifying Candidate Improvements” in the *HERS Technical Report* (December 2000).

Widening Feasibility

Several types of deficiencies introduce the possibility of widening the road. Constraints are placed, or can be placed, on the extent to which this occurs. Widening can include widening lanes or shoulders or medians, as well as adding lanes. The constraints are:

(1) The user can specify the maximum number of lanes that a road can have, by functional class (if a section already exceeds this number, no lanes will be added or subtracted).

(2) If HERS adds any lanes, the resulting total will always be an even number of lanes.

(3) Each HPMS section includes a widening feasibility code, determined by the submitting state, indicating one of the five conditions shown in Table 4-3.

TABLE 4-3. **Widening feasibility codes**

Code	Description
1	no widening is feasible
2	partial lane may be added
3	one lane may be added
4	two lanes may be added
5	three or more lanes may be added

(4) The state-supplied widening feasibility code can be overridden by the system-wide widening feasibility override code, which uses the same codes as Table 4-3.

Widening feasibility is explained in more detail in section 4.5 of the *HERS-ST Technical Report* (December 2002).

Special Case: Substandard Conditions on Urban Freeways

HERS distinguishes four actions that can be taken to eliminate substandard conditions on urban freeways: improving median type to positive barrier; improving shoulder type to surfaced; improving access control to full; and improving median width to design standard. HERS presumes that whenever a substandard urban freeway is reconstructed, any of these actions that are necessary and feasible are taken.

Capacity Calculation

Capacity calculations are performed (1) to design the number of lanes needed to correct a present or future capacity deficiency, and (2) to calculate the actual capacity after improvements such as lane widening and shoulder improvements, as well as adding lanes, have been made.

The 1998 Transportation Research Board's Highway Capacity Manual (HCM), Special Report 209, contains procedures for calculating highway capacity. These procedures are used to the greatest possible extent in HERS, given the data available from the section data. HCM 2000 will be incorporated in the upcoming versions of HERS-ST.

Capacities for the HPMS highway sections may be contained in the sample section data records furnished by the states, but HERS also calculates capacities. When a highway improvement adds capacity, the model calculates the additional capacity. If the coded capacity in the section record is different from what HERS calculates, the model maintains the ratio between calculated and coded capacity.

The HERS model calculates the design number of lanes from the forecast design hour (30th highest hour) volume, capacity per lane, a rural density factor, percent trucks in the design year peak, and the passenger-car equivalent (PCE) for trucks. Subtracting the existing number of lanes from the design number (after checking for widening feasibility) yields the number of lanes to be added. See section 4.6 of FHWA, *HERS Technical Report* (2002) and FHWA, *HERS-ST User's Guide* (2002) for more detail.

CHAPTER 5

ESTIMATION OF IMPACTS

For HERS to select the best improvements, it must calculate changes that occur over time in pavement condition and congestion, and the changes in user and agency costs, and externalities, that result from an improvement. User benefits represent the reduction in travel time, operating costs, and the number and severity of crashes. Agency benefits represent the reduction in the cost of routine maintenance of highways, as well as the residual value at the end of the BCA period.

Role of Impacts in Project Evaluation

Impacts, for benefit-cost purposes, must be estimated relative to a base alternative. Typically, the base case is the do-nothing or no improvement alternative, but because HERS uses IBCRs (incremental benefit-cost ratios) to approach the maximum-net-benefit alternative incrementally, the base is often a less aggressive but worthwhile alternative. Impacts are the differences between the base case and the improvement candidate, as shown in Figure 5-1. HERS does not attempt to estimate the differences directly, but, rather, estimates conditions for each alternative (e.g., average effective speed) and then subtracts them (to derive travel time changes).

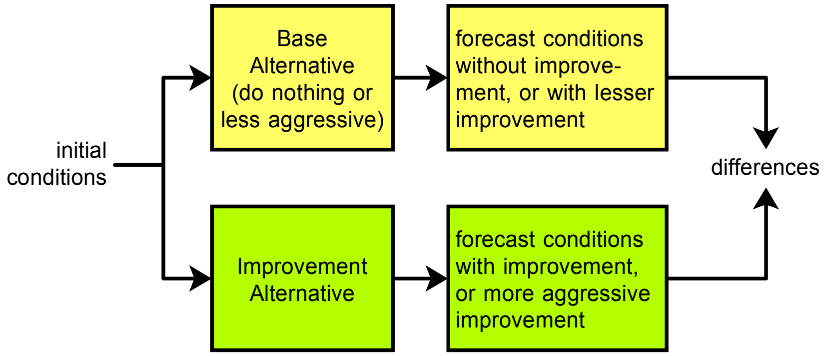

FIGURE 5-1. **Estimation of impacts for each improvement option.**

The overall logic chain into which impact estimation fits is shown in Figure 5-2. Once the candidate improvement alternatives have been designed, the next step becomes the estimation of the impacts of the improvements on benefits. Because benefits are measured relative to the base case, the consequences of doing nothing must also be estimated.

Impacts of Improvements on Section Attributes

An improvement may have an impact on any or several of the 18 section attributes listed in Table 5-1 (a more detailed description of which improvements affect which attributes is given in Tables 6-1 through 6-5 of FHWA, *HERS-ST Technical Report*, 2002). Some of these changes in section attributes affect user costs directly (pavement quality), or indirectly (median width), or affect the rate of pavement deterioration (SN), or affect the design of alternatives for the section in subsequent periods (widening feasibility).

TABLE 5-1. **Section attributes potentially affected by an improvement**

Section Attribute	Possible Changes
Number of Lanes	increase or NC
Lane Width	meet Design Standard or NC
Shoulder Type	Existing or MTC, or NC
Right Shoulder Width	meet Design Standard or NC
Pavement Condition	recalculate
Pavement Thickness	recalculate
SN or D	increase or NC
Surface Type	meet Design Standard
Peak Capacity	recalculate or NC
Median Width	Design Standard or feasible
Median Type	unprotected, none, or NC
Access Control	full or partial
Grades	meet Design Standard
Curves	meet Design Standard
Passing Sight Distance	improve to average or NC
Weighted Design Speed	recalculate
Widening Feasibility	lower code or NC

NC = no change
Design Standard = set attribute to design standard
MTC = set attribute to minimum tolerable condition
code = adjust value of attribute code

Benefits from Changes in Section Attributes

Subsequent steps—estimate the impacts of changes in pavement on speed, estimate the change in speed and pavement on operating costs, and compare those to the base case—are described below. Also provided is the HERS process for determining maintenance benefits accruing to highway agencies. Interrelationships among impacts were shown in Figure 2-4.

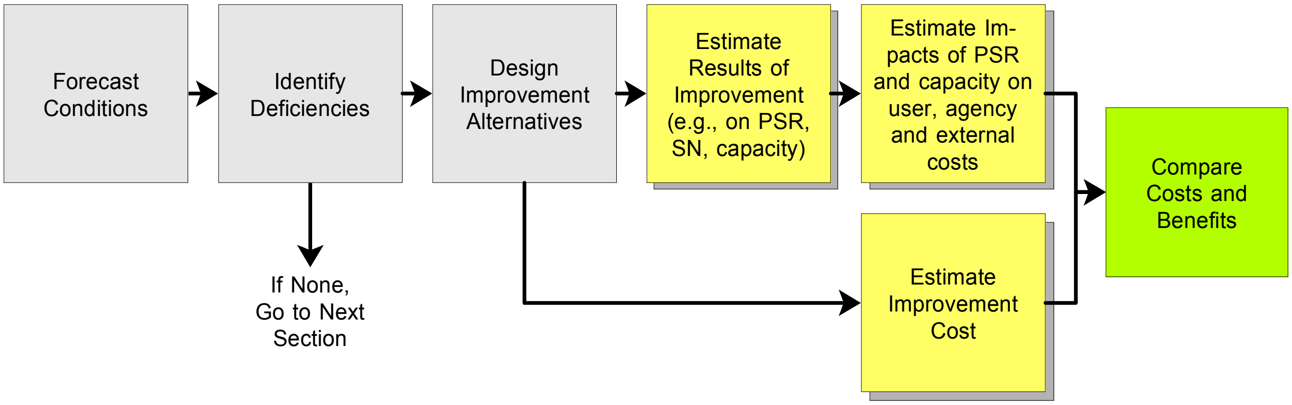

FIGURE 5-2. **Impact estimation within the evaluation framework.**

Pavement Deterioration Model

Pavement deterioration occurs partly due to weather and partly to the application of heavy truck axles. Pavement surface quality, which can be measured directly as PSR or IRI, affects speed and operating costs. The pavement model is used to estimate the deterioration of pavement over time, thereby determining when a pavement improvement will be needed. The pavement deterioration model is based on American Association of State Highway and Transportation Officials (AASHTO) pavement deterioration procedures developed from the AASHO road test in the early 1960s.[1] These procedures have formed the core of the AASHTO Pavement Design Guides since that time. The basis for pavement deterioration in this procedure is a reduction of AADT expressed as the number of Equivalent Single Axle Loads (ESALs) of 18,000 pounds (18 kips) passing over the pavement. The pavement deterioration relationship is based on the damage caused by an equivalent number of applications of this axle load to a pavement structure.

HERS also applies both an upper bound and a lower bound, each of which is a function of time, to ensure that weather is accounted for when there are few trucks, and that deterioration is not too rapid when the pavement is new. Weather effects include precipitation and freeze-thaw cycles.

The curves in Figure 5-3 shows the effect of ESALs on the PSR of flexible pavement for two structural numbers, one representing a heavy duty pavement and the dashed line representing a medium pavement. The shapes of the two curves are similar, but a single ESAL has more impact on a lighter pavement. The effect of ESALs is cumulative, over

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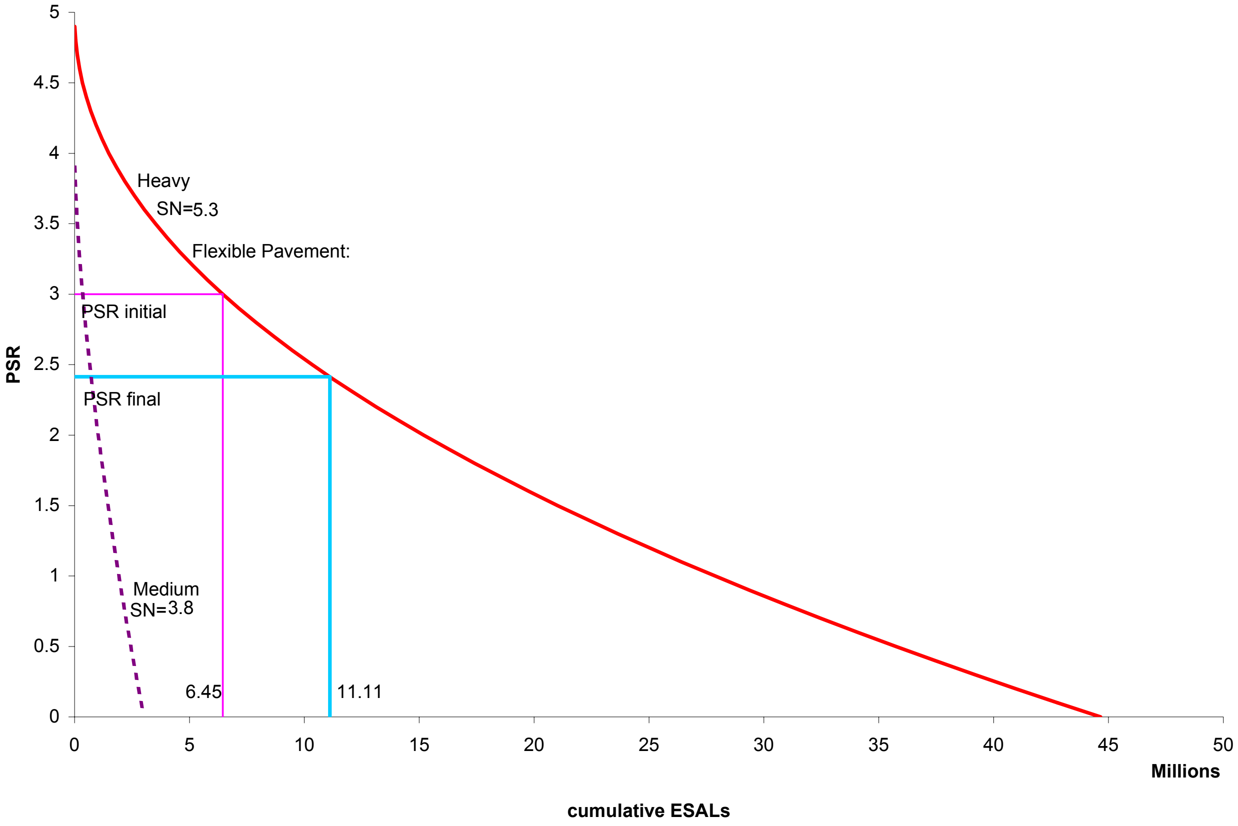
[1] American Association of State Highway and Transportation Officials, *AASHTO Guide for Design of Pavement Structures, Washington, DC,* 1993.



source: extracted from equations in FHWA, *HERS-ST Technical Report* (2000).

FIGURE 5-3. **Pavement quality (PSR) as a function of cumulative ESALs for flexible pavement.**

the lifetime of the road, so that a road can be designed to withstand a given number of truck axle loads before the road must be resurfaced or rebuilt. From the curves it is obvious that stronger pavements can withstand substantially larger ESAL loads, and hence the accuracy with which the structural number (for flexible pavements) is measured is very important for predicting the rate at which the pavement will deteriorate.

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 that have six or more tires (separate averages for single-unit and combination 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. Functional class and rural/urban locations represent different distributions of truck types and therefore yield different ESAL factors. 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. The lane-load adjustment factor is taken from the AASHTO Pavement Design Guide. The percentage of single unit and combination trucks for each sample section in the base year is contained in the data record describing the section.

HERS has no knowledge of the age of the pavement or its history of truck traffic, so the model estimates remaining ESAL life of the pavement from its current PSR and the applicable deterioration curve such as shown in Figure 5-3.

Operating Cost Model

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, of curves and grades, and of traffic control devices. These cost estimates exclude fuel and other excise taxes.

For each vehicle type, and for both directions for trucks on grades, total operating costs are obtained by combining the following three components:

- Constant-speed operating costs as a function of average effective speed, average grade, and pavement condition (PSR);
- Excess operating costs due to speed variability; and
- Excess operating costs due to curves.

Total operating costs for the section are estimated by taking a weighted average of the corresponding costs for each vehicle type.

Constant-Speed Operating Costs

Constant-speed operating costs are estimated, by vehicle type, as a function of average effective speed, average grade and PSR. These cost estimates reflect the sum of user-related costs for fuel, oil, tires, maintenance and repair, and depreciation. The conceptual strategy for this model is to start with a set of detailed constant-speed operating cost consumption relationships (e.g., fuel consumption per vehicle mile for 0-3% positive grade) constructed in 1980, update the 1980 consumption rates to 1997, adjust for additional costs of curves and stops, and apply current unit costs to the resulting consumption rates. The structure of the vehicle operating cost model is diagrammed in Figure 5-4.

The general form of the constant-speed operating cost equations from HERS combines five cost components: fuel, oil, tires, maintenance and repair, and depreciation. Adjustments for pavement surface roughness are also incorporated into the equations.

$$CSOC_v = \sum_{i = \text{cost component}} CRAT_{vi} \times PAVAJ_i \times UCOS_{vi} / CADJ_{vi}$$

where

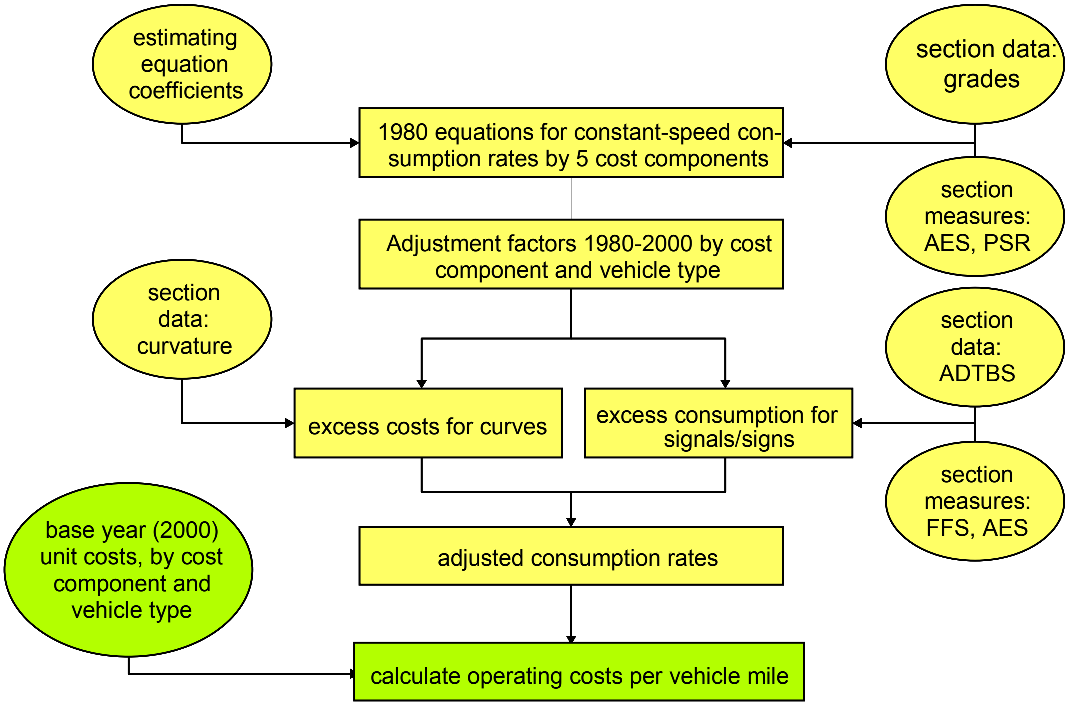


FIGURE 5-4. **Structure of the HERS vehicle operating cost model.**

$CSOC_v$ = constant-speed operating cost for vehicle type v

$CRAT_{vi}$ = consumption rate for cost component i in vehicle type v

$PAVAJ_i$ = pavement condition adjustment factor for component i

$UCOS_{vi}$ = unit cost for component i

$CADJ_{vi}$ = time adjustment factor for component i in vehicle v

The time adjustment factor updates the consumption rates from the 1980 estimates, to recognize changes in technology. The consumption rate factors are themselves equations, for each vehicle type and cost component.

Vehicle Types

Equations for constant-speed operating costs by vehicle type depend on average effective speed and grade. A different equation is used for each grade range and speed range, from steep upgrades to downgrades, and speeds above or below 55 mph. Fuel consumption, for example, is zero for 5-or-more-axle trucks on downgrades greater than 1.5%.

1980-2000 Adjustment Factors

Consumption rates are adjusted from 1980 to 1997 to address changes in technology that have occurred in the past twenty years. Fuel consumption, for example, has gone down for some vehicle types (or fuel efficiency has gone up), although the change for trucks has been less than for passenger vehicles, in part because of the increasing (and higher) weight of trucks.

Current Prices

Finally, unit costs or current prices are applied to the adjusted consumption rates to yield estimates of current vehicle operating costs, for the conditions pertaining to the specific highway section.

Effect of Speed-Change Cycles

Excess operating costs due to speed variation, on sections with signals or stop signs, are estimated from a series of equations, for each vehicle type. Excess operating costs due to speed-change cycles are a function of the maximum speed of the speed variation and the vehicle type.

Effect of Curves

For each vehicle type, HERS estimates excess operating costs as a function of average effective speed and radius of curvature. The strategy is parallel to that for constant-speed operating costs, in that consumption rates (fuel, etc.) are adjusted and unit costs are applied to yield a dollar cost effect.

Safety Model

Annual safety costs of a highway section are estimated through a series of steps, shown in Figure 5-5.

Incident Rates

Incident or crash rates per 100 million VMT are estimated for three separate highway classes or facility types: expressways with medians, multi-lane roads, and two-lane roads. These types are modeled separately for urban and rural, and the rates are then adjusted so that the results are consistent with national accident statistics. The adjustment (or “calibration”) factors apply to a larger number of highway classes than the initial six.

Example: Rural Two-Lane Roads

The safety model, like several of the other models, is constructed using different equations for each highway class. For rural two-lane roads, crashes per 100 million VMT is the sum of crashes at intersections plus non-intersection crashes, based on empirical evidence indicating that crashes are much more likely to occur at intersections than on equivalent length sections without intersections. Driveways are factored in separately from intersections.

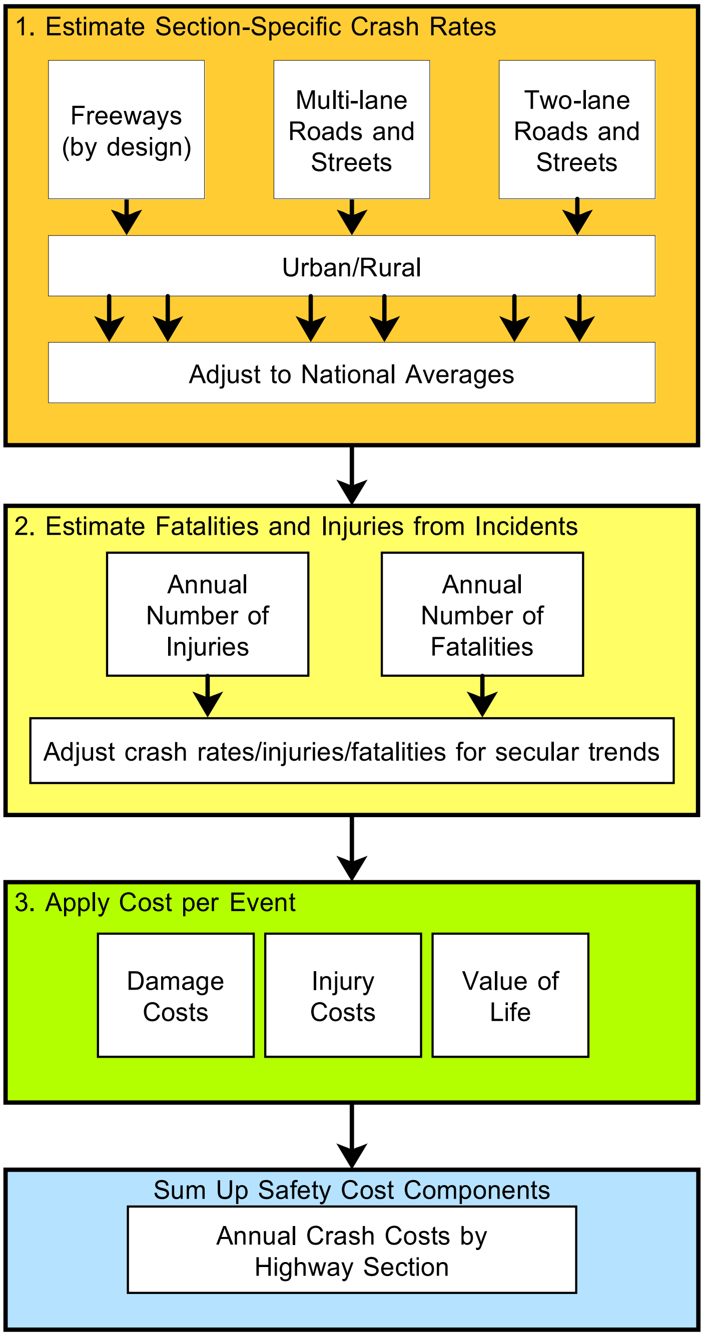


FIGURE 5-5. **Calculation of highway safety costs.**

Non-Intersection Crashes

The model for non-intersection crashes on two-lane rural roads has the form,

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

where

$CNINT$ = number of non-itersection crashes (per 100 million VMT)
$SLEN$ = section length (in miles)
$ADJSL$ = section length adjusted to exclude segments within 250 feet of an intersection
LW = lane width (in feet)
SHW = shoulder width (in feet)
RHR = roadside hazard rating (3.0)
DD = driveway density per mile (=3.7 for rural and 50 for dense development)
$CURV_i$ = average degrees of curvature in HPMS curve class i
$LCURV_i$ = total length (in miles) of all curves in curve class i
GRD_i = average percent grade in HPMSgrade class i
$LGRD_i$ = total length (in miles) of all grades in grade class i
$CCGR$ = crest curve grade rate in percent per hundred feet (=0 or 0.0)

This form is typical of many equations in HERS, which are taken from different pieces of the research literature and are adapted as necessary to fit the HERS model's requirements.

Rural Multi-Lane Roads

Because a four-lane road with median is a different type of road than a two-lane, it has different equations. In estimating crash rates on a two-lane road upgraded to four-lane, the estimating equations will be treating them as entirely different roads (with different accident parameters as well as parameter values). Because multi-lane (ML) divided roads are safer than undivided roads, the equation for rural ML roads is sensitive to the existence and width of a median. Other variables are similar to those in the two-lane road equation above.

Injuries and Fatalities

Property damage costs are normally based on per-incident averages, so incident rates can be directly factored into damage costs with a unit cost. Injuries and fatalities do not occur with every incident, however, and sometimes more than one arise from the same incident. Hence, injury and fatality rates must be applied to incidents. For this purpose, separate rates for injuries and fatalities are applied to each of the nine functional classes (see Table 5-8 of the *HERS-ST Technical Report*, 2002).

Crash Costs

The cost of incidents is obtained by multiplying the estimated numbers of incidents, injuries, and fatalities by their respective unit cost averages. Estimated costs per nonfatal injury and estimated property damage per crash are provided in Table 5-9 of the *HERS-ST Technical Report* (2002).

Speed Model

Underlying the calculation of travel time and operating costs are speed determination models. Average effective speed is an input to the calculation of travel time costs, vehicle operating costs, and emissions costs, as indicated in Figure 5-6.

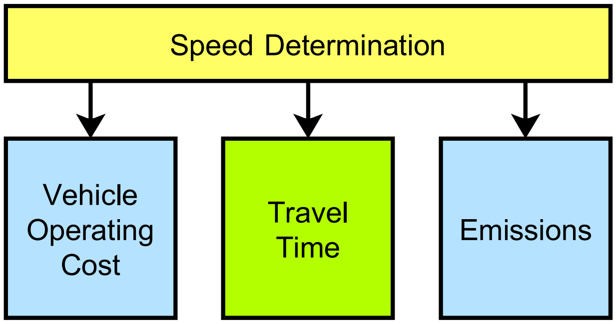


FIGURE 5-6. **Impacts and benefits affected by speed model.**

The HERS speed determination procedure includes two distinct processes, or models. The first estimates unconstrained speed, the average speed that would exist in the absence of any other traffic. The second determines average effective speed by modifying the unconstrained speed estimates to reflect the effects of congestion and traffic control devices.

For each highway section, speed estimates are developed separately for each of seven vehicle types and, for each section with grades, in both directions, for each truck category. Speed variability is required to estimate vehicle operating costs on sections with traffic control devices (TCDs).

In the HERS model, speed is assumed to be affected by vehicle type, curves, grades, pavement surface quality, speed limits, congestion, and traffic control devices. For each vehicle type, the model first determines the limiting velocity, as constrained either by curves, pavement, or speed limit. Then this “free-flow” speed is adjusted for the effects of congestion delay and traffic control devices. The components of the speed model and its input variables are shown in Figure 5-7. This procedure is used for freeways, rural roads, and city streets with and without traffic signals.

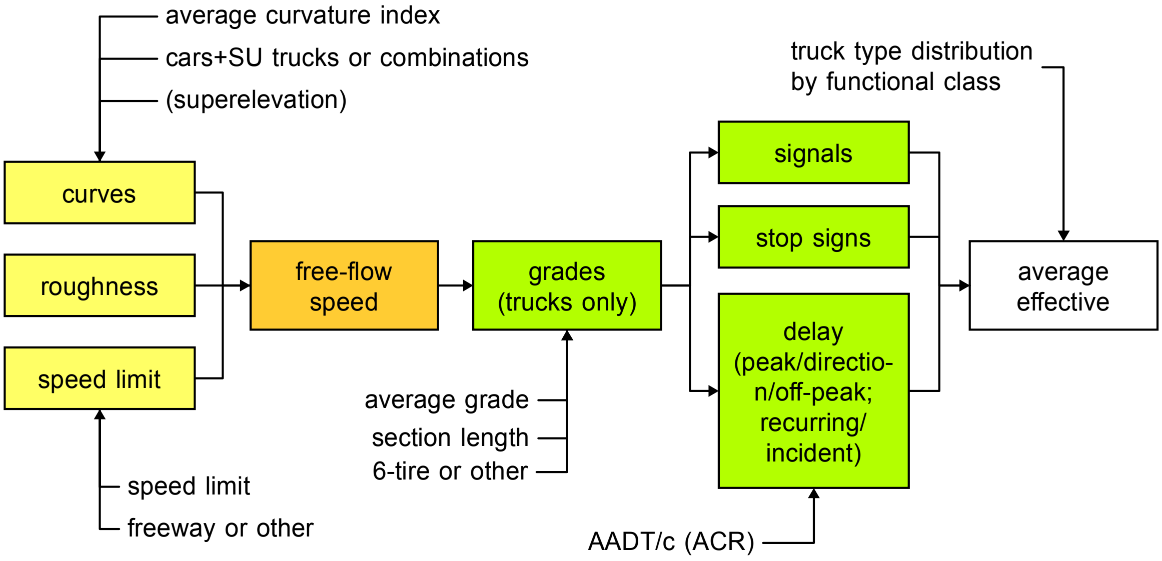


FIGURE 5-7. **Internal structure of the HERS speed model.**

The section characteristics for estimating speed are dependent upon the data items collected in the HPMS sample section record, or equivalent data.

Calculation of Free Flow Speed

The HERS procedure for estimating unconstrained speed is based on the Texas Research and Development Foundation (TRDF) adaptation of the Aggregate Probabilistic Limiting Velocity Model (APLVM), originally developed by the World Bank.[2]

The HERS version of the APLVM is based on the computation of three limiting velocities. These limiting velocities represent the approximate speeds that would be obtained should a single factor (e.g., pavement condition) limit speed to a value lower than would otherwise be the case. The three factors potentially limiting free speed are curves, pavement roughness, and the speed limit.

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

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

Curves

As a vehicle travels the curved section of a roadway it is subjected to centrifugal force, which tries to cause the vehicle to leave the curved path of the roadway. The vehicle is held in its curved path by side friction between the tires and pavement. The maximum speed safely attainable on a curve is determined by basic laws of physics relating to the radius of the curve, superelevation, the vehicle speed, and frictional forces.

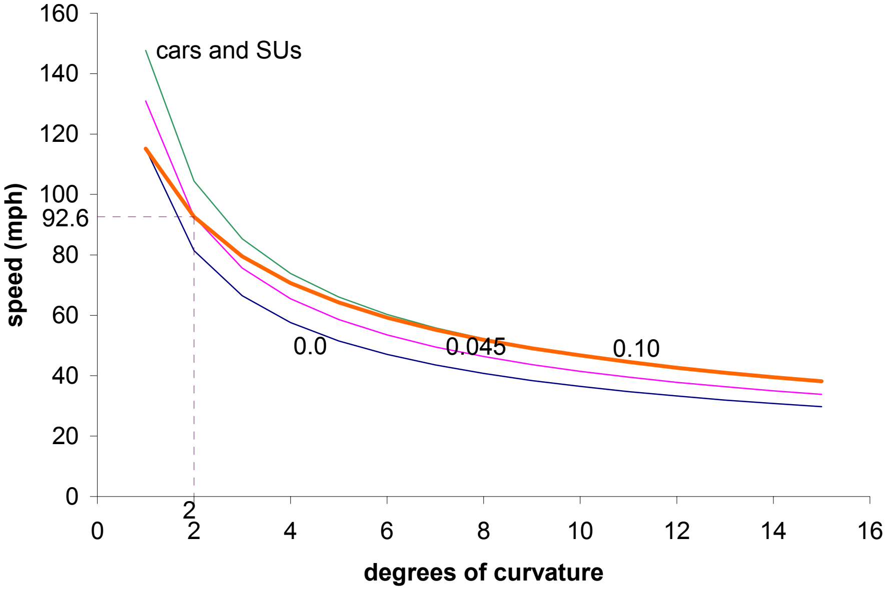

FIGURE 5-8. **Curvature and speed for cars and single-unit trucks.**

In HERS, this vehicle speed is estimated as a function of the degree of curvature (a measure of the radius of curvature); superelevation (a measure of the banking of the curve); and a maximum perceived friction ratio, by vehicle type (which is the ratio of the lateral force on the vehicle to the force due to the vehicle's weight acting downward through its center of gravity). The relationship between degrees of curvature and speed are shown in Figure 5-8 for three superelevations, for passenger vehicles (vehicle classes are aggregated to two types for curve-and-speed purposes). The friction ratio is a single number for all sections and vehicles types, and is fixed. Superelevation is not included in the curves data in the HPMS section record, so it is calculated endogenously within HERS from the curve data (on the assumption that tighter curves are more steeply banked). The degrees of curvature variable is estimated as an average for the section from the HPMS data on curves. The net result is a single-valued curve for each of two vehicle types, represented by the heavier lines in the two figures. For curvatures under about two degrees, speed is not constrained by curves.

Grades

Only trucks are assumed to be affected by grades with respect to speed. Two truck types are distinguished: 6-tire trucks, and larger trucks. The relationship between length of grade and speed is shown in Figure 5-9. The longer the length of the grade, the closer the truck approaches its “crawl” speed, or the speed it could maintain on an infinitely long upgrade of a given steepness (percent grade). The curves shown apply to a grade of 15%.

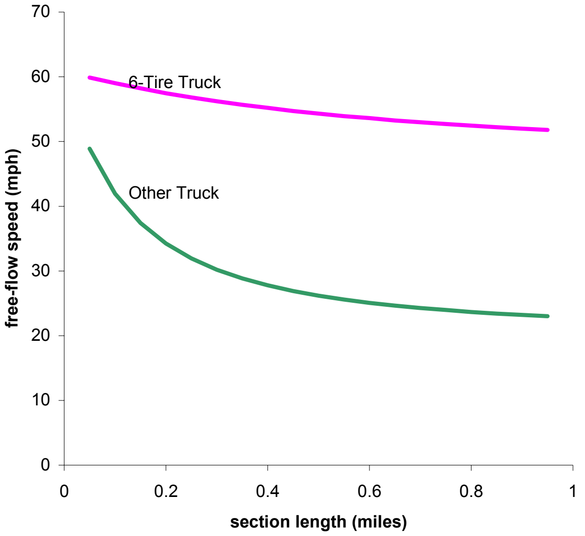

FIGURE 5-9. **Grades and speed for trucks.**

Speed Limits

When no other constraint is binding, posted speed limits are assumed to govern. Average speeds tend to be above speed limits, slightly more so for freeways. The relationship between speed limit and actual speed is shown in for two types of highway, freeway and other. For freeways, actual speeds are estimated to be about 9.3 mph above posted limits, and for other roads actual speed is estimated to be about 6.2 mph above the limit. The default maximum speed limit is 75 mph.

Pavement Roughness

The HERS procedure used to specify the value of speed when limited by pavement condition recognizes that pavement condition begins to become a limiting factor on high speed roads at approximately the boundary between good (3.0 to 4.0) PSR and fair (2.0 to 3.0) PSR (See “Pavement Deterioration Model” on page 5-3).

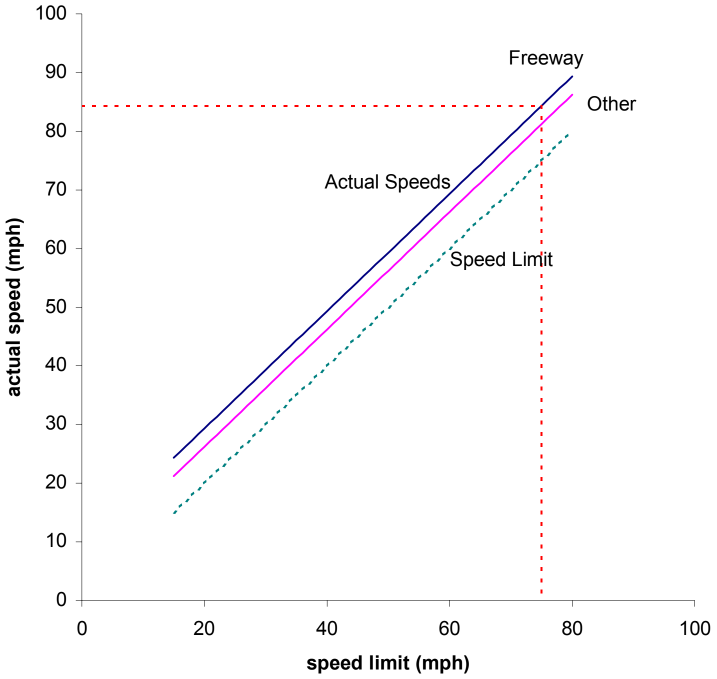

FIGURE 5-10. **Average speed as a function of speed limit.**

In HERS, the effect of PSR on speed is represented by a piece-wise linear function, that is a pair of line segments with different slopes meeting a user-specified break point. The analyst may exercise significant control over the function used to specify speed limited by pavement roughness.

Free-Flow Speed

Free-flow speed (FFS) for a rural highway with two opposing lanes, no curves or grades, and a speed limit of 55 mph is shown in Figure 5-11, as a function of pavement quality. At low levels of surface smoothness (PSR<2.0), the poor pavement prevents vehicles from going as fast as they would prefer; when the pavement is smooth, however, average speed is governed mainly by speed limits.[3] The effect of pavement alone is represented by the curve marked “vrough.” If there are curves or grades, those factors may be binding under some conditions. The formula for free-flow speed weights all three factors—curves, speed limits, and pavement surface quality—in such a way that the lowest value is the primary determinant.

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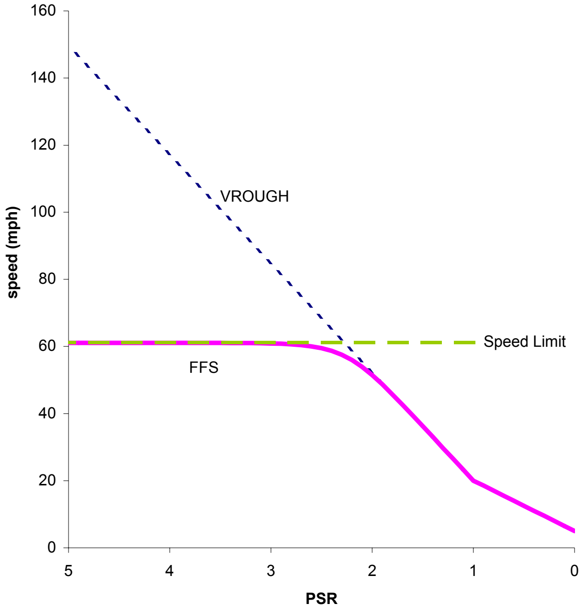
[3] Enforcement of speed limits is not explicitly considered in this model.



source: constructed from equations in FHWA (2002).

FIGURE 5-11. **Free speed as constrained by surface roughness and speed limits.**

Grades

Grades are assumed to have no effect on the free-flow speeds of passenger vehicles (automobiles, pickup trucks, and vans). For trucks, “crawl” speed is estimated as a function of the percentage (uphill) grade, where crawl speed is the equilibrium speed of the vehicle if the grade were infinitely long. These crawl speeds are then adjusted for the type of truck and the length of the grade to estimate an amount of delay such vehicles will incur on that section.

Delay

Three kinds of delay are estimated in HERS:

(1) Recurring delay or non-incident delay

(2) Incident delay

(3) Zero-volume delay

The third of these is the additional travel time required on a section by the presence of traffic control devices (stops signs and traffic signals), and this delay is not included in total delay.

Equations for estimating delay are designed around six “Flow Designations:”

(1) Stop signs only

(2) Traffic signals only

(3) Both stop signs and traffic signals

(4) Free-flow facilities with one lane in each direction

(5) Free-flow facilities with 3 lanes and 2-directional flow

(6) Free-flow facilities with 2 or more lanes in each direction

In all cases, delay is estimated using the usage ratio or average capacity ratio, AADT/c. In some cases—flow designations (2), (3), and (6)—the total daily traffic is broken into three phases or demand periods:

(1) Peak period volume in the peak direction

(2) Peak period volume in the counterpeak direction

(3) Offpeak volume

An example of an equation for a single demand period (e.g., peak period peak direction) is shown in Figure 5-12, with the dashed line indicating a density of 45 vehicles per lane per mile, the standard adopted by HCM2000 to represent capacity (the upper boundary of LOS E). Traffic volumes differ among these three demand periods as determined by the direction factor and the K factor. Capacity may differ among demand periods if there are reversible lanes or parking is permitted in one period but not in another. For those sections where daily traffic is broken into the three demand periods, the travel delay function (minutes per vehicle mile as a function of AADT/c) is constructed by re-assembling the three demand periods, before equilibrating delay with the demand curve.

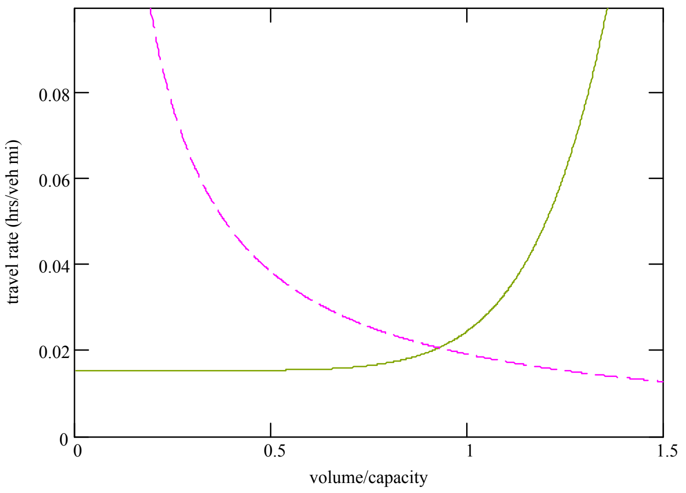


FIGURE 5-12. Peak travel time function.

Other flow designations are modeled with combined daily demand, measuring AADT/c as total daily traffic divided by hourly two-way capacity. The equations differ by highway type, and most equations are segmented, meaning that they are made up of several equations covering different ranges of the independent variable (AADT/c). The curves were developed using simulations, and implicitly assume a degree of peaking that is inherent to the volume and capacity. In other words, as more traffic is added to a section, some will be added to the peak, but progressively less as the peak volume exceeds capacity and drivers learn to avoid the peak if possible. An example is shown in Figure 5-13. Delay is added to normal travel time to derive average speed.

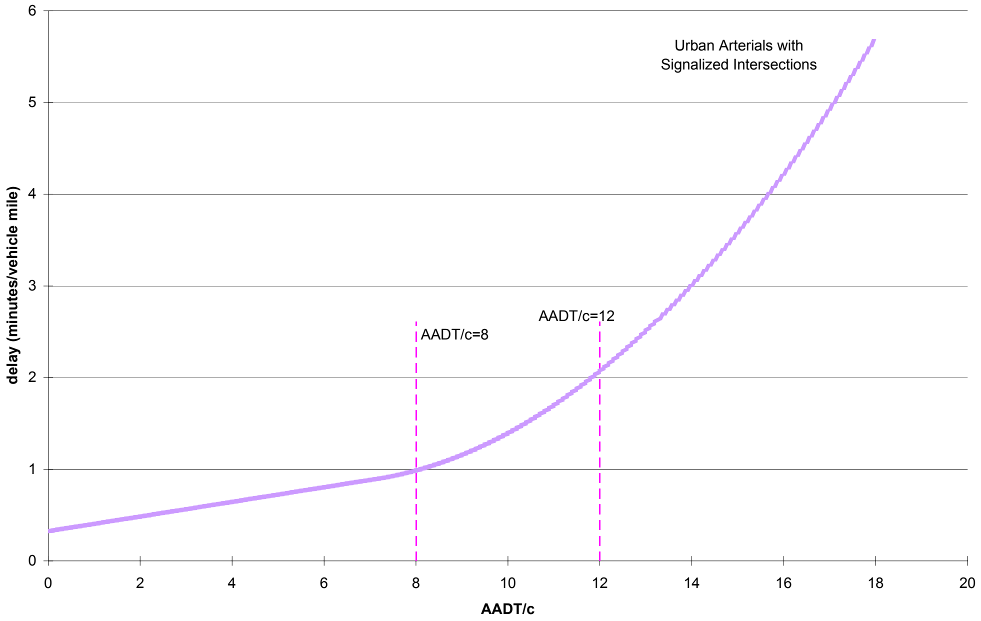


FIGURE 5-13. **Unit delay curve for signalized arterials.**

Travel Time Costs

The HERS procedure for calculating travel time costs recognizes that 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 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.

Alternatively, off-the-clock time savings reflect the results of research examining choice situations (e.g., toll versus free route, speed, or housing location) that require choosing to save time versus money or safety.

Table 5-2 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. For each vehicle type, average effective speed and travel time costs per hour are used by HERS to develop estimates of travel time costs on each section.

TABLE 5-2. **Estimates of the value of travel time (2000$)**

	Small Auto	Medium Auto	4-Tire Trucks	6-Tire Trucks	3-4 Axle Trucks	4-Axle Comb.	5-Axle Comb.
Business Travel							
Value per Person	$21.20	$21.20	$21.20	$18.10	$18.10	$18.10	$18.10
Avg. Vehicle Occupancy	1.43	1.43	1.43	1.05	1.00	1.12	1.12
Vehicle Depreciation	$1.23	$1.64	$2.15	$3.00	$8.11	$7.26	$6.98
Inventory Costs	--	--	--	--	--	$1.78	$1.78
Total Business	$31.55	$31.96	$32.47	$22.01	$26.21	$29.31	$29.03
Personal Travel							
Value per Person	$10.60	$10.60	$10.60	--	--	--	--
Avg. Vehicle Occupancy	1.67	1.67	1.67	--	--	--	--
Total Personal	$17.70	$17.70	$17.70	--	--	--	--
Percent Personal	89%	89%	75%	--	--	--	--
Weighted Average	**$19.23**	**$19.27**	**$21.39**	**$22.01**	**$26.21**	**$29.31**	**$29.03**

On-the-Clock Trips

Travel time for on-the-clock trips is valued on the basis of costs to the employer, including wages and fringe benefits paid, costs related to vehicle productivity, and inventory carrying costs of the cargo.

Labor Cost

Labor costs represent the sum of the hourly wage rate and fringe benefits. The hourly wage per vehicle occupant is based on statistics, specific to vehicle type, from the U.S. Bureau of Labor Statistics (BLS). Fringe benefit values are based on U.S. averages. Wages and fringe benefits per vehicle occupant are multiplied by average vehicle occupancy to compute employee costs per hour of work travel time.

The first row in Table 5-2 shows the labor and fringe benefit costs per hour by type of vehicle.

Vehicle Costs

For autos in commercial motor pools and four-tire trucks, the cost per hour is computed as the average vehicle cost per year (assuming a five-year life, with a 15 percent salvage value at the end, with the initial cost from the Motor Vehicle Manufacturers Association) divided by 2000 hours per year of sign out time (the shift when maximal vehicle use occurs).[4]

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[4] Motor Vehicle Manufacturers Association, *Motor Vehicle Facts and Figures,* 1984, Washington, DC, 1989.

For heavier trucks, the cost per hour is computed as the average vehicle cost per year divided by the number of hours in service per year.[5]

- Six-tire trucks and four-axle combination trucks: 2,000 hours per year.
- Five-axle combinations: 2,575 hours per year.
- Three- and four-axle single-unit trucks: 1,600 hours per year.

The second row of Table 5-2 shows the vehicle costs per hour by type of vehicle.

Inventory and Spoilage Costs

To compute the inventory costs for five axle combination trucks, an hourly discount rate is computed and multiplied by the value of a composite average shipment. The discount rate selected was 9.8 percent. The average payload of a five-axle truck is estimated to have a value of roughly $45,000, yielding a time value of $0.505 per hour.

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 is assumed to be the same for both types of trucks.

The inventory cost for three- and four-axle single-unit trucks is assumed negligible because dump trucks dominate this category and rarely haul goods of significant value. The inventory cost of delay for six-tire trucks is assumed negligible because these trucks are used primarily for local pick-ups and deliveries.

Finally, autos and four-tire trucks (pick ups and small vans) are 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 Table 5-2 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.

Off-the-Clock Trips

Off-the-clock trips include trips for commuting to and from work, personal business, and leisure activity. The HERS analysis assumes that the average value of travel time does not differ between these purposes. However, the value of travel time is assumed higher for drivers than passengers.

The HERS value of travel time is based on an evaluation of 19 studies published since 1970 where this relationship was estimated using route-choice models, surveys, speed-choice models, or models of housing-location choice.[6] The HERS values drivers' off-the-clock travel time at 60 percent of the wage rate (excluding fringes). The travel time of auto passengers is valued at 45 percent of the wage rate. The value of travel time used in HERS does not vary by trip length.[7]

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[5] Jack Faucett Associates, *The Effect if Size and Weight Limits on Truck Costs*, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, DC: 1990.

[6] See Jack Faucett Associates, *Value of Travel Time,* study memorandum submitted to the U.S. Department of Transportation, Federal Highway Administration, Washington, DC, September 18,1989.

Average vehicle occupancy per vehicle mile for off-the-clock trips is assumed to be 1.6 in urban areas and 2.0 in rural areas.

Values for Use in HERS

Heavy and medium trucks are assumed to be used only for work, therefore the value of heavy truck travel time equals the on-the-clock value. Lighter vehicles are assumed to be used both for work and for other purposes. The value of travel time for 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.

The sixth row of Table 5-2 shows the off-the-clock costs per hour by type of vehicle, and the fifth 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. For autos and four-tire trucks, separate values generally are used for urban and rural travel.

User Costs and Demand

Once all of the user costs associated with travel on a given section have been calculated, it becomes possible to determine the intersection of supply and demand, and the resulting volume. User costs that comprise the generalized price (in HERS) consist of travel time, vehicle operating costs, crashes, and user taxes. All of these are largely unaffected, per vehicle mile, by AADT/c, except for the time cost of delay. The supply side, then, is built up from all user costs, and has the same shape as the delay curves shown above.

The demand curve for a section for a given BCA period unit (one FP in length) is established from the baseline demand forecast (a future volume and time), the baseline price typically representing the current level of service on the section, and the short-run elasticity set by the user. A short-run demand curve is shown in Figure 5-14, fitted to the forecast volume and baseline price. Current conditions indicating the type of facility, normal travel time, pavement condition, and accidents are used to establish the “price without delay” that is the left end of the “supply” curve where it intersects the vertical axis. Delay as a function of volume relative to capacity, when added to the other user costs, generates the supply curve.

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[7] Ted R. Miller, *The Value of Time and the Benefit of Time Savings,* The Urban Institute, Washington, DC, 1989, and Garder, “‘Value of Short Time Periods,” Draft Report, University of North Carolina, Highway Safety Research Center, Chapel Hill, NC, May 1989.

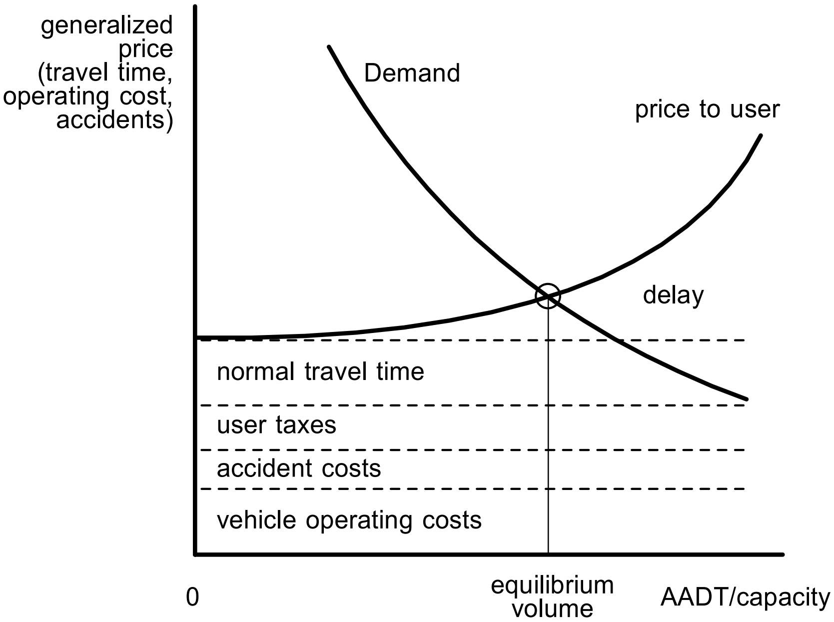

FIGURE 5-14. **Short-run demand showing prices with and without improvements.**

Equilibrium Volume With Delay

The equilibrium traffic volume at a point in time is the resolution of demand and supply. The demand curve represents a relationship between volume and generalized price, in which a higher price implies a lower volume. The supply function is a relationship between volume and unit cost to the user (the price) of travel, in which higher volume results in higher price, due to congestion. These two relationships must be simultaneously reconciled.

Because the delay curves are of different functional form for each type of facility, and the equations are segmented as well, defining the intersection of supply and demand in closed algebraic form is not feasible. Hence, a two-step numerical approximation (as shown in Figure 5-15) is employed that uses the slopes of the curves to estimate an initial point (labeled 1), and the slopes at that point used to generate another point (labeled 2) that is fairly close to the true intersection.

The initial volume is taken from the demand curve using a price that includes operating costs and normal travel time, but no delay. Actual delay that would occur at this volume (shown by the long-dash line) is then added to the price without delay to obtain the price with delay at the initial volume. The triangulation process for the numerical approximation starts from this point and its counterpart on the demand curve.[8]

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[8] See sections 6.3.4 and 6.3.5 of the *HERS Technical Report* (December 2000) for further detail.

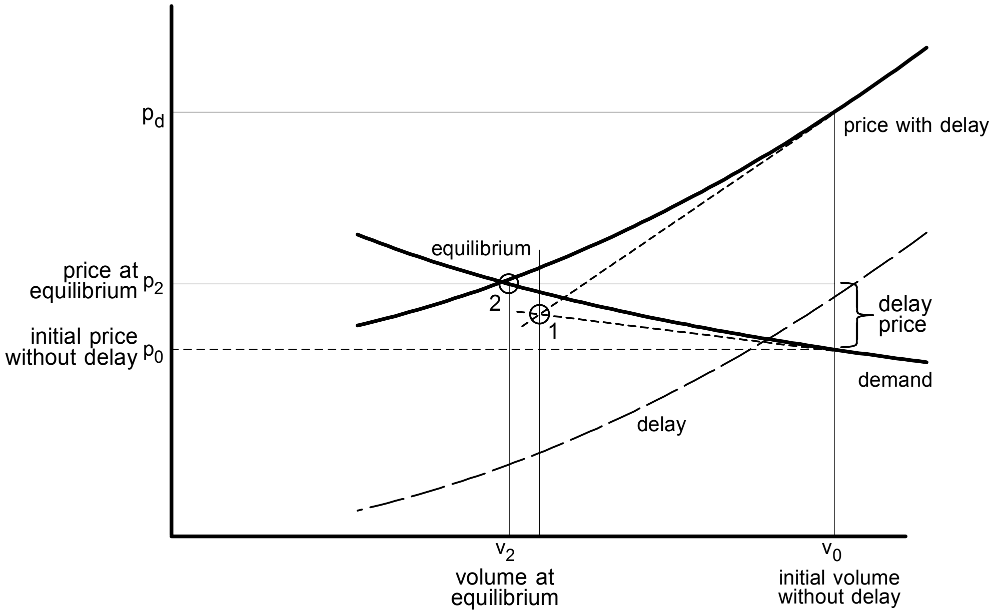

FIGURE 5-15. **Equilibrium volume with elasticity and delay.**

Highway Agency Costs

HERS recognizes two types of benefits of improving a section of highway to the agency in charge of building and maintaining the highway:

- A reduction in the cost of routine maintenance resulting from resurfacing or reconstruction of pavement; and
- A reduction in the cost of the next improvement resulting from the improved condition of the section when that improvement is implemented.

The second type of benefit is the “residual value” of the improvement. The estimation of residual value is discussed at some length in conjunction with the presentation of the HERS BCA procedure in Chapter 6. This section presents the HERS procedure for estimating the other type of agency benefit: reductions in maintenance costs.

To simplify the analysis of maintenance expenditures, a maintenance cost period is defined to be a period beginning at the midpoint of a FP and ending at the midpoint of the next FP. Estimates of pavement maintenance expenditures over each maintenance cost period are then derived from PSR estimates for the beginning and end of each period.

Maintenance costs per lane-mile for flexible pavements are estimated from a continuous function whose key variables are PSR and structural number.[9] In the absence of readily available information about maintenance costs for rigid pavements, HERS assumes these costs are identical to those for flexible pavements having a thickness of 5.5 inches, the thickest flexible pavement considered by HERS.

Emissions Costs

The HERS model includes estimates of the costs of damages from vehicular emissions of air pollutants in its calculation of benefits and disbenefits resulting from the implementation of an improvement. HERS uses a look-up table containing per-mile emission costs. The table indices are: vehicle class (4-tire, single unit truck, combination truck); average effective speed (integral from 5 through 70 mph); and functional class. HERS next selects a decay factor for each vehicle class based upon functional class. The decay factors are applied to the emission costs of the corresponding vehicle class:

$$EMSCST_{vc} = EMICOST_{vc} \times \exp(-DKFAC \times DKYR) \qquad [1]$$

where:

$EMSCST_{vc}$ = the final emission cost per mile for vehicle class vc;

$EMICOST_{vc}$ = the emission cost per mile for vehicle class vc as obtained from the look-up table;

$DKFAC$ = the decay factor for the combination of vehicle class and functional class; and

$DKYR$ = the number of years between base emissions year (2000) and target year.

The target year is capped at 2015: emission costs do not decay after that year. Each functional class has a set of emission constants and emission factor values. Differences in these values reflect differences in the mix of vehicle types that typically use each functional class, differences in the rates at which specific types of vehicles emit various air pollutants, and differences in the density of development typically found along facilities of different functional classes. The emission constant and emission factor values for each functional class change during each successive five-year period, reflecting projected reductions in the rates at which all types of vehicles emit air pollutants and changes in the composition of the U.S. vehicle fleet. A more complete discussion of the derivation of the emission factor values is contained in Appendix G and Appendix F of the *HERS-ST Technical Report* (2002).

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[9] 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, and also the *HERS Technical Report* pp. 7-32 to 7-34.

Improvement Costs

The HERS analysis requires estimates of the initial cost of an improvement as input to the BCR calculation. Improvements consist of various combinations of pavement, widening, alignment and special urban freeway initiatives, as shown in Figure 5-16. In addition, improvements and their costs can be specified in the user-specified improvements file for the HERS-ST model (refer to the *HERS-ST Users Guide*).

Pavement and Widening Improvements

Pavement, widening and special urban freeway improvement costs are provided from table look-ups. Alignment costs are sensitive to certain section attributes and are calculated by the model. Improvement costs are incurred at the time of implementation. Construction is assumed to include an allowance for minor structures, and new bridges are included, but maintenance or replacement or widening of existing bridges are not (other than paving).

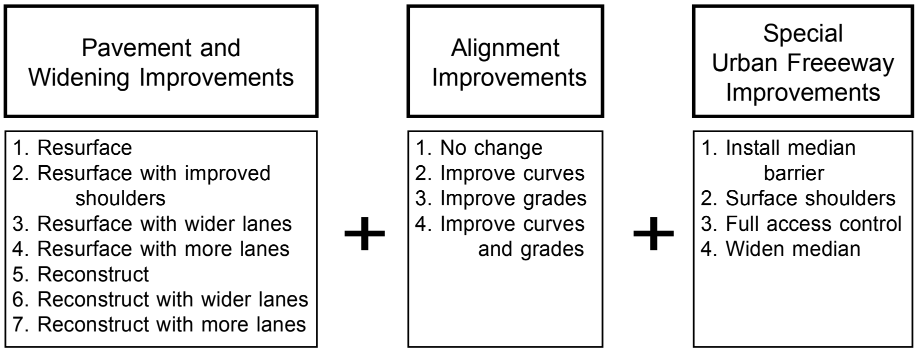

FIGURE 5-16. **Possible improvements and combinations.**

Estimates of construction costs for pavement and widening are based on costs of actual construction projects. HERS uses a single estimate of improvement costs per lane-mile, rather than separate estimates for construction and Right-Of-Way (ROW) costs. Costs are nationwide averages, adjusted by a state cost factor for improvements in each state.[10]

Pavement and widening improvement costs are determined for each of 12 rural and 3 urban highway types, as indicated in Figure 5-3, with a table for each type of improvement. The values used for the 2002 *Conditions and Performance* report are shown in FHWA, *HERS-ST Technical Report* (2002). These default values may be altered by the user. Alignment costs are estimated separately for each section, including new ROW.

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[10] The existing HPMS improvement costs have been developed over a number of years, using improvement costs (1)furnished by the states for the 1972 National Highway Needs Report and updated by the Highway Improvement Unit Cost Case Study conducted in 1979; (2) developed under contract with Dwight Briggs and (3) developed by Bellomo-McGee for Jack Faucett Associates'.

TABLE 5-3. **Highway classes for improvement cost purposes**

Rural				
Terrain Type	Inter-state	Other Principal Arterial	Minor Arterial	Major Collector
Flat				
Rolling				
Mountainous				

Urban		
Freeway and Expressway	Other Divided	Other Undivided

When considering the feasibility of widening a highway section, HERS makes a distinction between high cost lane-miles and normal cost lane-miles. HERS allows the analyst to override the state-submitted values by setting the widening feasibility code to 'add three or more lanes' (See “Widening Feasibility” on page 4-9). The result is that if HERS chooses an option in excess of what the state has coded, then additional lanes are added as high-cost lane miles. For example, suppose the state has determined that, for a given highway section, only two lanes may reasonably be added. HERS, however, determines that four lanes are necessary to meet future demand. The result is that the two extra lanes beyond the two lane state coded widening feasibility are considered high cost lane-miles for cost calculation purposes, while any widening up to and including the first two lanes are costed as normal cost lane-miles. Figure 5-17 illustrates the methodology.

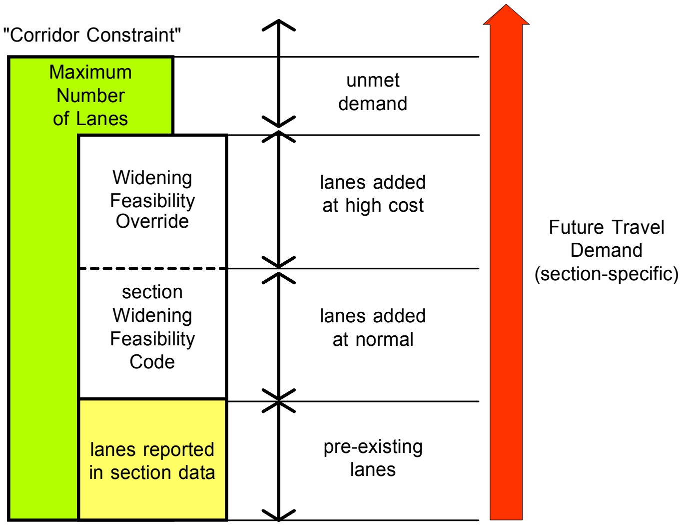

FIGURE 5-17. **Procedure for calculating high cost lanes on a section having capacity requirements exceeding state-supplied widening feasibility code and the 12-lane corridor constraint.**

Unit costs for the high cost lane additions were developed from a weighted average of Federal-aid project records for major new highway capacity additions in and near larger urbanized areas. The addition of new high cost lanes to existing roads in HERS can also be interpreted as the construction of highways on new alignment. The intent is to estimate the costs that would be incurred, and not to specify how such improvements would be made on a case-by-case basis. These unit costs are provided in Table 5-11 of the *HERS-ST Technical Report* (2002).

Alignment Costs

As suggested in Figure 5-16, any of the pavement and widening improvements can be combined with an alignment improvement. 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. Table 5-4 provides the several components and indicates the factors influencing their unit costs.

TABLE 5-4. **Cost components and their related factors**

Cost Component...	Is a Function of...
Clearing and Grubbing	roadway width after improvement length of realigned segment unit costs terrain type
Earthwork	terrain type climate zone average road gradient unit costs length of realigned segment
Drainage Culverts	average number of box culverts average number of pipe culverts unit costs terrain type length of realigned segment
Structures	number of structures on original section average cost of one bridge length of realigned segment
Pavement	pavement type number of pavement layers pavement layer thickness unit costs pavement width length of realigned segment
Right-of-Way	Unit costs terrain type facility and location type length of realigned segment
Miscellaneous	derived costs for guard rails, fencing, painting, and lighting length of realigned segment

Assuming that realigned pavement is designed and constructed as a new pavement structure, pavement thickness is a function of pavement material and traffic load. HERS assumes that reconstruction of either rigid or composite (flexible over rigid) pavement is performed with rigid pavement, and that reconstruction of flexible pavement uses flexible pavement. A table look-up provides pavement thickness for reconstruction and realignment.

In HERS, an alignment improvement generally results in improving all of a section's substandard curves and grades to the design standard (as provided in Table 3-11 of the *HERS-ST Technical Report*, 2002).

For any section, improvement of substandard grades is presumed to result in replacing all segments with grades that just meet the design standard for the section. Similarly, for any section, improvement of substandard horizontal curves is presumed to result in replacing all segments whose curvature is substandard with segments whose curvature just meets the design standard. Straightening of horizontal curves generally results in an appreciable increase in the length of the somewhat straightened curves. The HERS alignment cost estimates reflect this effect.

Improvement costs for segments with modified alignment are obtained by estimating costs for each of the highway construction elements required in modifying the section's alignment.

HERS uses individual procedures to estimate the cost for each component. Default values for unit costs (in 1997 dollars) specific to each of the above categories are shown in Tables 5-14 and 5-15 of the *HERS-ST Technical Report*.

For any section, the total initial improvement cost for combining pavement and widening improvements with alignment improvements is obtained by combining the cost of reconstruction for the 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, pavements, and miscellaneous costs. The latter cost is obtained by multiplying the cost per lane-mile for the pavement and widening improvement by the length of the portion of the section that would continue to follow the existing alignment.

Substandard Conditions on Urban Freeways

HERS distinguishes four actions that can be taken to eliminate substandard conditions on urban freeways. These include: installing an improved median barrier; surfacing shoulders; widening the median; and/or improving access control to full. When HERS identifies substandard conditions (by comparing the state-supplied data with the design standards) and determines that reconstruction of the section is required, any of these four actions that are necessary and feasible are taken to correct the deficiency. Table 5-5 provides the assumptions underlying development of these costs. Recommended values for these costs have been developed, and are included as default values in the model (See Table 5-19 of the *HERS-ST Technical Report,* 2002).

TABLE 5-5. **Urban freeway improvement types and cost assumptions**

Improvement Type	Cost Calculation Assumptions
Surface Shoulders	Difference between costs for resurfacing with and without shoulder improvements for urban freeways
Implement Full Access Control	Cost of one additional lane of right-of-way
Install Positive Barrier	Derived from recent cost study
Widen Median to Design Standards	Combination of one additional lane of right-of-way and the cost of resurfacing

CHAPTER 6

DEMAND FORECASTS AND THE EFFECT OF ELASTICITY

The future benefit stream developed by the HERS model for an improvement is driven in large part by the future volume of traffic expected to use the improvement. Thus, the traffic demand forecast for a highway section is a critical input to the model. As a first estimate, the HERS model uses the baseline demand forecast in the HPMS data to measure future traffic growth. The model assumes that this baseline demand forecast will be realized if the “price” of using that section (as determined by user delay, vehicle operating costs, accident rates, and/or user fees associated with the section) remains constant over time. However, in most real world instances, the price of using a section will change as congestion and pavement quality increase or diminish, which would, in turn, cause future traffic volumes to change. An important innovation of the HERS model is its ability to adjust the baseline demand forecast, based on the economic concept of price elasticity of demand, to reflect changes in the price of using a section over time.

This chapter provides a basic description of the process by which the HERS model adjusts the baseline demand forecast and the economic basis for these adjustments.[1] An understanding of this material will enhance the model user's ability to interpret model outputs. However, it is important to note that, unless instructed otherwise by the user, the HERS model makes these adjustments automatically using default values. Therefore, a complete understanding of this chapter is not essential to model application.

Demand Forecasts

The demand forecast used by HERS begins with the HPMS data pertaining to expected traffic growth on a section.

Baseline Demand Forecast

A demand forecast is a functional relationship between time and traffic volume, assuming a set of conditions. This forecast is driven by whatever *exogenous* factors were thought to be relevant by the forecaster who provided the HPMS demand forecast data. Exogenous conditions typically include population and economic growth, but may also

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[1] A much more thorough discussion of the material in this chapter is provided in Lee, Douglass B., Jr., *Induced Demand and Elasticity*, Federal Highway Administration, 2002.

include assumptions about land use and available substitute transportation alternatives. The HERS model will interpolate between current traffic levels and the traffic level in the forecast year, using either linear or geometric growth. The selected curve, as illustrated in Figure 6-1, represents the baseline demand forecast used by the model.

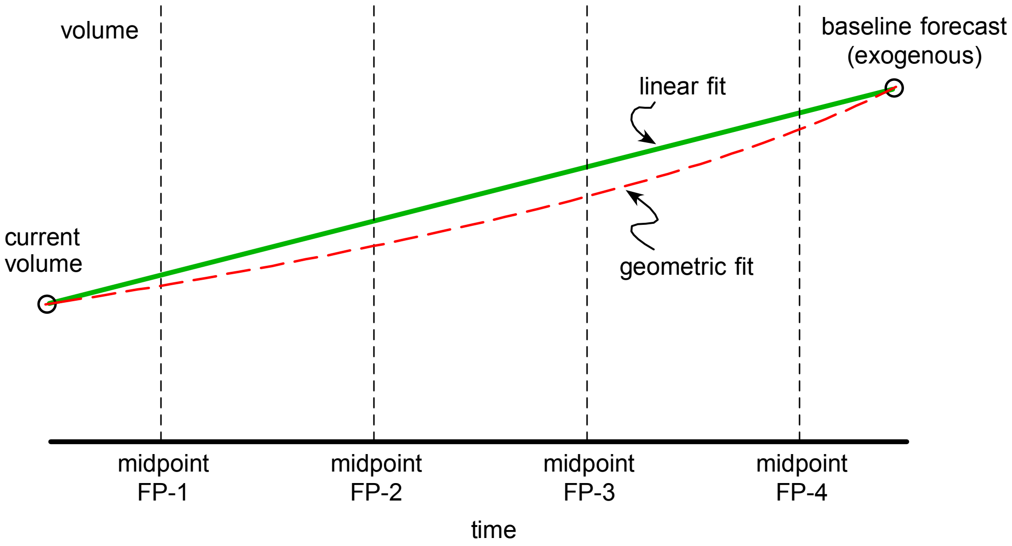

FIGURE 6-1. **Long-run travel forecasts.**

Exogenous conditions do not include the “price” of travel, which is made up of components such as driver and passenger delay, vehicle operating cost, crash rates, and user fees associated with using the section. In the case of the baseline demand forecast in the HPMS record, price is assumed to have been held constant (implicitly or explicitly) by the forecaster. Because there is no data item in the HPMS record that specifies the baseline price, the HERS model calculates it based on traffic and roadway characteristics for the section as recorded in the HPMS data.

Need to Adjust Baseline Demand Forecast

Whereas the exogenous baseline demand forecast is premised on the price of travel remaining constant over time, in fact the price of travel will likely change as LOS and pavement quality increase or diminish. Similarly, the imposition of user fees or other restrictions may affect the price of travel to highway users. The changes in the price of travel will cause changes in the demand for travel relative to the baseline forecast. These changes are referred to as *endogenous* because they reflect changes internal to the highway system as experienced by system users. In the HERS model, all endogenous factors are reflected in the generalized price of using the road. Capacity and LOS, for example, would both be subsumed under travel time cost, and monetized as part of the price.

As the price of any good or service changes, consumers will use more or less of it. In the case of highways, as price of use increases due to rising travel delay or vehicle operating costs (such as those associated with growing congestion), travelers will tend to make fewer trips on a particular section than they would if there were less congestion. As noted above, the HERS model is able to adjust the exogenous baseline demand forecast to reflect changes in user costs as congestion levels or fees change. The method by which the model makes this adjustment is described below.

Meaning and Application of Elasticity

The economic concept used to measure the response of traffic to changes in generalized price is known as price elasticity of demand (elasticity).

An Analytic Tool for Representing Travel Demand

Elasticity is the concept in economics that measures the responsiveness of one variable to a change in another. One form of elasticity, called price elasticity of demand, measures the change in the amount of a good or service that is purchased given a change in its price.

The change in quantity demanded as a result of a change in price is generally normalized so that the changes are in percentage rather than absolute terms. In slightly more formal terms, elasticity can be defined as follows:

$$e = \frac{\%\Delta q}{\%\Delta p} \quad \textbf{[1]}$$

where e = elasticity, q = quantity or volume of travel, p = price, and the Δ (delta) means the difference or change in the quantity or the price. The sign is normally negative (price and quantity move in opposite directions), although sometimes the sign is omitted if the relationship is in the expected direction. A “large” or “high” elasticity refers to one that is large in absolute value or magnitude, so that -1.0 is “higher” than -0.2. Generally, a price elasticity with an absolute value below 1.0 is referred to as “inelastic,” whereas one with an absolute value above 1.0 is referred to as “elastic” (a value exactly equal to one is called “unitary elasticity”).

To better understand the concept of price elasticity, one should imagine a “demand curve” for travel (see Figure 6-2 for an example). The demand curve shows the relationship between the price of something and quantity of it demanded at that price. In the case of highway travel, price is generalized to include travel time, operating costs, and crashes, as well as user charges such as tolls, fees, or fuel taxes. Quantity is measured in terms of average annual daily traffic (AADT) or vehicle miles traveled (VMT). All endogenous changes in quantity are movements along the demand curve. The shape of the demand curve defines the relative responsiveness of travel to changes in price.

Constant-Elasticity Demand

The HERS model uses elasticity measures to adjust traffic volumes to respond to changes in endogenous demand factors, such as pavement quality and congestion. The mechanism for the response is the generalized price of travel and an elasticity that relates price to volume. This relationship permits the construction of a demand curve for each funding period (FP) for each improvement, and the shifting of that demand curve between FPs.

It is possible to construct a demand curve such that the elasticity is constant along the length of the curve. Such a curve has the form

$$q = \alpha p^{e} \qquad [2]$$

where α is a constant term that allows the curve to be fitted to any given demand point (price and volume) and also exhibit a pre-determined elasticity (*e*). HERS uses this constant-elasticity form. The main virtue of this functional form is that the elasticity is always that which is specified, no matter where along the demand curve the price happens to fall. The curve has the appearance of that in Figure 6-2. The HERS model fits a demand curve to each section for each FP under each improvement alternative.

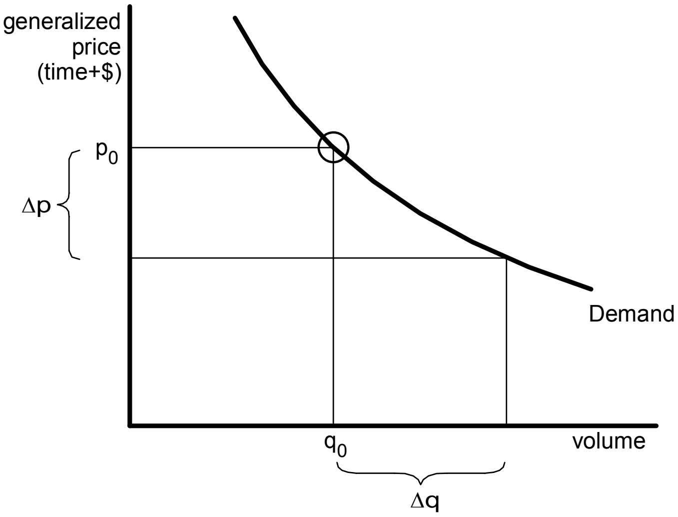

FIGURE 6-2. Demand curve with constant elasticity.

Short-Run versus Long-Run Elasticity

In economics, the “short run” can be any period of time over which one or more variables remains fixed (i.e., does not change). What is fixed might be the capacity of a highway, fuel efficiency of the vehicle fleet, locations of employment, or anything else that changes slowly. The “long run” is enough time for all of these characteristics to change, and may be as long as 20 years. The short run is typically assumed to be about a year in transportation planning, but the dividing line depends upon the practical context.

Short-run demand elasticity tends to be lower (less elastic) than long-run elasticity, because more opportunities to increase or reduce consumption can be developed over the long run than in the short run, while short-run options do not diminish in the long run. If the price of fuel goes up, for example, highway travelers can reduce fuel consumption by taking fewer trips and chaining trips together, by carpooling to share expenses, by driving in ways that achieve better mileage, and by taking a larger share of trips on transit. In the long run they can also switch to more fuel-efficient vehicles, and change their workplace and residence locations. If the price stays high, vehicle manufacturers will develop and produce more fuel-efficient vehicles, and better transit service may be offered.

The distinction between short-run and long-run effects in the HERS model is critical because the model works by breaking the long-term into a series of shorter funding periods, specified by the user usually to be from one to seven years in length. Analysis is conducted in each FP based on price and short-run demand and elasticity conditions that apply for that period. The HERS model then allows long-run elasticity effects to carry over to the next FP.

Factors Affecting Elasticity

Approximation of the Long Run

The two user-provided inputs to the HERS model for elasticity are those for short-run elasticity (SRE) and long-run elasticity (LRE) (default values for SRE and LRE are provided in the user interface). The SRE and LRE values correspond directly to the conceptual meanings of short-run elasticity and long-run elasticity, respectively, so the input values for SRE and LRE are used by HERS as is. However, because funding periods are finite in length (specified by the user, but generally less than twenty years), HERS never reaches a true long-run equilibrium. Rather, it applies the SRE within the FP and then calculates a long-run share (LRS) to represent the portion of LRE adjustment that occurs from one funding period to the next.

The relationship between the LRE, SRE, and LRS parameters is illustrated in Figure 6-3. The LRS will be greater for longer funding periods than for shorter funding periods. Studies undertaken to date suggest that short-run elasticities tend to fall in a -0.4 to -1.0 range, and long-run elasticities from -1.0 to -2.0; a within-period short-run elasticity for a 5-year period would thus be -0.6 to -1.0 and the between-period elasticity from -1.0 to -1.6, yielding an LRS of about -0.4 to -1.0. However, it should be noted that there is significant variability among these studies in terms of items considered and assumptions made.

The HERS model calculates the LRS based on the user-provided LRE and SRE, the length of the user-specified FP, and the adjustment factors illustrated by the curve shown in Figure 6-4. Figure 6-4 is an approximate curve that represents the amount of total long-run elasticity adjustment that may be expected to occur in the first *X* years of the 20 year long-run process—such as 60% adjustment within five years (a quarter of the time to long-run equilibrium). If, for example, short-run elasticity is chosen to be -0.6, and LRE is -1.4, then the purely long-run component of total elasticity is -1.4 - (-

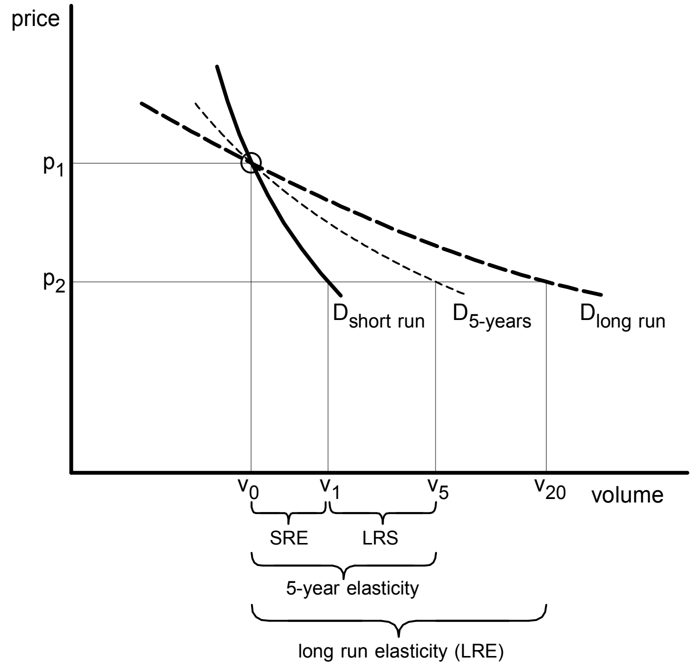

FIGURE 6-3. **Relationship of LRE, SRE, and LRS.**

0.6) = -0.8. If the FP is 5 years, then 60% of the adjustment takes place in 5 years, and the LRS is 60% of -0.8, or -0.48.

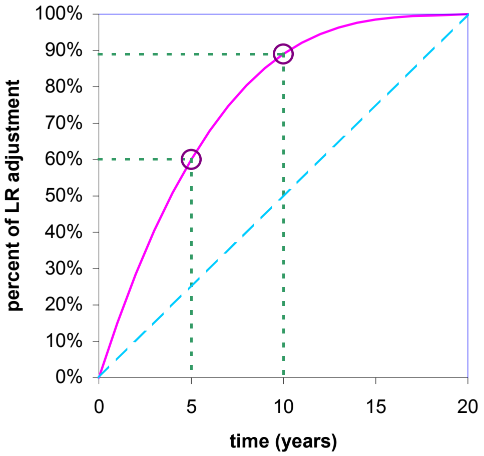

FIGURE 6-4. **Path to long-run equilibrium.**

Adjusting the Overall Elasticity to the Specific Section

In HERS project evaluation, the short- and long-run elasticities are applied to traffic on the section being evaluated. Empirical elasticities pertain to travel in general, and they must be adjusted for the characteristics of the specific highway section. The adjustments currently made automatically by the HERS model are three:

> **Occupancy:** Some components (money costs, such as fuel and user charges) of the generalized price can be reduced for the individual traveler by sharing the cost among occupants of the vehicle, while other components (travel time and accident risk) cannot be so reduced. Those components that can be shared create an incentive for ridesharing, so that higher operating costs or tolls will lead to higher occupancy as one response to higher prices. Lowering money prices has the opposite effect, leading to lower occupancy. This feature in HERS, in conjunction with the explicit price component, allows for testing of the impacts of higher or lower user fees, such as through fuel excise tax changes.
>
> **Section Length:** An improvement to a section reduces the price of travel on that section, but has little or no effect on the price per mile of the rest of the vehicle trip. If the section is very short, then it has only a small effect on the price of typical trips using that section, and not much response in terms of induced traffic would be expected. Because HERS constructs price in units of volume per day (AADT) rather than the price per trip on the facility, the length of the section is implicitly ignored. Rather than reconstructing the price for each section, HERS adjusts the elasticity to take account of section length. This is done by multiplying the elasticity by the ratio of the section length to the length of a typical vehicle trip on the functional class.
>
> **Diversion:** Sources of empirical data on elasticities seldom include diversion as a means for avoiding or lowering the generalized price (an exception is the effect of changing the toll on a toll road). When an improvement reduces the user cost on a particular section, some-perhaps large-portion of the additional traffic is drawn from alternative parallel routes. The magnitude of diversion elasticity depends upon the opportunities for selecting another route. In rural areas, especially on arterials, route choice options occur relatively infrequently, compared to urban areas and lower functional classes

The effect of the occupancy adjustment is small, except perhaps for a major shift in user fee policy, such as congestion pricing. The adjustment for section length tends to reduce section elasticities from the input values, because most sections are much shorter than the average trip. Diversion elasticities tend to increase the section elasticities, but generally not enough to offset the section length adjustment.

Forecast Adjustment Process

Breaking the Forecast Into Discrete Periods

In the HERS model, the distinction between long-run and short-run effects of price on travel volume is implemented by constructing a short-run demand curve for each of the funding periods, with the demand curves shifting from FP to FP, based on the exogenous baseline demand forecast (see Figure 6-1). In effect, the baseline demand forecast becomes a series of discrete points, within each FP, that provide the calibration points for the associated short-run demand curves, as illustrated in Figure 6-5.

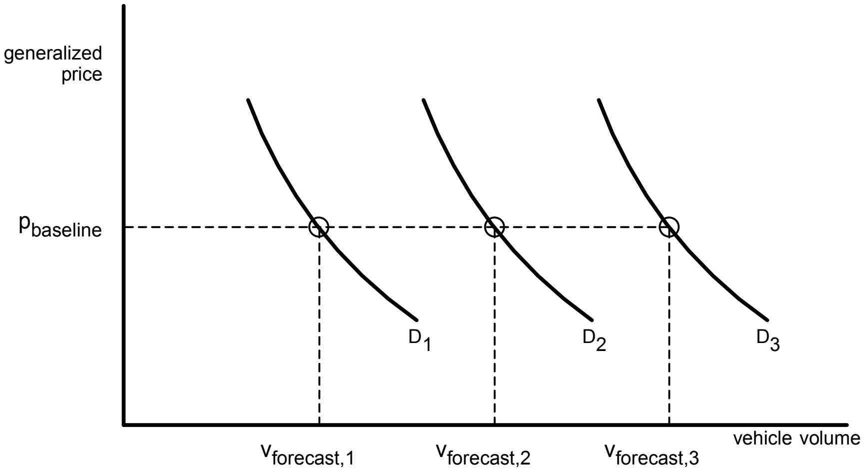

FIGURE 6-5. **Baseline demand forecast for several periods**

Long-Run Shifts in the Demand Curve

Evolution of demand in the long run is built upon what takes place in the short run. Operationally, there is a shift in the short-run demand curve caused by the change in price in the previous period. If the price in all previous periods is the same as the baseline price, then the short-run demand curve is fitted to the baseline forecast for that period. If an improvement is made in one period that reduces the price below the baseline price, this leads to a shifting of the demand curve outward (in addition to the exogenous shift due to the baseline forecast), according to the percent by which the price in the previous period is below the baseline price. If no improvement is made, the price increases relative to the baseline forecast price due to building congestion, and the demand curve shifts inward in the next period.

The former of these two possibilities is shown in Figure 6-6. The long-run share parameter LRS is applied to the difference between the baseline price and $p_{improved}$ to shift the demand curve from point 1 to point 2 in the diagram. There is no long-run demand curve as such, but the shift attributed to induced demand is a displacement of the short-run demand calibration point along the baseline price line.

Using the numbered points in Figure 6-6 as steps in the calculations, the sequence is:

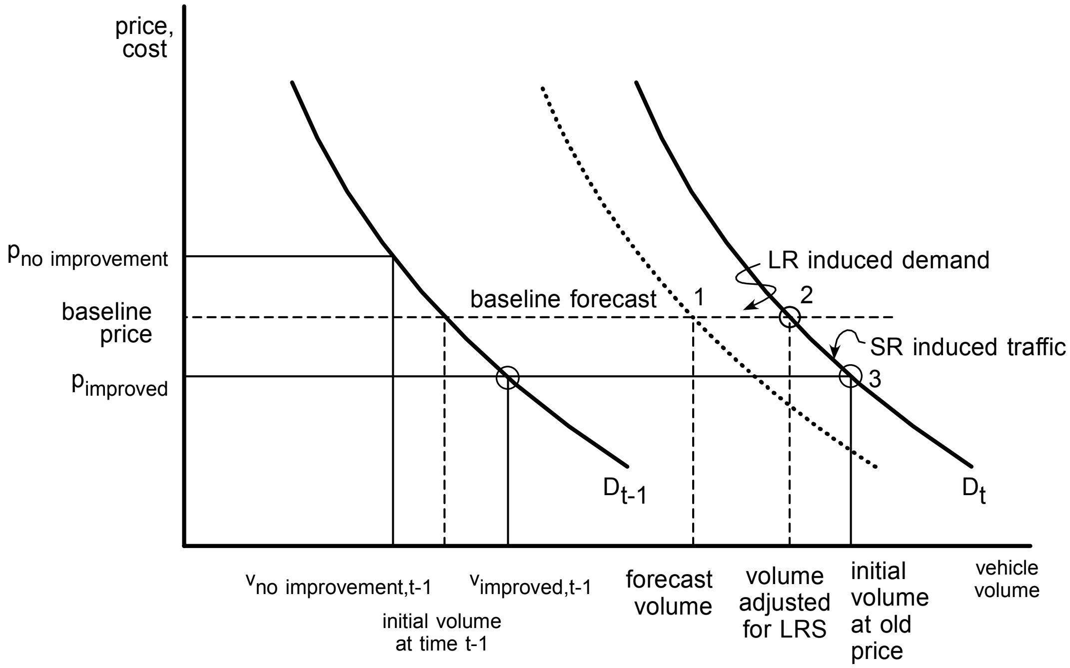

FIGURE 6-6. **Long-run demand shift from one period to the next.**

(1) Calculate the baseline volume in the second FP (FP_t) as if the baseline forecast rate of growth (which assumed constant baseline price) were realized. This is represented by the dashed demand curve, which intersects the baseline price above the forecast volume for that period.

(2) Adjust the volume using the calculated LRS and the amount by which the current price ($p_{improved}$, reflecting the improvement made in FP_{t-1}) differs from the baseline price; then fit the demand curve (D_t) to this point, using the short-run elasticity (SRE).

(3) Move along the short-run demand curve based on the current price to obtain the volume in the current FP. For example, if $p_{improved}$ remains the same during the FP, the new initial volume will correspond to point 3.

Incorporating traveler responses to price, then, allows each period's demand curve to be a function of the previous period's investment (as it affects price to the user). Investment that keeps the price in each period below the baseline price for the baseline demand forecast produces demand curves that shift farther and farther outward, compared to the baseline forecast. Similarly, if improvements are not made and price is allowed to rise in each period (due to growing congestion, pavement roughness, and crashes), the demand curve will be continually shifted inward relative to the baseline.

Effects of LRS Shifting on Baseline Demand Forecast

The effects of the various adjustments made due to short and long-run demand elasticity are illustrated in Figure 6-7. The baseline long-run demand forecast represented by the straight, solid diagonal line is the same one illustrated by Figure 6-1. As noted previously, the baseline long-run demand forecast assumes a generalized price, as well as whatever exogenous factors are thought to be relevant by the forecaster. The dashed line segments in Figure 6-7 represent the effects of short-run and long-run responses to endogenous price changes. The individual slope of each dashed segment represents the SRE response, whereas the shifting of the dashed line segments from FP to FP, above and below the solid line forecast, represents the long-run elasticity effects (note that these impacts occur instantly at midpoints of FPs). The adjusted forecast used in HERS benefit calculations is represented by the path of the dashed line segments. This adjusted forecast embodies all exogenous and endogenous factors.

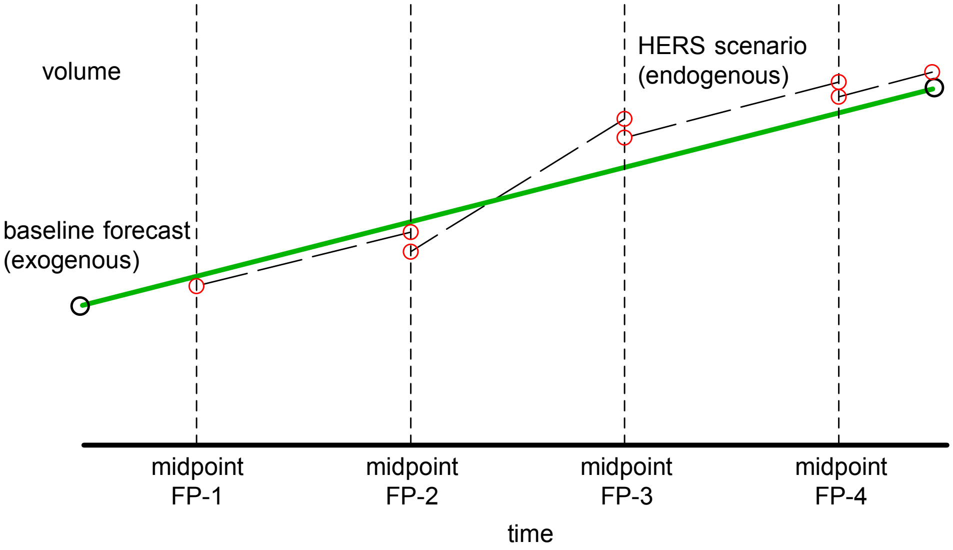

FIGURE 6-7. Long-run travel forecasts with adjustments for demand elasticity.

Note that if the LRE parameter were set to zero, the location of each short-run demand curve is determined by the baseline forecast, without regard for improvements made in any previous demand period. Short-run movements along the demand curve can still occur, depending upon the short-run price elasticity, but there will be no cumulative endogenous effects from one period to the next. Alternatively, with a high LRE (and subsequently, LRS), endogenous effects could alter the baseline forecast, even to the point of potentially offsetting the trend of the initial forecast.

A Note on “Induced Demand”

The elasticity effects described in this chapter are sometimes discussed under the heading of “induced demand.” Some discussion of what induced demand is and how the HERS model approximates it is therefore appropriate.

The term “induced demand” arose in an attempt to describe the apparent relationship in which more highway capacity seems to result in more traffic. At issue is cause and effect: would the traffic have been there anyway, without the capacity addition (therefore the traffic caused the road); or was the traffic induced to use the highway because of the available capacity (the road caused the traffic)?

As noted above, there are economic reasons as to why there would be some relationship between new capacity and additional traffic levels. If a road is congested, then adding capacity will reduce travel times. This increase in service level, which reduces the price of travel, will attract some additional trips that would not have been there without the improvement. Some of these trips will be diverted from another facility, some may result from taking longer or more frequent trips, some from choosing different destinations. In any event, more VMT occurs if the improvement is implemented than if it is not. This additional traffic has come to be known by some parties as “induced demand” (although items included under this term vary from author to author).

In fact, short-run responses to price changes do not constitute a change in demand, per se. Underlying demand in the short run, as illustrated by the short-run demand curve, remains constant-the VMT will change in response to price (as measured by the SRE factor) at this demand level. Shifting of the short-run demand curve, from period to period (caused by the calculated LRS factor in the HERS model), does represent an induced effect, as at any give price, more travel will be demanded. Therefore, a distinction can be made between “induced traffic” (or induced travel) and “induced demand.” “Induced traffic” is a movement along the *short-run* demand curve, while “induced demand” is an endogenous *shift* in the short-run demand curve.

Induced traffic may result from:

- Diverted traffic that changes its route onto the improved facility.
- Shifts from other modes -- which may or may not have used the facility before -- including changes in occupancy.
- Destination shifts resulting from the improvement of the facility.
- Additional travel by persons already using, or in the market for, the facility.
- Rescheduled traffic that previously used the facility at a different time (spreading or contracting the peak).[2]

An induced shift in the demand curve might be due to:

- Land development that is more compact or spread out as a result of the level of access provided.

- Reduced warehousing facilities stemming from lower freight costs and just-in-time delivery.
- Relatively more transportation used in the production of goods and services because transportation has declined in cost relative to other inputs.
- Relatively more or less personal travel and goods movement taking place on highways relative to other transportation modes, as a consequence of highway improvements.

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[2] If the demand curve represents both peak and off-peak (as it currently does in HERS), then the elasticity will be lower than if peak is separated from off-peak. Because the two periods are so closely interrelated (off-peak demand depends upon peak price, and vice versa), failing to separate them analytically may incorrectly estimate the impacts of policies that differentially affect peak and off-peak demand, such as congestion pricing. HERS has separate delay curves for peak and off-peak travel, but uses a single daily demand curve for each section.

CHAPTER 7

PROJECT EVALUATION

Evaluation of an improvement for a given section consists of gathering together the estimates of the impacts of the improvement, comparing the improvement to the base alternative, supplying dollar values where needed, and aggregating costs and benefits over the life cycle of the improvement.

Principles of Benefit-Cost

The accepted method by which the public sector evaluates investment choices is BCA: invest only in those projects for which the benefits exceed the costs. Making this common sense objective operational requires the use of theory and quantitative techniques.

For each alternative, a time stream of constant-dollar costs and benefits is estimated for the lifetime of the project. Future benefits are measured relative to the base alternative, and discounted so as to allow for the opportunity value of resources with respect to time. The projects are then compared according to net benefits, measured in present value or annualized terms.

This pure benefit-cost approach must often be compromised in practice to accommodate constraints on project selection arising from restrictions on capital funds available, requirements that infrastructure conform to engineering standards, or other requirements. For example, when assembling a program of recommended capital improvements, ratios of benefit-to-cost may be useful for selecting projects that will maximize net benefits subject to constraints.

Alternatives

To conduct a benefit-cost evaluation, it is necessary to have at least two alternatives. One is the base alternative, loosely referred to as the do-nothing case. Other project alternatives, to be compared with the base, typically involve higher levels of investment. Disinvestment—i.e., not replacing existing capital as it wears out—may be considered as either a base or project alternative.

Time Streams of Costs and Benefits

Because the time dimension is a critical aspect of BCA, the information describing the project alternatives must be time-specific. Conceptually, this means that both costs and benefits are stated year-by-year in perpetuity, for the base and each project alternative.

In practice, the lifetime of the project is usually an adequate time horizon, with allowance for salvage value or capitalized values for subsequent costs and benefits.

Figure 7-1 shows a hypothetical pattern of costs and benefits over the life of a project. Capital costs occur primarily in the first years, perhaps with a major rehabilitation effort at mid-life. Benefits are shown to grow gradually, after the facility becomes fully operational and demand for its services continues to increase. A plateau may be reached at some point due to a leveling off in demand, or if the facility reaches capacity.

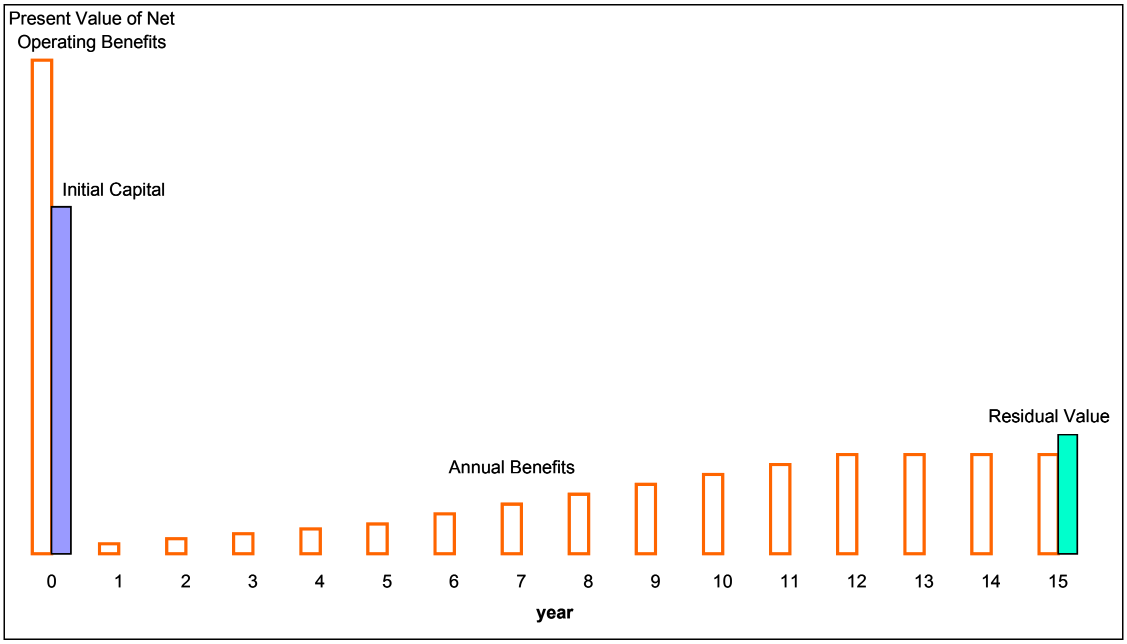

FIGURE 7-1. **Time stream of costs and benefits.**

All measures of benefit at this stage in the evaluation are differences between the improvement scenario and the base case. Whether a given impact is classified as a cost or benefit is less important than ensuring that all costs and benefits are counted exactly once (neither omitted nor double-counted) and given the right sign. Normally, however, up-front capital costs are classified as costs, and all other impacts of value—whether positive or negative, i.e., benefits or disbenefits—are classed as benefits.

Incremental Benefits

The objective of BCA is to compare the state of the world with and without the project, as best as can be estimated before-the-fact. It is a matter of empirical strategy whether costs and benefits are measured in absolute terms for each alternative, or whether only the differences between the base and the project are measured. In either event, the relevant data are the year-by-year differences between the base and the project for each project alternative. These are referred to as incremental costs and benefits, to emphasize that only the difference between the project and what would have happened without the project is of interest.

Constant Dollars

All costs and benefits, to the extent they are valued in dollar terms, are stated in constant dollars of a convenient year, normally as close to the present time as is practicable. All effects of inflation are removed before discounting. Inflation and discounting are separate and independent dimensions: inflation pertains to the scale on which costs or dollars are measured, and discounting pertains to the opportunity cost of time. Although they are often confused, it is important to avoid doing so. Discounting would still be required even if inflation were zero.

The base year for discounting need not be the same as the base year for constant dollars, but normally they are the same (e.g., it would be Ok to have the present value in year 2002 stated in year 2000 dollars).[1]

Discounting

The time streams of costs and benefits can be summarized by discounting and summing. Discounting means that each cost and benefit is multiplied by the appropriate discount factor, given by

$$PV = \frac{1}{(1+r)^t} B_t \qquad [1]$$

where PV = present value of benefit B_t, r = discount rate, t = time measured from the base year, and B_t = benefits (or costs) occurring in year t. The factor on the right-hand side preceding B_t is called the *discount factor*. The PV for an improvement project is the summation of **[1]** over all time periods.

Discounting is based on the idea that benefits received ten years from now are not as valuable as the same benefits received sooner, because the resources available sooner could be put to use in the meantime. The primary function of discounting is to allow for the opportunity cost of taking resources from some other purpose to apply to the project alternative. The discount rate can be thought of as the minimum acceptable real (net of inflation) rate of return that must be achieved by the project investment.

The choice of an appropriate discount rate has received a great deal of attention in the past, but its importance may have been exaggerated from a practical perspective. The real opportunity cost of withdrawing resources from the economy is generally regarded as about 3-5% (per year), with a high rate of 7% used for sensitivity testing. Capital-intensive projects with long lifetimes fare less well under high discount rates, but if this range of discount rates makes a dramatic difference to the feasibility of a project, the problem may lie in the time lag between initial costs and the onset of benefits. This time lag may be unavoidable, or it may be correctable by redesigning the project and its phasing.

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[1] The base year for the cost or price index used to transform historical costs into project base year dollars is immaterial.

Net Benefits Criterion

The bottom line of BCA is net benefits. Any investment which creates positive net benefits is worthwhile, because alternative uses of the funds in the rest of the economy have been considered in selecting the discount rate. It is assumed that the investment projects under consideration are small enough in relation to the rest of the economy that investment in them would not cause the discount rate to rise.

Net benefits can be stated in either Net Present Value (NPV) form or as Annualized Net Benefits (ANB), sometimes referred to as equivalent annual costs or benefits. For analytical purposes these two are identical, and the choice between them is solely one of preference for interpretation.

Benefit-Cost Ratio

When costs are restricted to expenditures from a budget that is exogenously constrained (e.g., by political decision), it is sometimes possible to find enough projects offering positive net benefits to more than exhaust the limited budget. In this case, maximizing net benefits from the constrained budget can be achieved by ranking projects according to their BCR, where the denominator is the project's impact on the limited budget. All other cost elements—whether expenditures or in-kind losses—are treated as negative benefits. Projects are accepted in order of declining BCR, until the constrained budget is exhausted.

Use of the BCR implies that dollars from the constrained budget are more valuable than other dollars, whether expenditures, cost savings, or in-kind benefits. While this constraint may be necessary and legitimate in the given circumstances, the solution is only second best: if the unfunded projects are truly worthwhile, it would be preferable to expand the budget.

Other Parameters

A number of assumptions and parameters are necessary to carry a BCA to conclusion, and these must be made explicit. For transportation projects, the value of travel time savings for different types of vehicles and purposes is essential. Dollar valuations of human life, injury, and property damage from crashes are required if the benefits from safety improvements are to be assessed explicitly. Vehicle operating cost savings, including fuel consumption, are also needed along with whatever parameters (speed-volume functions, capacity, forecasts) are used to estimate benefits. Similarly, cost estimation functions may also be parameterized.

Some impacts of highways affect resources that are not traded in normal markets and therefore do not have an easily observable dollar value. Such impacts include noise, air and water pollution, loss of wetlands, and disturbance of historical sites. Methods have been developed for placing reasonable bounds on the worth of these impacts, but such estimates are subject to even greater uncertainty than are direct travel impact measures such as the value of travel time.

Selection of the Best Alternative Using IBCRs

When all costs and benefits have been estimated in constant dollars and discounted to the base year, the worth of a single project alternative is its net benefits, or net present value, or discounted benefits minus costs. If several alternatives for the same project show positive net benefits, the one with the highest net benefits is preferred. Two examples are shown in Figure 7-2.

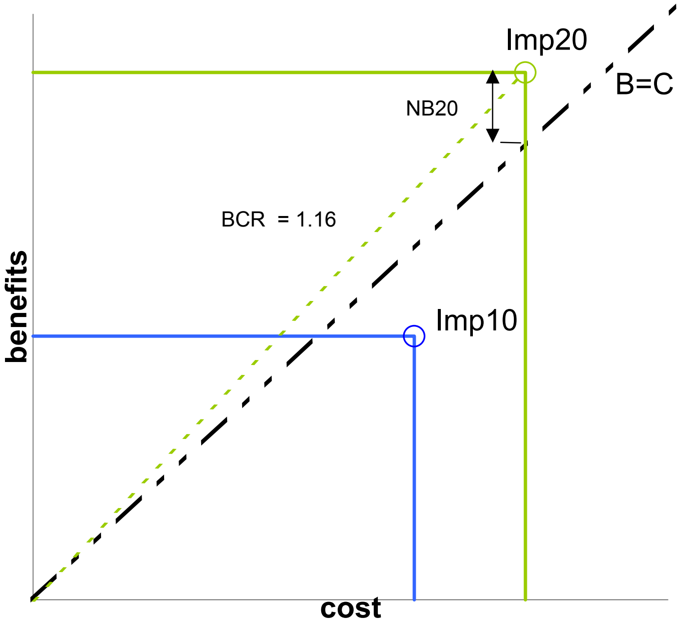

FIGURE 7-2. **Example evaluation of 2 alternatives.**

Along the diagonal of the diagram is a dashed line at a 45-degree angle, labeled “B=C,” that shows the locus of points for which benefits exactly equal costs. Alternatives below this line have negative net benefits, whatever their size, and alternatives above have NB>0. The slope of the is 1.0, indicating that any alternatives lying on the line have a BCR = 1.0. Improvement 10 (“Imp10”) lies below the BCR=1 line, and a line through Imp10 would have a slope of less than 1.0. Imp20 lies above the line, and a line through the origin and this point has a BCR=1.16 (in this example). The positive net benefits of this alternative can also be shown on the diagram, and are labeled “NB20.” The economic efficiency objective is to maximize total net benefits, but this objective can also be pursued by selecting projects using BCRs, if done properly.

Figure 7-3 represents five alternative improvements for the same segment, ordered from Imp10 having the lowest cost to Imp50 with the highest. The 45-degree dashed line through the origin (labeled B=C) separates alternatives having benefits less than costs (below the line) from alternatives having positive net benefits. One alternative—Impl0—fails this test and should not be a candidate for implementation. The best alternative from a benefit-cost standpoint is Imp40, because it generates the highest net benefits, measured as the vertical distance from the circled point to the diagonal.

If each alternative is evaluated in sequence from lowest to highest cost, Imp20 is the first alternative to produce positive net benefits. On the basis of incremental net benefits

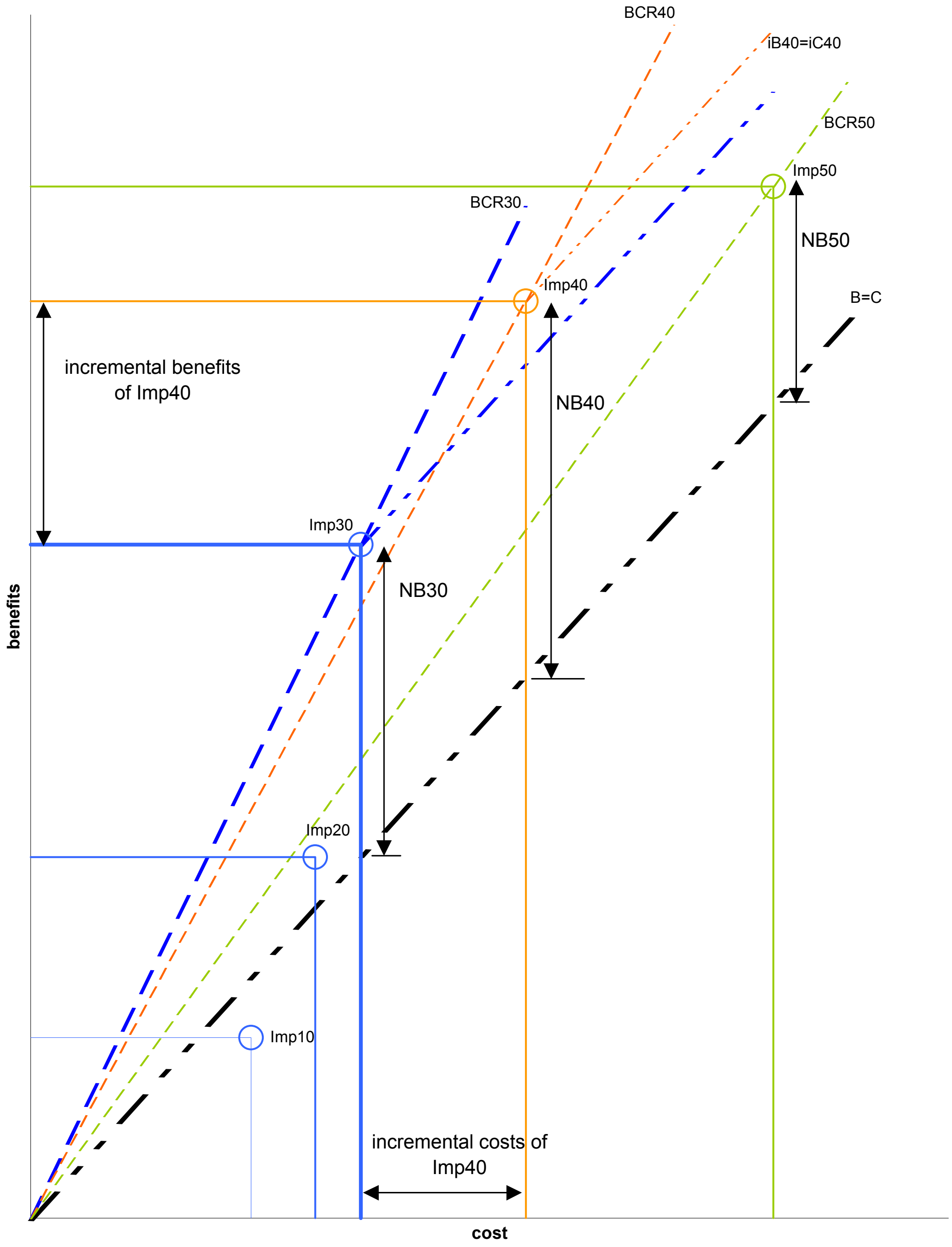

FIGURE 7-3. **Example alternative improvements for a given section.**

with respect to the best previous (lower cost) alternative, any alternative adding more benefits than costs, relative to Imp20, must lie above the 45-degree line (not shown) through that point. By this test, Imp30 is superior to Imp20, so Imp30 becomes the reference standard. Similarly, Imp40 is superior to Imp30, because the incremental costs from Imp30 to Imp40 are less than the incremental benefits, hence Imp40 lies above the 45-degree diagonal through Imp30. Alternative Imp50, however, is superior to Imp30 but not to Imp40. Thus an incremental evaluation of the alternatives leads to the same preferred alternative (Imp40), implying that maximizing incremental net benefits via pairwise comparisons also maximizes total net benefits.

Ratios of benefit-to-cost can also be calculated for the five alternatives, and are represented graphically by the slope of a line from the origin through the point corresponding to the project. The highest BCR (i.e., the steepest line) is for Imp30. As described above, Imp40 is preferred to Imp30 because Imp40 generates incremental benefits that exceed its incremental costs, compared to Imp30. If, however, the budget available to finance an entire set of such projects—including potential improvements to other sections of the system—were arbitrarily restricted, then some combination of projects might maximize net benefits but not include Imp40. If, for example, an improvement on another section had a higher BCR than Imp40, then Imp30 plus this other project might be superior to Imp40, for the same total costs. Under some constrained circumstances, then, Imp30 would be the preferred alternative.

Substitute Versus Synergistic Projects

Two levels of BCA can be distinguished. At the *project* evaluation level, alternative improvements for a given segment are substitutes for each other, i.e., they are mutually exclusive: only one among the possible candidates will be selected. Once the preferred alternative is chosen, the others are discarded. Thus, project alternatives are substitutes for each other.

At the second or *program* level of investment analysis, a group of individual projects is assembled into a recommended combined list and scheduled for implementation. Such projects may be completely independent of each other, in which case any project meeting the net benefits standard should be implemented. In other situations, two or more projects may interact with each other in positive or negative ways. Improvement of one segment may result in increased traffic on another (increasing the benefits for improvements to the second segment) or in decreased traffic (by diverting users to the first facility). Ideally, these interaction effects are anticipated and accounted for, whether through simultaneous network analysis or by simply staging the project BCAs in the right sequence. Projects at the program level, then, are complementary to each other.

BCA is appropriate for both levels of project/program evaluation, but the use of the results is different. At the single project level, substitute alternatives must be removed from further consideration, whereas alternatives are accumulated at the program level. In particular, if BCRs are used at the program level because of a constrained budget, the selection or ranking criterion is different at each level.

Improvement Selection With a Funding Constraint

The procedure just described for finding the improvement with the highest net benefit using only BCRs and IBCRs can be applied to the case where total funds are insufficient to implement all cost-beneficial projects. This problem arises when the objective is to assemble a program from a pool of worthwhile complementary projects, and the funding constraint is binding. In this situation, the choice can often be that of selecting a more aggressive improvement on one section that already has a selected worthwhile project, versus selecting an improvement on another section. By ordering all candidate projects (on all sections) by the IBCRs of their best initial improvement or more aggressive improvement (if they already have a selected improvement), the constrained funds can be allocated sequentially to those projects that will maximize net benefits with the constraint. This is a subtler and more optimal process than simply selecting the "best" improvement for each section, and then ranking the sections by their BCRs.

Externalities

Some of the costs and benefits of transportation investments—including the impacts of vehicle travel as well as the construction of the facility, are not reflected in expenditures by, or revenues to, the government agency responsible for the investment. Vehicle operating cost savings are reflected in reduced expenditures, but by users of the facility rather than by the owner. Travel time savings are also benefits to users, but are monetized only indirectly, in the opportunity value of the time saved. Safety savings are user benefits that are partially monetary and partially in-kind.

Other impacts, such as loss of wetlands and increased air pollution, are neither monetized as direct expenditures nor limited to users in their consequences. Such third party impacts—usually negative—are known as externalities. Persons affected, narrowly as individuals and broadly as members of society, are not parties to the transactions giving rise to the externalities (e.g., the decision to build a highway or drive on it), and are thus affected involuntarily. Table 7-1 lists a number of highway related externalities.

TABLE 7-1. Possible highway externalities

Increased Noise
Reduced Air Quality
Increased Water Pollution
Increased Rainfall Runoff
Danger to Pedestrians
Loss of Wetlands
Community Disruption
Loss of Wildlife and Wildlife Habitat
Loss of Threatened and Endangered Species
Loss of Floodplain
Loss of Wild and Scenic Rivers
Visual Degradation
Loss of Parkland

To ensure that markets function properly—i.e., in a manner that is beneficial both to the parties to the transactions and to society as a whole—it is desirable that externalities be internalized, meaning that the impacts are brought into consideration in the decisions potentially creating the externalities.

Means for controlling externalities include setting emissions standards and pricing the externalities explicitly. For example, the user could be charged for the damage caused by the emissions from her/his vehicle. For investment analysis, estimates of the cost of negative externalities can be included by subtracting them from benefits, or regulatory constraints can be imposed to restrict or eliminate the externalities. The requirements that there be no net loss of wetlands or parklands are examples of such restrictions.

Second-Best Evaluation With Externalities

HERS currently performs a "second-best" evaluation, which means that conditions for "first-best" efficiency cannot be met so the evaluation attempts to maximize net benefits (efficiency) subject to constraints. The primary efficiency condition that is not met is the efficient pricing of the alternatives: first-best efficiency requires that each alternative be priced at marginal cost, ensuring that the alternatives each maximize benefits given the capacity that is available. For highways, first-best efficiency requires a monetary toll that, when added to the average travel time and operating costs faced by the user, equates the cost to the user to the marginal cost to society, including delay imposed on other users as well as environmental externalities.

Consumer Surplus

Under the simplifying assumption that price to the user equals average variable cost, the measurement of net operating benefits (benefits resulting from changes in variable costs, i.e., excluding fixed costs such as initial capital expenditures and residual value) is simplified. A diagrammatic representation is shown in Figure 7-4. The shaded rectangle measures savings in average costs for "old" users, and the triangle shows travel benefits for "new" users.

With a demand curve and generalized prices, with and without the improvement, HERS can calculate the benefits of traffic induced by the improvement (or that would be deterred by letting conditions worsen). This benefit is known as incremental consumer surplus, and is represented by the triangle in Figure 7-4. The average variable cost curve AVC_0 represents the "supply" function for the base alternative, and AVC_1 represents the improved facility. Savings in time and operating costs are benefits to previous "old" users of the facility, while Δ *consumer surplus* is a valuation of "new" travel induced on the facility. This travel includes trips not previously taken, longer trips that may have been taken by old users, and travel diverted from other facilities.

The magnitude of incremental consumer surplus obviously depends upon demand elasticity. If, for example, elasticity were zero, the demand curve would be a vertical line, there would be no incremental consumer surplus, and average cost would be lower (e.g.,

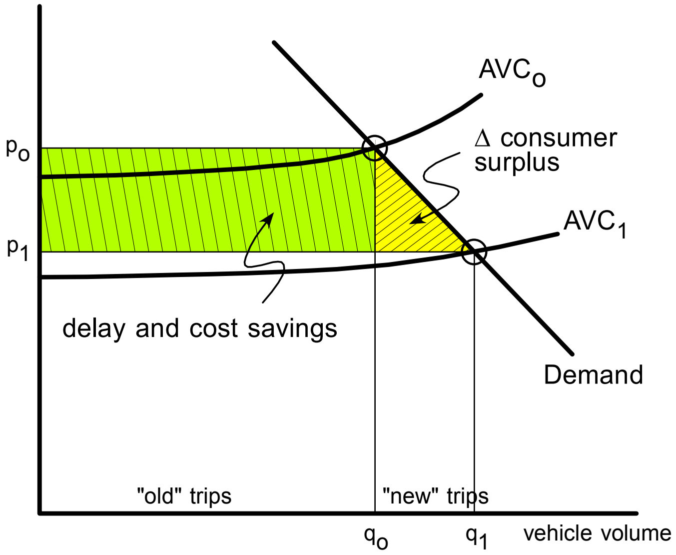

FIGURE 7-4. **Travel benefits and incremental consumer surplus.**

lower travel time). If elasticity were very high, new trips would be high but the savings per trip might be much lower because of congestion.

The simplification that price to the user follows the average cost curve is generally not the case and is not the case in HERS due to fuel taxes, agency costs, and externalities (fuel taxes are part of the price to the user, but are not costs; agency costs and externalities are costs that are not included in the price).

Pricing

The main rationalization for conducting second-best rather than first-best evaluation is that highways in general are priced inefficiently—at a level that is closer to average cost than marginal cost—and this policy is likely to continue over the life of most capital improvements made in the near future.

Under second-best pricing (shown in Figure 7-5), the price to the user follows a relationship (marked as “price function”) with traffic volume on the section that is different from both average variable cost (AVC_0) and marginal cost (not shown). The price function could be almost anything, but—since both average cost and user cost include travel time—both curves tend to rise with increasing V/C. Whether price is above or below average cost depends on user charges and externalities. The intersection of the demand curve and the price function determines the equilibrium volume (v_0). Costs, however, are measured from the average cost curve (ac_0), which is not necessarily equal to user costs (in this case differing only by emissions). Thus user costs determine the location on the demand curve, but benefits are measured from the average cost curve.

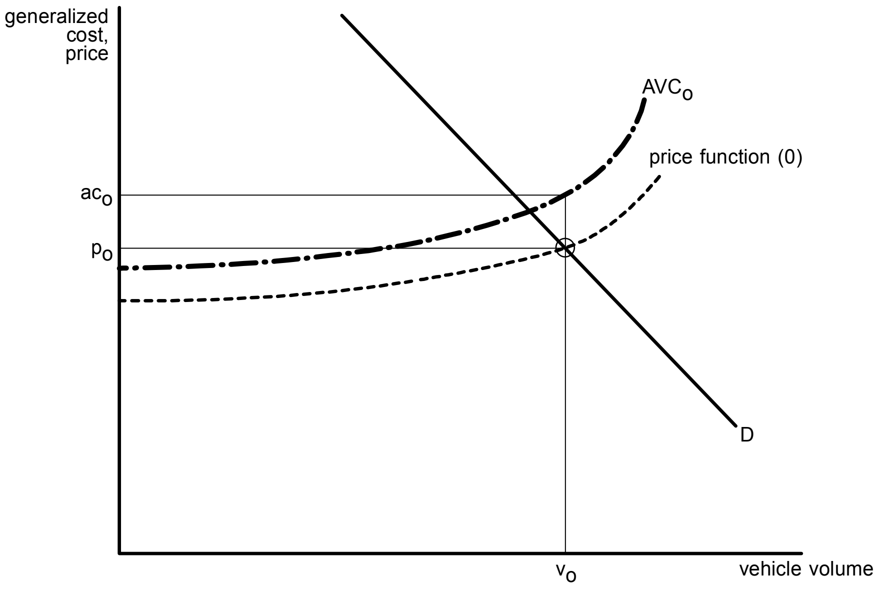

FIGURE 7-5. **Second-best pricing on highway projects.**

User Costs, Social Costs, and Transfers

A distinction has been made in the above between three types of costs: user costs that are included in the generalized price to the user, externalities that are social costs but not included in the price paid by the user, and user taxes that are paid by the user but are transfers from society's perspective and not costs. These distinctions can be clarified by reference to Table 7-2.

TABLE 7-2. **Social versus private costs.**

	included in price?	social cost?
travel time	yes	yes
vehicle operating costs	yes	yes
accidents	yes	yes
agency costs		yes
user fees and excise taxes	yes	
emissions		yes

The first three user costs are social costs that are included in the price to the user, and therefore any savings in these costs are counted as benefits from an improvement. They also affect volume as determined by the demand curve. Agency costs are social costs but not paid directly by the user, as are emissions that result in pollution, so they are external; external costs do not affect demand, but any changes caused by an improvement are included in benefits. Finally, user fees are transfers, therefore not included in the calculation of benefits but nonetheless having an effect on traffic volume through demand elasticity. All of these cost categories are used in HERS, and the distinctions among them are helpful in interpreting the diagrammatic representation of net operating benefits.

Net Operating Benefits

The components of benefits calculated by HERS can be represented diagrammatically, as in Figure 7-6. Only variable costs are represented, hence the “operating” benefits label. The base alternative is described by the AVC_0 curve, which includes all social costs such as travel time, crashes, and externalities. The “price function” represents those costs or user fees that are “paid” by the user, which adds user taxes and tolls to average costs, and omits externalities. Thus the price function might be above average cost if user charges exceed emissions and agency costs. The price function is shown as being below the average cost curve, as if emissions per vehicle mile and agency costs exceeded user taxes (the drawing is not to scale, and the magnitude of emissions costs is exaggerated to facilitate explanation). The improvement alternative is represented by AVC_1 and its associated price curve. The improvement is assumed to lower travel time and operating costs, and, due to demand elasticity, attract additional traffic.

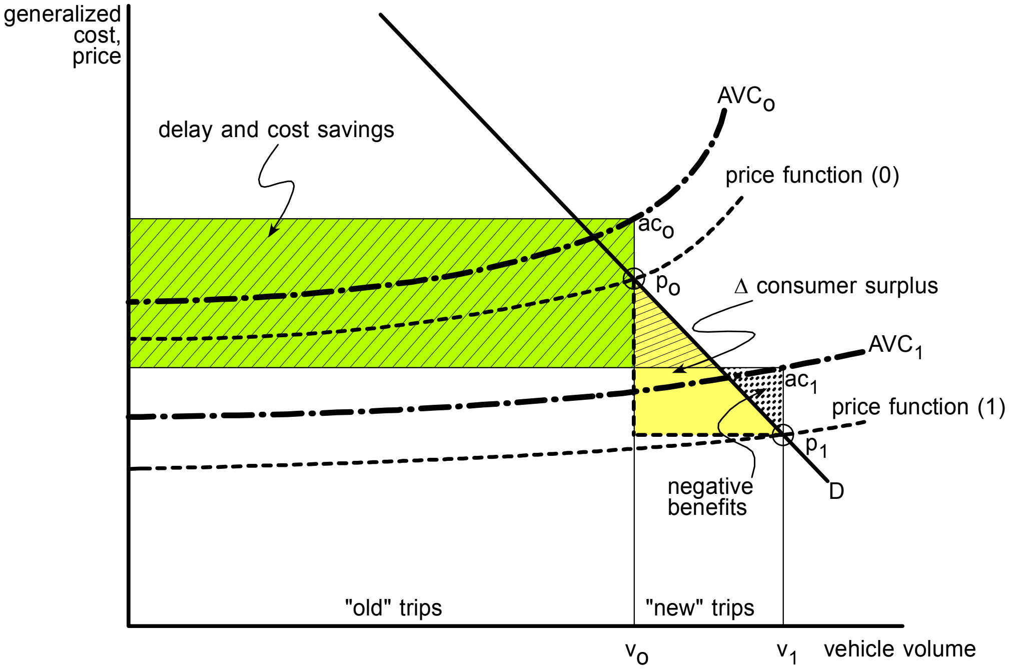

FIGURE 7-6. Components of HERS Net Operating Benefits.

Benefits (second-best) are determined from the average social cost curves, while traffic volume is determined from the price and demand curves. For the base case, the price of p_0 sets the volume at v_0, which gives rise to average unit costs of ac_0. For the project alternative, the price of p_1 results in volume v_1 and average cost ac_1. The reduction in average cost per trip (ac_0-ac_1) times the base or “old” volume v_0 yields the rectangle labeled “delay and cost savings.”

Valuation of the induced traffic must account for the benefits to users from additional travel and the cost to society of additional pollution. The former—incremental consumer surplus—depends only on the change in price and the elasticity of the demand curve, and is represented by the triangle between p_0 and p_1 with legs shown as dashed lines. From this is subtracted the cost of additional pollution, the rectangle whose height is (ac_1-p_1) and whose length is (v_1-v_0), which leaves the positive area marked as "consumer surplus" and the negative area marked as "negative benefits."[2]

Multi-Period Evaluation

The analysis period for an improvement is conducted, ideally, over the lifetime of the project. Within that lifetime, the demand curve may shift inward or outward from year to year. Net Operating Benefits (*NOB)* need to be aggregated over all of these demand periods, using the method outlined above for each period. A two-period example is shown in Figure 7-7. The benefits in demand period 1 (associated with demand D_1) are those shown above in Figure 7-6, and an additional demand period has been added.

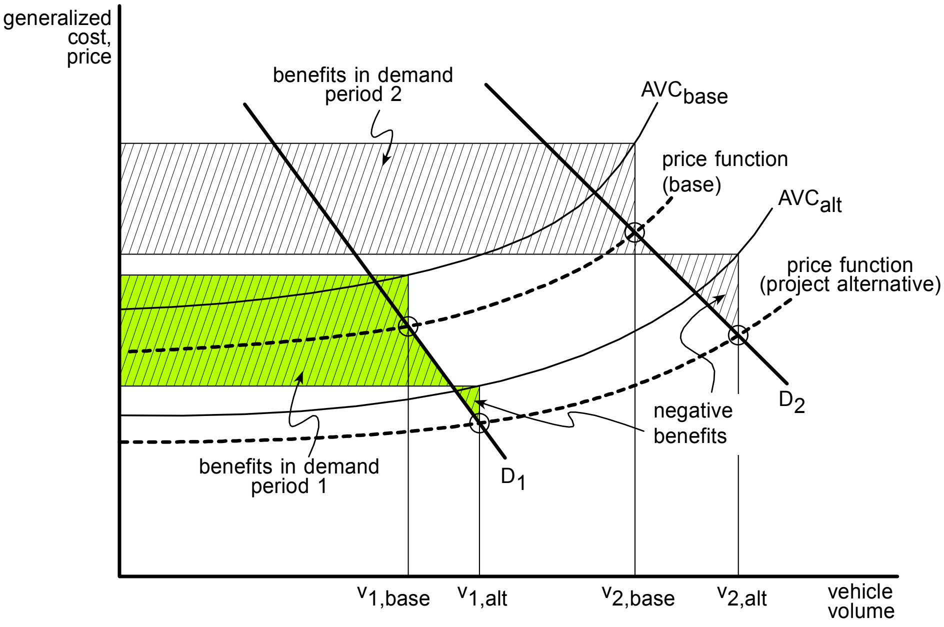

FIGURE 7-7. *NOB* **for two demand periods with price below average cost.**

In the example, demand in the second funding period shifts outward, presumably for exogenous reasons. The diagram represents two periods for a single improvement on a single section, and shows the incremental benefits (shaded) between the base and the improvement alternative. Both price and cost rise in the second period under the base alternative, as well as with the improvement, due to increased congestion. Although the

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[2] A more thorough explanation of the theory of project evaluation, including a numeric example, can be found in Appendix D, "Basic Theory of Highway Project Evaluation," in Camus and Weinblatt (2000).

price in the second period *with* the improvement is almost as high as the price in the first period *without* the improvement, the relevant price (and cost) in the second period is what the price and cost *would* be without the improvement, not what they were in the previous period. If each demand period represents the daily NOB for the given demand curve, then benefits are aggregated over all the days of the year and the number of years in the funding period, for each demand period.

HERS Benefit-Cost Procedures

HERS simulates the complex case-by-case real world improvement selection procedure by evaluating prototype segments on somewhat simplified grounds. It is not intended to define a complete set of individual projects, but rather to produce a representative set of worthwhile improvements that is unbiased toward either over- or under-investment. In other words, HERS is designed to select the right improvements on average, not necessarily to produce a specific program of ideal projects.

Determining Benefits and Costs

All benefits are estimated for the duration of the BCA period and discounted to the beginning of this period by applying a user-specified discount rate. Reductions in (agency) maintenance and user costs are estimated for the entire BCA period and the residual value of the improvement is calculated at the end of the period. Benefits are evaluated under the assumption that the improvement is implemented at the beginning of the BCA period, and the initial cost of the improvement is also assumed to be incurred at this time.

Residual Value

Residual Value is the preferred concept for valuing an improvement after it has passed through its normal lifetime or through an initial phase. Computation of this value, however, requires information and assumptions that are not currently contained in the HERS model. An expedient is used instead that provides a “refund” of a portion of the project’s costs if the analysis period is truncated before the end of the improvement’s normal lifetime. This concept is the Remaining Service Life (*RSL)*.

The residual value of an improvement is the capital value remaining at the end of the analysis period. HERS uses *RSL* is a substitute for either residual value or salvage value, although it is not equivalent. Salvage value is applicable if the asset is being terminated and liquidated, which is not normally the case for highway sections. Residual Value (RV) is the capitalized net benefits of the asset in its current use in perpetuity.

The computation of *RSL* is given by the formula

$$RSL_t = C_0 \times \frac{n-t}{n} \tag{2}$$

where t = length of the benefit-cost analysis period (BCAP), C_0 = initial cost of the improvement at time 0, n = the normal or expected lifetime of the improvement, and $t < n$. This *RSL* is the value at time t, which must be discounted to time 0 for evaluation of benefits and costs

$$RSL_0 = RSL_t \times \frac{1}{(1+r)^t} \qquad [3]$$

where RSL_0 = Remaining Service Life in present value terms at time 0, and r = discount rate.

Possible Biases From Using *RSL*

The effect of the *RSL* is to give the improvement a “credit” for the unused portion of the investment, scaled proportionately to the percentage of the lifetime that has not already passed. Use of the *RSL* introduces some qualifying considerations to the analysis:

(1) If the improvement is worthwhile, benefits after the end of the BCAP are likely to occur at a greater rate per year than the comparable rate that costs would be “spread” over the life of the improvement. Since truncating the analysis period treats these net benefits as zero (i.e., benefits are equal to costs), improvements with long lifetimes suffer a bias against them.

(2) Truncating the benefits and rebating a portion of costs yields a different project than the one specified: a shorter lifetime with shorter benefit period, and lower costs. It is likely that such an improvement does not exist, e.g., it is not possible to add half a lane and get whole-lane benefits for half as long.

(3) For the *RSL* algorithm to yield reasonable results in HERS, the BCAP must be equal to or less than the life of the shortest-lifetime improvement. If not, the more aggressive alternative is being compared to a base case that has been allowed to deteriorate to unrealistic levels. The proper base case would be repetition of a less aggressive improvement (e.g., resurfacing), until the lifetime of the more aggressive improvement or until the BCAP. HERS does not implement subsequent improvements, so it is necessary that the BCAP be no longer than the lifetime of the least durable improvement being evaluated. As long as more aggressive improvements have longer lifetimes, this condition is satisfied.

An *RSL* Example

In the following numerical example, a more aggressive improvement project (B) is compared to another improvement (A). Both projects are measured against a do-nothing base case. The assumed data are given in Table 7-3. HERS selects the lifetime of the least aggressive improvement as the BCAP.

Diagrammatically, the projects can be represented as shown in Figure 7-8, with the BCAP and project lifetimes indicated.

TABLE 7-3. **Example Improvement Projects**

	Project	
	A	B
initial cost (Co)	10	30
constant benefits	5	4
begin benefits (yr)	1	1
lifetime	10	20
analysis period (BCAP)	10	
discount rate	5%	

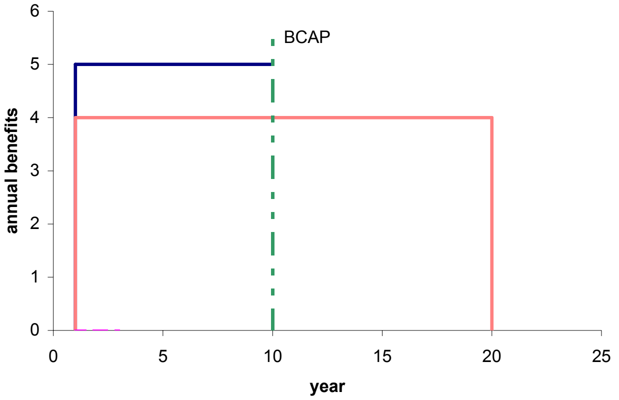

FIGURE 7-8. **Time profile of benefits for two example improvements.**

Benefits and costs for each improvement can be calculated relative to the do-nothing base, with the results shown in Table 7-4. Improvement *A* has no *RSL* because the BCAP coincides with the life of the improvement. The more aggressive improvement receives a benefit in the form of a share of its initial cost (1/2 in this instance), discounted to year *0*.

TABLE 7-4. **Present value of costs and benefits, including RSL**

present worth	fixed BCA period	
costs	10.00	30.00
benefits	38.61	30.89
remaining service life	-	9.21
net benefits	28.61	10.10
BCR	3.86	1.34

Evaluation Scenarios

For each scenario, the analyst indicates a minimum acceptable benefit-cost ratio, a funding level, or user-cost performance goal. In addition, the analyst may revise the default values contained in certain of the model's input files. The ability to change various assumptions provides for a great deal of latitude in defining scenarios and greatly facilitates the sensitivity testing of the model's conclusions to the values ascribed to critical (and often uncertain) parameters.

Three Basic Scenarios

The analyst may ask questions in one of three basic forms:

(1) What funding level is required to implement all improvements generating benefit-cost ratios greater than one (or some other BCR threshold), or

(2) What funding level is required to maintain a certain level of performance as measured by user costs, or

(3) What user cost level will result from a given level of funding?

Scenario (1) with BCR = 1 is the “economic efficiency” scenario and represents full needs in the benefit-cost sense. That is, HERS will identify all deficiencies, but will implement improvements to correct those deficiencies only when the corresponding improvement generates a benefit-cost ratio which exceeds one.

By setting the threshold BCR to negative infinity, this scenario can generate an “engineering full needs” scenario. When the specifications for this type of analysis are provided, HERS will identify and correct all deficiencies regardless of economic merit. Essentially, HERS is directed to turn off the benefit-cost rules and consider only engineering standards.

In the second “maintain conditions” scenario, HERS will select improvements for implementation only as required to maintain user cost levels present at the beginning of an analysis timeframe (e.g., funding period). Some sections will improve and some will be allowed to deteriorate, but overall system user cost performance levels will remain the same. The third is the constrained funding scenario, which will seek to maximize net benefits for the given funding.

A single funding constraint or performance goal may be specified for the entire highway system, or separate constraints may be provided for each functional system, or for specific groupings of highway systems.

Special Features

HERS applies economic principles in the evaluation of alternative highway policies and programs. The model was designed to apply benefit-cost rules to determine which deficient highway sections should be improved. By definition this implies that only improvements generating discounted benefit streams greater than the initial cost of the improvement will be selected. And, in the case of a limited budget, only those improvements with relatively more attractive benefit-cost ratios will be selected for implementation.

However, for a number of reasons the analyst may find it useful to restrict the strict application of benefit-cost analysis in the improvement selection process. The model includes a number of features which will allow the benefit-cost rules to be avoided or modified. These features are implemented at the analyst's discretion.

High Priority Deficiencies

If the deficiency level for a particular characteristic of a section is violated, then appropriate improvements that address this condition are evaluated by the benefit-cost analysis procedure and an improvement may be selected if the resulting incremental BCR is high enough.

The analyst may, however, set aside funds to guarantee correction of unacceptable conditions. This feature is used to avoid the situation where a low-volume road would be allowed to deteriorate indefinitely.

If the unacceptable condition level for a particular characteristic of a section is violated, then an inexpensive improvement that addresses this condition is normally (provisionally) selected automatically. The BCR for the improvement is considered only if funds available for correcting unacceptable conditions are insufficient to correct all such conditions.

HERS evaluates sections for unacceptable conditions during a 'first pass.' All sections are checked again, for deficient conditions, during a 'second pass.' Inexpensive improvements tentatively selected during the first pass may be replaced with a more aggressive improvement that correct deficient conditions (as opposed to only unacceptable conditions).

Funds to be reserved for correcting unacceptable conditions can be specified as a percentage of total funds available for each functional system or group of functional systems, or as a set of dollar amounts. It is desirable that at least some funds be reserved for making high benefit-cost ratio improvements to sections that are not in unacceptable condition. HERS allows the analyst to specify a maximum percentage of available funds that can be allocated to correct unacceptable conditions during any funding period.

Alternatively, the user can specify an improvement that will not be subject to BCA unless combined with another improvement., and the uses to which an analyst could employ the mechanism.

Modified Weights Used in Calculating IBCRs

Regardless of the type of objective specified, the sequence in which potential improvements are selected is determined by their Incremental BCRs. For any potential improvement, this ratio is obtained by estimating the discounted present value of a weighted average of all incremental benefits expected by produced by the improvement and dividing by the discounted present value of all incremental costs.

The different types of benefits and costs used in the IBCR can be weighted separately by the analyst; e.g., agency benefits and costs can be weighted twice a heavily as highway users benefits. Also, different weights can be used for each of the highway functional systems. A 'true' benefit-cost analysis would, of course, weigh all benefits and cost equally.

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