Chapter 5:

Estimation of Impacts

This chapter discusses the way HERS models discrete processes: pavement wear, vehicle operating costs, crash costs, traffic forecasts, speed calculation, travel time costs, demand elasticity, agency costs, and external costs. All of these processes are affected by the implementation of an improvement or the passage of time on an unimproved section.

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

5.1 The Pavement Deterioration Model

HERS models pavement wear as a function of traffic and environment. First, HERS calculates the effects of vehicular traffic on a section's PSR. Then, HERS figures both a minimum and a maximum rate of deterioration. The minimum rate is designed to reflect the effects of weather. The maximum rate of deterioration is designed to limit deterioration on sections with low structural numbers[1]. HERS applies these limits to the PSR value (which reflects pavement wear due to traffic) to arrive at a forecast pavement condition. HERS does not deteriorate unpaved sections, and roads without reported truck traffic are deteriorated at the minimum rate.

5.1.1 Equivalent Single-Axle Loads

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

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

1. Structural numbers (SN), which range from 1.0 to 6.0, indicate the strength of pavement. Sections whose SN is in the range from 1.0 through 3.0 are considered "light".

- a lane-load adjustment factor.

The 18-kip equivalent load factor is a function of pavement type, functional class, and truck type; values for this factor are given in Table 5-1. The lane load adjustment factor provides an estimate of the percentage of trucks that travel in the lane most heavily used by trucks as a function of the number of lanes in one direction; these values follow the AASHTO Pavement Design Guide[2] and are given in Table 5-2.

Table 5-1. Equivalent 18-KIP Load Applications per Truck

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

Table 5-2. Lane Load Distribution Factors

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

HERS estimates pavement deterioration using Percent Average Daily Single Unit Commercial Vehicles and Percent Average Daily Combination Commercial Vehicles. HERS allows the user to specify a set of annual growth factors to be applied to each section's percent truck values. (See section 2.11 “The Fleet Composition Model” on page 2-15.)

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

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

$$TOTRAF = \frac{(AADT_{t_0} + AADT_{t_f})}{2} \times 365 \times (t_f \angle\, t_0) \qquad \textbf{Eq. 5.1}$$

where $(t_f \angle\, t_0)$ represents the length of the period in years.

HERS then calculates ESALs for the time period:

$$\begin{aligned} ESALS = {} & (TOTRAF \times PCAVSU \times ELF_{SU} \times LF) \\ & + (TOTRAF \times PCAVCM \times ELF_{CM} \times LF) \end{aligned} \qquad \textbf{Eq. 5.2}$$

where:

ESALS	=	ESALs accumulated during the time period;
PCAVSU	=	average percentage of single-unit trucks during the time period;
ELF_{SU}	=	equivalent load factor for single unit trucks for this pavement type and functional class (from Table 5-1);
PCAVCM	=	average percentage of combination trucks during the time period;
ELF_{CM}	=	equivalent load factor for combination trucks for this pavement type and functional class (from Table 5-1); and
LF	=	lane load distribution factor (from Table 5-2).

HERS uses one-half the length of a funding period as the time period for calculating total traffic and incremental ESALs in order to capture changes in both AADT and average percentages of trucks. Therefore, when estimating the number of ESALs which will accumulate during a funding period, it utilizes Equations 5.1 through 5.2 twice, once for the first half and once for the second half of the funding period.

5.1.2 Pavement Condition

HERS determines present and future pavement condition using the AASHTO 1993 guidelines. The first step is to obtain the number of ESALs that would have resulted in causing PSR to decline from 5.0 to its base-year value. The number of ESALs applied during any subsequent period is then estimated and added to the previous ESAL value. This result is then used to estimate PSR at the end of this period.

For flexible pavement, the HPMS database contains either the structural number (SN) or pavement weight (light, medium or heavy); for rigid pavement it contains either thickness (D) or pavement weight. If any of the optional information is not provided for a section, HERS uses the default values shown in Table 5-3 to obtain values describing the initial pavement. When the pavement is improved, procedures described in section 4.2.4 “Effects of HERS Improvements” on page 4-20 are used to obtain the thickness of the overlays or of the new pavement and, for flexible pavements, a new value of SN.

5.1.2.1 Flexible Pavement

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

$$ESAL = 10^{LOGELA} \qquad \textbf{Eq. 5.3}$$

Table 5-3. Pavement Section Default Values

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

where:

$$LOGELA = XA + XG/XB + X0 + XM \quad \textbf{\textit{Eq. 5.4}}$$

$$XA = 9.36 \times \log(SNA) \angle 0.2 \quad \textbf{\textit{Eq. 5.5}}$$

$$XB = 0.4 + 1094/SNA^{5.19} \quad \textbf{\textit{Eq. 5.6}}$$

$$XG = \log((5 \angle PSRI)/3.5) \quad \textbf{\textit{Eq. 5.7}}$$

$$SNA = SN + \sqrt{(6/SN)} \quad \textbf{\textit{Eq. 5.8}}$$

$$X0 = ZR \times S0 \quad \textbf{\textit{Eq. 5.9}}$$

$$XM = 2.32 \times \log(MR) \angle 8.07 \quad \textbf{\textit{Eq. 5.10}}$$

$$ZR = ANORIN(REL) \quad \textbf{\textit{Eq. 5.11}}$$

and

PSRI = PSR at the beginning of the base year;
ANORIN = name of the function that evaluates the inverse of the standard normal (Gaussian) distribution function;
S0, *REL*, *MR* = input parameters taken from Table 5-4;

and all logarithms are taken to the base ten.

Table 5-4. Flexible Pavement Input Parameters

Input Parameter	Description	Varies By	Default Values	
S0	Prediction error	Pavement type	0.49 0.39	Flexible Rigid
REL	Reliability Factor	Functional Class	90% 85% 80%	Interstates Other Arterials Collectors
MR	Modulus of Resistance	Functional Class	4000 for all FC's	

The PSR at the end of any subsequent time period, *PSRF*, is then obtained by adding the number of ESALs incurred during that time period to the initial value of ESALs, substituting *PSRF* for *PSRI* in Equation 5.7, solving the above system of equations for

PSRF, and performing the indicated computations. Solving Equation 5.7 for *PSRF* produces:

$$PSRF = 5 \angle 3.5 \times PDRAF_{pt} \times 10^{XG} \qquad \textbf{\textit{Eq. 5.12}}$$

where:

$PDRAF_{pt}$	=	A user-specified pavement deterioration rate adjustment factor for pavement type *pt*, normally set to one[3];

and solving Equation 5.3 and Equation 5.4 for XG produces:

$$XG = XB \times (\log(ESALTF) \angle XA \angle X0 \angle XM) \qquad \textbf{\textit{Eq. 5.13}}$$

where *ESALTF* is the total number of ESALs accumulated at the time of interest.

5.1.2.2 Rigid Pavement

The procedure for obtaining the pavement condition of rigid pavements follows the same approach as that for flexible pavements: it also is based upon Equation 5.3. But for rigid pavements, LOGELA is defined:

$$LOGELA = X0 + XA + XG/XB + XN \times XC \qquad \textbf{\textit{Eq. 5.14}}$$

where:

$$XA = 7.35 \times \log(D+1) \angle 0.06 \qquad \textbf{\textit{Eq. 5.15}}$$

$$XB = 1 + 16.24 \times 10^{6}/(D+1)^{8.46} \qquad \textbf{\textit{Eq. 5.16}}$$

$$XN = 4.22 \angle 0.32 \times PT \qquad \textbf{\textit{Eq. 5.17}}$$

$$XC = \log\left\{\frac{SCP \times CD \times (D^{0.75} \angle 1.132)}{215.63 \times J \times (D^{0.75} \angle 18.42/(EC/K)^{0.25})}\right\} \qquad \textbf{\textit{Eq. 5.18}}$$

and

X0	=	as per flexible pavement in Equation 5.9;
XG	=	as per flexible pavement in Equation 5.7;
D	=	pavement thickness;

and PT, SCP, CD, J, EC, and K are input parameters as shown in Table 5-5 .

For rigid pavement, the solution for *XG* (the analogue to Equation 5.13) becomes:

$$XG = XB \times (\log(ESALTF) \angle XA \angle X0 \angle XN \times XC) \qquad \textbf{\textit{Eq. 5.19}}$$

and HERS uses Equation 5.12 to solve for *PSRF*, the PSR at the time of interest.

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

Table 5-5. Rigid Pavement Input Parameters

Input Parameter	Description	Default Value
PT	Design terminal serviceability index	2.5
SCP	Modulus of rupture	600
CD	Load transfer coefficient	1
J	Drainage coefficient	3.0
EC	Modulus of elasticity	3.5×10^6
K	Modulus of subgrade reaction	200

5.1.2.3 Minimum Deterioration Rate

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

$$PSRMAX_t = PSR_{t_0} \times ((PDL)/(NPSRAI))^{((t \angle t_0)/ML)} \qquad \textbf{\textit{Eq. 5.20}}$$

where:

t	=	any time of interest;
$PSRMAX_t$	=	upper limit on the PSR of a given section at time t;
t_0	=	time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
PDL	=	pavement deficiency level;
NPSRAI	=	“normal” PSR after improvement; and
ML	=	maximum life of the section in years from Table 5-6.

The use of Equation 5.20 requires knowing the time that each section was last improved (t_0) and the PSR immediately after the improvement (PSR_{t0}). For all improvements analyzed or selected by HERS, this information is readily available. For improvements that occurred prior to the start of a HERS run, the preprocessor uses the time of last improvement specified in the HPMS dataset, if available, or the middle of the year preceding the start of the HERS run. If the preprocessor finds that the section’s initial PSR is greater than the maximum PSR on that section after resurfacing, the time of improvement t_0 is set to six months before the beginning of the analysis period and the initial PSR is used as the PSR after improvement *NPSRAI.* Otherwise, the preprocessor uses the maximum permissible PSR after resurfacing.

The maximum pavement life values for rigid and flexible pavements for three types of pavement section (light, medium and heavy) are shown in Table 5-6.

Table 5-6. Maximum Pavement Life Values (Years)

Surface Type	Pavement Section		
	Heavy	Medium	Light
Flexible	25	20	15
Rigid	30	25	20

The HERS model then enforces the minimum deterioration rate:

$$PSRMX_t = \text{the lesser of} \begin{cases} PSRMAX_t \\ PSR_{t_{ESALS}} \end{cases} \qquad \textbf{\textit{Eq. 5.21}}$$

where:

$PSRMAX_t$	=	upper limit on PSR at time *t* from Equation 5.20;
PSR_{tESALS}	=	PSR at time *t* as a function of ESALs (PSRF from Equation 5.12); and
$PSRMX_t$	=	PSR at time *t* after enforcement of the minimum deterioration rate.

5.1.2.4 Maximum Deterioration Rate

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

$$PSR_t = \text{the larger of} \begin{cases} PSR_{t_0} \angle MAXPDR \times (t \angle t_0) \\ PSRMX_t \end{cases} \qquad \textbf{\textit{Eq. 5.22}}$$

where:

t	=	any time of interest;
PSR_t	=	PSR at the time *t* after enforcement of both the maximum and minimum deterioration rates;
t_0	=	time at which the section was last improved or, if not known, six months before the beginning of the HERS run;
$PSRMX_t$	=	PSR at time *t* after enforcement of the minimum deterioration rate from Equation 5.21; and
$MAXPDR$	=	maximum PSR deterioration rate per year.

5.1.2.5 Minimum PSR Level

Having forecast the future PSR based upon ESALs, and then applied limitations based upon minimum and maximum pavement deterioration rates, HERS applies a minimum PSR level below which no section is permitted to deteriorate. The minimum level is defined by *PSRUPS*, the PSR value for unpaved sections. The user specifies *PSRUPS* as a control input to HERSPP (see paragraph 3.2.1, ”The Preprocessor Control Inputs”). The supplied *PSRUPS* value is 1.0.

5.2 Estimating Operating Costs

The cost of operating a vehicle on a given section is a function of costs for fuel, oil, tires, maintenance and repair, and mileage-related depreciation. This section discusses the method by which HERS estimates operating costs. These estimates exclude the effect of taxes.[4]

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

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

Figure 5-1 provides an overview of the operating cost calculations.

The operating cost calculation process, as outlined above and detailed in the paragraphs below, is performed for each of the seven vehicle types. For the two truck categories the process is performed once for each direction unless free-flow speed and uphill free-flow speed are the same (see section 5.4.1 “Free-Flow Speed and the APLVM” on page 5-33). The process is performed only once for four-wheel vehicles, as HERS assumes that grades do not affect free-flow speed for these vehicles.

5.2.1 Operating Cost Components

HERS recognizes five components of operating costs:

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

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

5.2.1.1 Component Prices

Table 5-7 shows estimates of component prices in 1997 dollars for use in estimating operating costs. The sources of these estimates are described below.

Fuel prices for two-axle vehicles were derived by subtracting federal and state gasoline taxes[5] from the 1997 retail price of gasoline, and fuel prices for larger vehicles

4. From the standpoint of the user, taxes are part of user costs. However, from the standpoint of the overall economy, taxes are transfer payments that entail no resource costs.
5. U. S. Department of Transportation, Federal HIghway Administration, *Highway Statistics, 1997*, Washington, D.C., 1998, Table MF-121T.

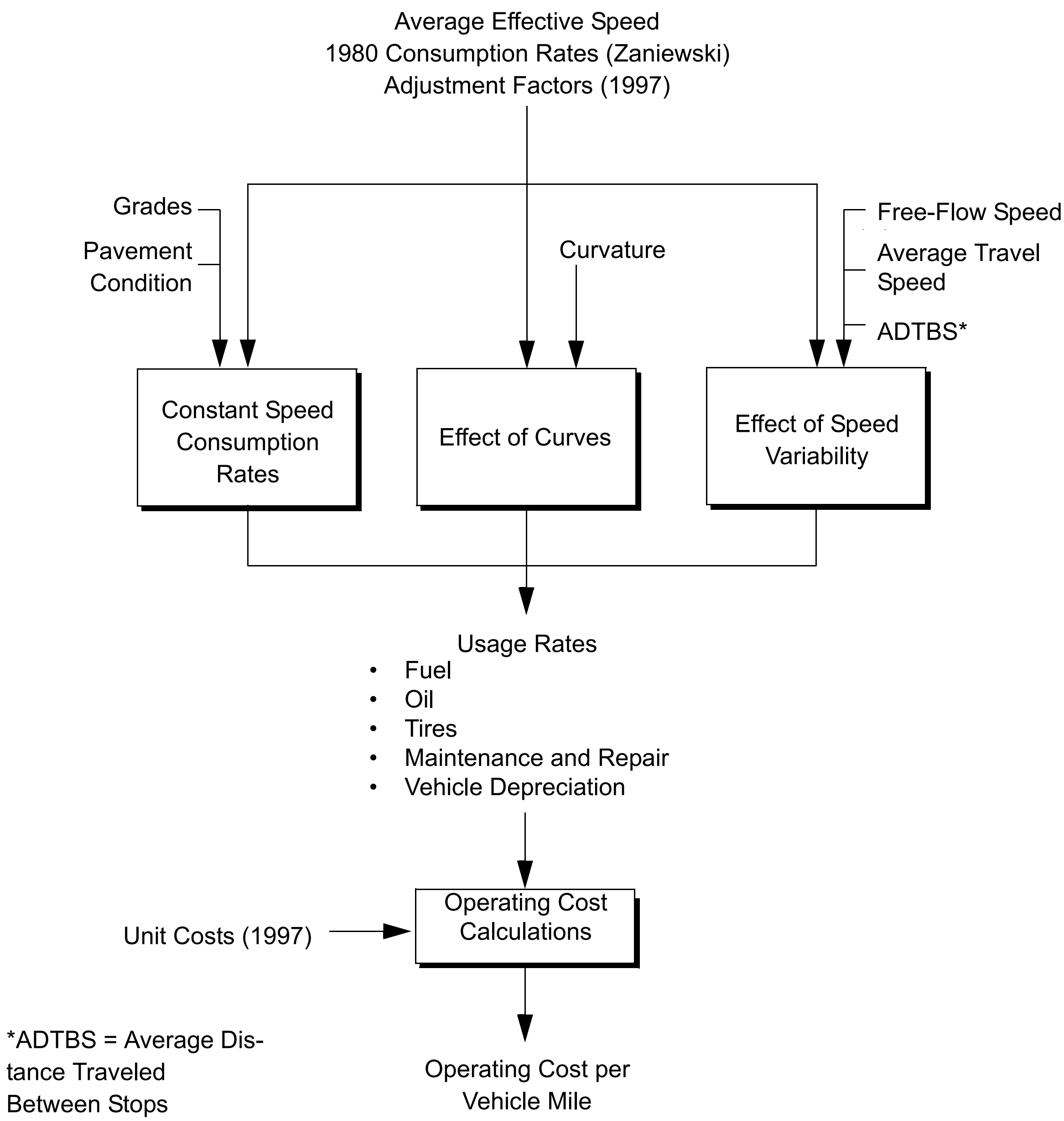

Figure 5-1. Operating Cost Calculation Flow

were derived by subtracting taxes on diesel fuel from the average 1997 retail price of highway diesel fuel.[6]

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

Table 5-7. Component Prices (1997 dollars)

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

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

Values for the cost of oil and tires were obtained by applying appropriate price indexes to the 1995 estimates previously developed[7] from the original Zaniewski estimates[8]. The price index used for oil is the consumer price index (CPI)[9] for motor oil, coolant, and fluids (SS47021). Tire costs were indexed using the CPI for tires (SETC01). The tire-cost index reflects the effects of improvements in quality (as downward adjustments in the index) - improvements that generally decrease the rate of tire wear. Maintenance and repair costs were indexed using the CPI for motor vehicle maintenance and repair (SETD).

For medium and heavy trucks, following Zaniewski, depreciable value was obtained by subtracting tire costs from the vehicle's retail price and then subtracting ten percent salvage value. For the three heaviest vehicles, the vehicle prices were those used by the recent Federal Highway Cost Allocation Study[10] (for three-axle dump trucks and for combinations with a tandem-axle van semi-trailer). The retail price of a 1995 28,000 pound gross vehicle weight six-tire truck was obtained from the Truck Blue Book[11] and adjusted to include a van body.

For the two classes of automobiles, 1995 depreciable value was obtained by adjusting the 1993 values[12] for changes in the average price paid for a new car.[13] For four-tire

7. Cambridge Systematics, Inc., *Revisions to HERS*, prepared for the Federal Highway Administration, December 1997, Chapter 7.
8. J.P. Zaniewski, *et.al.*, *Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors*, Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1982, Table 2, p. 7.
9. U.S. Department of Labor, Bureau of Labor Statistics, Consumer Price Index Database.
10. U. S. Department of Transportation, FHWA, *1997 Federal Highway Cost Allocation Study*, August 1997.
11. Maclean Hunter Market Reports, *Truck Blue Book*, Chicago, January 1995.
12. Cambridge Systematics, Inc., *op. cit*. The 1993 values were derived from the original Zaniewski values using the same procedure.

trucks, 1995 depreciable value was obtained judgementally from the 1995 value for medium/large automobiles by comparing the range of list prices of minivans and sport-utility vehicles to the range for medium and large automobiles.[14] For all vehicle classes, 1997 depreciable value was then obtained by applying the change in the average price of a new car between 1995 and 1997.

5.2.1.2 Adjustment Factors for Consumption Rates

The parameters used by the operating cost equations have been indexed to reflect reductions in fuel and oil consumption rates and depreciation rates that occurred between 1980 and 2000. Increases in tire durability are reflected in the consumer and producer price indexes (which have increased by only a few percent since 1980), so separate adjustments are not needed for changes in the rate of tire wear. Similarly, no adjustments were made in the amount of maintenance required; reductions in the requirements for routine maintenance are reflected in the data used for adjusting maintenance costs per mile through 1995[15] (but not in the BLS data used for the 1995-2000 adjustment).

The adjustments for changes in fuel efficiency, oil consumption, and vehicle depreciation are discussed below.

5.2.1.2.1 Fuel Efficiency Adjustment Factor

The fuel efficiency adjustment factors for automobiles and four-tire trucks were obtained by dividing on-road fuel efficiency for the 2000 fleet of automobiles and light trucks by corresponding 1980 values. The 1980 values were obtained from Energy and Environmental Analysis.[16] The 2000 values were developed using the following data from the *Transportation Energy Data Book* published annually by Oak Ridge National Laboratory (ORNL):[17]

- 1976-2000 sales of automobiles and 1970-2000 sales of light trucks
- 1976-2000 EPA fuel efficiencies by vehicle class
- estimated survival rates.

The surviving fleets of pre-1970 light trucks and pre-1976 automobiles were assumed to be three times the number of surviving 1970 light trucks and 1976 automobiles, respectively. Fuel efficiencies of pre-1976 automobiles were estimated by extrapolation, while fuel efficiencies of pre-1976 light trucks were assumed to be the same as those of 1976 light trucks (which are 11 percent below those of 1977 light trucks). All

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13. U.S. Department of Commerce, Bureau of Economic Analysis, "Average Transaction Price of a New Car," quoted in American Automobile Manufacturers Association, *Motor Vehicle Facts and Figures, 1996*, Detroit, 1996, page 60. This source provides a better indication of changes in vehicle prices than the appropriate components of the CPI and PPI, because the latter indexes are adjusted (downward) to exclude the effect on prices of improvements in the quality of new vehicles. On the other hand, none of the adjustments reflect the effects that some of these improvements have had on servicing requirements or depreciation rates (which, ideally, should be handled by modifying the operating cost equations for maintenance and repair).
14. The alternative approach of adjusting the original Zaniewski values using data on changes in the price of a new car was rejected because it does not adequately reflect the increase in the quality of appointments of four-tire trucks that has occurred during the last several years. The rejected procedure produces a 1995 value of only $17,002 (instead of the $20,742 value actually used).
15. Runzheimer International, quoted in American Automobile Manufacturers Association, Motor Vehicle Facts and Figures, 1996, Detroit, 1996, p. 58.
16. Energy and Environmental Analysis, Inc., *The Motor Fuel Consumption Model: Thirteenth Periodical Report*, prepared for the U.S. Department of Energy, Washington, D.C., January 1988, page B-1.
17. Oak Ridge National Laboratory, *Transportation Energy Data Book*, various editions.

averaging was performed using fuel consumption rates (gallons per mile); and in-use fuel efficiency was assumed to be 15 percent below the EPA value.

A single 20-year fuel-efficiency adjustment factor for the three classes of heavy trucks was developed by obtaining the ratio of the 1997 and 1977 fuel-efficiency estimates for in use Class 8 trucks developed by ORNL using data from the Truck Inventory and Use Survey (TIUS). The relatively modest increase in fuel efficiency (39.6 percent over 20 years) is due, in part, to increases in vehicle weights.

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

The resulting fuel efficiency adjustment factors are shown in Table 5-8.

Table 5-8. Fuel Efficiency Adjustment Factors (2000 Factors)

Vehicle Type	Factor
Small Automobiles	1.550
Medium/Large Automobiles	1.550
4-Tire Trucks	1.666
6-Tire Trucks	1.344
3+ Axle Trucks	1.396
3-4 Axle Combinations	1.396
5+ Axle Combinations	1.396

5.2.1.2.2 Oil Consumption Adjustment Factor

The most common recommended oil-change interval for new automobiles was 7,500 miles in both 1980 and 2000. However, for various reasons, some slight reduction in oil consumption between these two years was likely. (These reasons include a reduction in the number of older cars with shorter oil-change intervals and reduced burning of oil.) Accordingly, an oil-consumption reduction factor of 1.05 was assumed for all vehicle classes.

5.2.1.2.3 Depreciation Rate Adjustment Factor

The average age of the automobile fleet increased from 6.6 years in 1980 to 8.6 years in 1996.[18] Extrapolating to 2000, we estimate average age to be 9.1 years, suggesting a 38 percent increase in longevity (or a decline in the average rate of depreciation of about 28 percent). The same increase in average longevity was assumed for trucks.

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

5.2.2 Constant-Speed Operating Costs

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

$$\begin{aligned} CSOPCST_{vt} = {} & CSFC \times PCAFFC \times COSTF_{vt} / FEAF_{vt} \\ & + CSOC \times PCAFOC \times COSTO_{vt} / OCAF_{vt} \\ & + 0.01 \times CSTW \times PCAFTW \times COSTT_{vt} / TWAF_{vt} \\ & + 0.01 \times CSMR \times PCAFMR \times COSTMR_{vt} / MRAF_{vt} \\ & + 0.01 \times CSVD \times PCAFVD \times COSTV_{vt} / VDAF_{vt} \end{aligned} \qquad \textbf{Eq. 5.23}$$

where:

$CSOPCST_{vt}$	=	constant speed operating cost for vehicle type *vt;*
$CSFC$	=	constant speed fuel consumption rate (gallons/ 1000 miles);
$CSOC$	=	constant speed oil consumption rate (quarts/1000 miles);
$CSTW$	=	constant speed tire wear rate (% worn/1000 miles);
$CSMR$	=	constant speed maintenance and repair rate (% of average cost/1000 miles);
$CSVD$	=	constant speed depreciation rate (% of new price/ 1000 miles);
$PCAFFC$	=	pavement condition adjustment factor for fuel consumption;
$PCAFOC$	=	pavement condition adjustment factor for oil consumption;
$PCAFTW$	=	pavement condition adjustment factor for tire wear;
$PCAFMR$	=	pavement condition adjustment factor for maintenance and repair;
$PCAFVD$	=	pavement condition adjustment factor for depreciation expenses;
$COSTF_{vt}$	=	unit cost of fuel for vehicle type *vt*;
$COSTO_{vt}$	=	unit cost of oil for vehicle type *vt*;
$COSTT_{vt}$	=	unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$	=	unit cost of maintenance and repair for vehicle type *vt*;
$COSTV_{vt}$	=	depreciable value for vehicle type *vt*;
$FEAF_{vt}$	=	fuel efficiency adjustment factor for vehicle type *vt*;
$OCAF_{vt}$	=	oil consumption adjustment factor for vehicle type *vt*;
$TWAF_{vt}$	=	tire wear adjustment factor for vehicle type *vt*;
$MRAF_{vt}$	=	maintenance and repair adjustment factor for vehicle type *vt*; and
$VDAF_{vt}$	=	depreciation adjustment factor for vehicle type *vt*.

Equations for estimating constant-speed consumption rates for fuel, oil, tires, maintenance and repair, and vehicle depreciation are shown in Appendix E, "Operating Cost

Equations." In these equations, *AES* is average effective speed in miles per hour (an output of the speed model), and *GR* is grade (in percent). The equations were estimated by applying ordinary least squares regression to the consumption tables presented in Zaniewski,[19] and have been modified to handle the higher speeds that HERS will encounter as a result of the recent increase in speed limits.

The Zaniewski tables represent estimated consumption rates for equipment in use in 1980 on roads with PSR = 3.5. Table E-16 on page E-11 presents equations for estimating pavement-condition adjustment factors for oil consumption, tire wear, maintenance and repair, and vehicle depreciation. These equations also were estimated by applying ordinary least squares regression to the adjustment factors presented in Zaniewski.[20]

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

5.2.3 The Effect of Speed-Change Cycles

HERS calculates excess operating costs due to speed-change cycles (or speed variability) for sections which have stop signs or traffic signals. The overall formula for calculating these costs is similar to that for constant speed operating costs (see Equation 5.23) with two exceptions: the consumption rates are derived from a different set of equations, and no pavement condition adjustment factors are used. For each vehicle type (*vt*), excess operating costs per thousand vehicle-miles due to speed variability (*VSOPCST*) is estimated:

$$\begin{aligned} VSOPCST_{vt} = {} & VSFC \times COSTF_{vt}/FEAF_{vt} \\ & + VSOC \times COSTO_{vt}/OCAF_{vt} \\ & + VSTW \times COSTT_{vt}/TWAF_{vt} \\ & + VSMR \times COSTMR_{vt}/MRAF_{vt} \\ & + VSVD \times COSTV_{vt}/VDAF_{vt} \end{aligned} \qquad \textbf{Eq. 5.24}$$

where:

$VSOPCST_{vt}$	=	excess operating cost due to speed variability for vehicle type *vt*;
VSFC	=	excess fuel consumption rate due to speed variability (gallons/1000 miles);
VSOC	=	excess oil consumption rate due to speed variability (quarts/1000 miles);
VSTW	=	excess speed tire wear rate due to speed variability (% worn/1000 miles);
VSMR	=	excess speed maintenance and repair rate due to speed variability (% of average cost/1000 miles);
VSVD	=	excess depreciation rate due to speed variability (% of new price/1000 miles);
$COSTF_{vt}$	=	unit cost of fuel for vehicle type *vt*;

19. *Op. cit*., Appendix B.
20. *Ibid*., Figure 5 and Tables 12, 15, and 19.

$COSTO_{vt}$	=	unit cost of oil for vehicle type *vt*;
$COSTT_{vt}$	=	unit cost of tires for vehicle type *vt*;
$COSTMR_{vt}$	=	unit cost of maintenance and repair for vehicle type *vt*;
$COSTV_{vt}$	=	depreciable value for vehicle type *vt*;
$FEAF_{vt}$	=	fuel efficiency adjustment factor for vehicle type *vt*;
$OCAF_{vt}$	=	oil efficiency adjustment factor for vehicle type *vt*;
$TWAF_{vt}$	=	tire wear efficiency adjustment factor for vehicle type *vt*;
$MRAF_{vt}$	=	maintenance and repair efficiency adjustment factor for vehicle type *vt*; and
$VDAF_{vt}$	=	depreciation adjustment factor for vehicle type *vt*.

These equations were also derived from Zaniewski, and are only applied to sections with stop signs or traffic signals. The equations are shown in Tables E-28 through E-91.

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

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

5.2.4 The Effect of Curves

HERS uses the original Zaniewski tables[21] and equations derived from those tables for estimating excess operating costs due to curves. Two-dimensional linear interpolation of table values is used for sections with average effective speed below 55 m.p.h., and equations fit to the tables are used for sections with average effective speed above 55 m.p.h. On sections with zero degrees of curvature, excess costs are set to zero.

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

21. *Ibid*., Appendix A, Tables A.73-A.80.

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

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

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

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

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

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

$$\begin{aligned} COPCST_{vt} = {} & CFC \times COSTF_{vt} / FEAF_{vt} \\ & + 0.01 \times CTW \times COSTT_{vt} / TWAF_{vt} \\ & + 0.01 \times CMR \times COSTMR_{ct} / MRAF_{vt} \end{aligned} \qquad \textbf{\textit{Eq. 5.25}}$$

where:

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

The equations used to produce *CFC*, *CTW*, and *CMR* are shown in Tables E-40 through E-53.