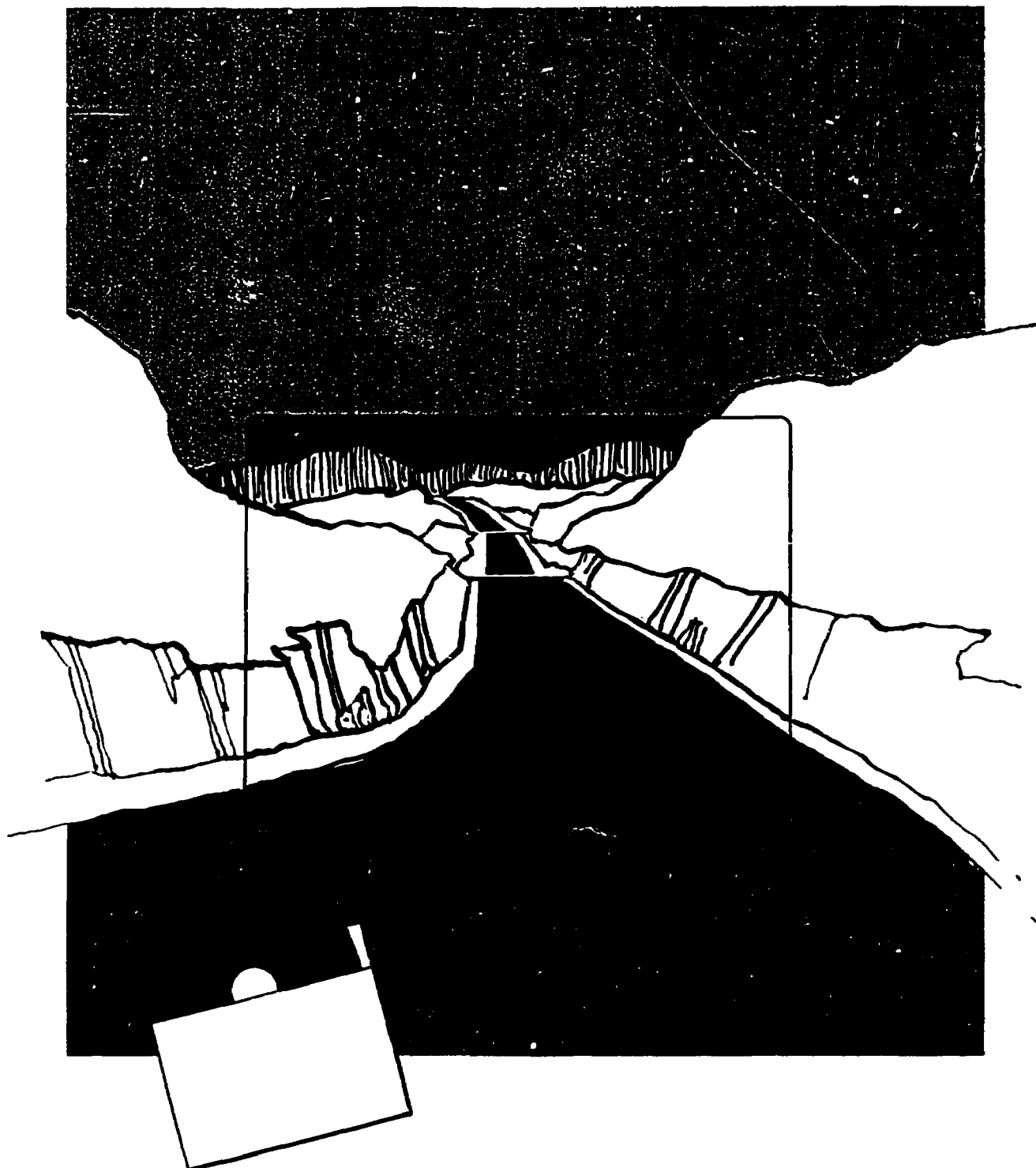


WTP 0234
HDM-VOC
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Estimating Vehicle Operating Costs

Rodrigo S. Archondo-Callao and Asif Faiz

January 1994



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Estimating Vehicle Operating Costs

Rodrigo S. Archondo-Callao and Asif Faiz

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Foreword

While the costs of road construction and maintenance consume a large proportion of national budgets, the costs borne by the road-using public for vehicle operation and depreciation are even greater. It is therefore important that road policies take account of total transportation costs. This requires quantitative methods for predicting performance and costs of both roads and vehicles over large and diverse road networks, and under various investment and management policies and strategies.

In order to develop such quantitative functions, the World Bank initiated a study in 1969 which later became a large-scale program of collaborative research with leading research institutions and road agencies in several countries. This Highway Design and Maintenance (HDM) Standards Study focused on the rigorous empirical quantification of tradeoffs between the costs of road construction, road maintenance and vehicle operation, and also on the development of planning models incorporating total life-cycle cost simulation as a basis for highway decision-making.

This volume presents the methods and relationships developed for estimation of vehicle operating costs, as a function of vehicle type and road characteristics. These procedures are combined in a computer model, HDM-VOC, for the calculation of user costs under a variety of road and traffic conditions, but not including congested traffic operations. The relationships were developed from controlled experiments and extensive user surveys in Kenya, Brazil, India and the Caribbean, which together produced an enormous body of knowledge on road user costs in three continents with diverse road conditions and economic environments. They can be adapted to local conditions in other countries using estimates of local vehicle prices, labor and repair costs, vehicle utilization and other parameters.

The study developed detailed mechanistic relationships for the prediction of vehicle operating costs as a function of road and vehicle characteristics. These are sometimes known as the "Brazil relationships", because of the country for which they were first developed. However they have a robust formulation which is suitable for application to other countries and vehicle fleets using local road and vehicle parameters.

The speed prediction methods used in the Brazil relationships give only the average free-flow speed for each vehicle type, taking account of grades, curves, surface roughness and desired speed, but not the delays caused by other traffic on the road. HDM-VOC version 4.0 gives an additional option to directly specify speed, where the user has other sources of information. This feature can be used to take some account of traffic congestion effects, but does not address all aspects of congestion effects on vehicle operating costs.

This report is one of a series of documents arising from the HDM study. The other volumes are:

Vehicle Operating Costs:

Evidence from developing Countries (1987)

Road Deterioration and Maintenance Effects:

Models for Planning and Management (1987)

The Highway Design and Maintenance Standards Model

Volume 1. Description of the HDM-III Model (1987)

The Highway Design and Maintenance Standards Model

Volume 2. Users' Manual for the HDM-III Model (1987)

Louis Y. Pouliquen

Director

Transport, Water and Urban Development Department

Abstract

Understanding the costs of road construction, road maintenance and vehicle operation is essential to sound planning and management of road investments. While the infrastructure costs borne by road agencies are substantial, the costs borne by road users are even greater. To quantify these relationships, the World Bank initiated a collaborative international study which led to the vehicle operating costs relationships developed in this study, and presents these in a small easy-to-use computer program which can be used independently of the larger model. The HDM-VOC program predicts the various components of vehicle operating costs based on road and vehicle characteristics and unit costs in a free-flow traffic environment. Calculations are provided for ten vehicle types ranging from small car to articulated truck, and compute speed, physical quantities consumed, and total operating costs. Total fleet operating costs, sensitivity tables and cost relationships are also developed.

Chapter 1

Installing HDM-VOC on Your Computer

System Requirements

Hardware

- An IBM XT, AT, 80386, 80486, or compatible computer.
- A minimum installed memory of 520 Kb.
- One floppy disk drive. A hard disk is optional.
- A color or monochrome monitor.
- A printer capable of printing 102 characters per line.

Software

- DOS version 3.0 or higher.
- Optional: Lotus 1-2-3 to analyze the results.

Installing and Running the Program

Floppy Disk System

You can run the program from a floppy disk or from a hard disk. To run the program from the floppy disk A:, follow the steps below.

- Turn on your computer and at the DOS prompt A > , place the HDM-VOC program disk in drive A:.
- Run the program with one of the following commands.

for English version

HDM-VOC

for Spanish version

HDM-VOC ES

for French version

HDM-VOC FR

for Portuguese version

HDM-VOC PO

Hard Disk System

To install the program on your hard disk, follow the steps below.

- Turn on your computer and at the DOS prompt C>, make a directory for HDM-VOC with the command:

MD\HDM-VOC

- Change to the HDM-VOC directory with the command:

CD\HDM-VOC

- Place the HDM-VOC program disk in drive A: and enter:

COPY A:*.*

To run the program from the hard disk, follow the steps below.

- Turn on your computer and at the DOS prompt C>, change to the HDM-VOC directory with the command:

CD\HDM-VOC

- Run the program with one of the following commands.

for English version

HDM-VOC

for Spanish version

HDM-VOC ES

for French version

HDM-VOC FR

for Portuguese version

HDM-VOC PO

Program Disk Backup

For safety, make a backup copy of the original HDM-VOC program disk with the DOS command:

DISKCOPY A: A:

Refer to the DOS manual for detailed instructions about this command.

Software Package Contents

The files supplied on the HDM-VOC program disk are listed below.

File	Description
HDM-VOC.EXE	HDM-VOC program
VOC.HLP	Help file
VOC.EN	English labels
VOC.ES	Spanish labels
VOC.FR	French labels
VOC.PO	Portuguese labels
CAR.VOC	Sample data for a passenger car
BUS.VOC	Sample data for bus
LIGHT.VOC	Sample data for light truck
MEDIUM.VOC	Sample data for medium truck
HEAVY.VOC	Sample data for heavy truck
ARTIC.VOC	Sample data for articulated truck
READ.ME	Latest documentation

Chapter 2

Using the Program

The Model

The HDM-VOC model predicts the various components of vehicle operating costs (VOC) based on the roadway characteristics, vehicle characteristic and unit costs in a free-flow traffic environment. The computations are based on the Brazil relationships derived from the World Bank's Highway Design and Maintenance Standards Model ¹ (HDM-III).

The Brazil relationships predict the vehicle operating costs for 10 vehicle types ranging from a small car to an articulated truck. Although the model requires around 70 input variables, you have to input only a fraction of these variables because the model supplies most of the vehicle characteristics as default values. When detailed information on vehicle characteristics is available, you may modify the default values to obtain more accurate results for a particular country and vehicle fleet.

The model computes for each vehicle type the vehicle speed, physical quantities of consumption, individual VOC components and total VOC. The model also produces sensitivity tables, computes the total VOC for a fleet of vehicles, and computes the regression equation coefficients that relate total VOC to roughness.

The Main Screen

The Main Screen is divided in the following areas (see Figure 1).

- **TITLE** Lines at the top of the screen that display the name of the program and the title of the run.
- **PAGES** Area below the title where the program displays the input data and the results pages. There are nine input data pages and six result pages.

- **MAIN MENU** Lines at the bottom of the screen where the program displays a menu of options, collects the required information and displays errors or warnings.

Figure 1 - The Main Screen

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0
F1-Help

Small Car Sample Data
Page : 1
INPUT

Roadway Characteristics

1 Surface type	Code: 1-Paved 0-Unpaved	1
2 Average roughness (IRI)	m/km	2.50
3 Average positive gradient	%	0.00
4 Average negative gradient	%	0.00
5 Proportion of uphill travel	%	50.00
6 Average horizontal curvature	deg/km	0.00
7 Average superelevation	fraction	0.00 D
8 Altitude of terrain	m	0.00
9 Effective number of lanes	Code:1-One 0-More than one	0

Data	Input	Save	Reports	Files	Quit
VOC	Modify	Load	Tables	Name	Clear
Load Input Data from Disk					

The Pages

The program presents the input data and the results in "pages" of information on a standard screen format. The program displays the page number and the type of information being displayed (input data or results) at the top of each page.

You are always free to move among the input data pages and, after you compute the results, among the result pages. Press the following keys to move among pages.

- Press PgDn to move to the next page.
- Press PgUp to move to the previous page.
- Press Home to move to the first page.
- Press End to move to the last page.
- Press a number to move to the corresponding page.

The Input Data

The input data is classified in the following groups.

- Roadway characteristics, displayed on input page 1.
- Vehicle type, displayed on input page 2.
- Vehicle characteristics, displayed on input page 3.
- Tire wear data, displayed on input page 4.
- Vehicle utilization data, displayed on input page 5.
- Unit costs, displayed on input page 6.
- Other vehicle characteristics, displayed on input pages 7 to 9.

The program always displays the up-to-date contents of all input variables. There are two types of input variables: variables without default values, and variables with default values that have the letter D displayed at the right side of the current value (see Figure 2).

Figure 2 - The Vehicle Characteristics

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0
F1-Help

Small Car Sample Data
Page : 3
INPUT

Vehicle Characteristics

1 Total weight	kg	970.00 D
2 Load carried	kg	230.00
3 Maximum used driving power	metric HP	37.00 D
4 Maximum used braking power	metric HP	20.00 D
5 Desired speed	km/hour	98.30 D
6 Aerodynamic drag coefficient	dimensionless	0.45 D
7 Projected frontal area	m ²	2.00 D
8 Calibrated engine speed	rpm	3900.00 D
9 Energy-efficiency factor	dimensionless	0.70 D
10 Fuel adjustment factor	dimensionless	1.18 D

Data	Input	Save	Reports	Files	Quit
VOC	Modify	Load	Tables	Name	Clear

The Steps

When you start the program, the program sets all variables to zero and is your task to fill all input pages and compute the results with the following steps.

- Go to input page 1 (press the Home key or the number 1 key).
- Input the roadway information (use the Input option).
- Move to input page 2 (press the PgDn key or the number 2 key).
- Select a vehicle type (use the Input or Modify option).

Note: When you select a vehicle type, the program collects the default vehicle characteristics (D's).

- Input the remaining required data (variables without D's) on pages 3 to 9 (use the Input or Modify option).
- Modify any default input variable (use the Modify option).
- Correct any input variable on input pages 1 to 9 (use the Modify option).
- Compute the results (use the VOC option).
- View the results on results pages 1 to 6 (use the PgUp and PgDn keys).
- Create reports (use the Report option).
- Create sensitivity tables (use the Tables option).
- Return to the input data pages (use Data option).

The Results

Use the VOC option to obtain the results. The program displays the result pages and you can now move among these pages with the same keys used in the input data mode (PgUp, PgDn, Home and End). The results are classified in the following groups.

- Physical quantities of consumption and vehicle speed, displayed on page 1 (see Figure 3).
- Vehicle operating costs, displayed on page 2 (see Figure 4).
- Percentage of total VOC of individual VOC components, displayed on page 3.
- Other computed intermediate values, displayed on pages 4 to 6.

Figure 3 - Physical Quantities of Consumption

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0				F1-Help
Small	Car Sample Data			
	Page : 1		RESULTS	
Physical Quantities per 1000 vehicle-km				
Fuel consumption		liters		78.23
Lubricants consumption		liters		1.93
Tire wear		# of equivalent new tires		0.06
Crew time		hours		11.46
Passenger time		hours		11.46
Cargo holding		hours		11.46
Maintenance labor		hours		2.36
Maintenance parts		% of new vehicle price		0.17
Depreciation		% of new vehicle price		0.50
Interest		% of new vehicle price		0.27
Vehicle Speed		km/hr		87.27

Data	Input	Save	Reports	Files	Quit
VOC	Modify	Load	Tables	Name	Clear
Compute and Display the Results					

Use the Data option to return to the input data pages, modify any variable and use the VOC option again to display the new results.

The Default Values

The program has default values (D's) for the superelevation (page 1) and for vehicle characteristics. The superelevation is a function of horizontal curvature, so when you enter the curvature the program collects the suggested value for superelevation. If necessary, modify the suggested superelevation with the Modify option.

The program collects the default vehicle characteristics when you select the vehicle type on page 2. The defaults are a function of the vehicle type and four of the defaults (desired speed, BW, FRATIO₀, and FRATIO₁) are also a function of the surface type and effective number of lanes defined on page 1. Note that if you change the surface type or the number of lanes after selecting the vehicle type, the program collects again the default values for desired speed, BW, FRATIO₀, and FRATIO₁.

Figure 4 - The Vehicle Operating Costs

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0 F1-Help

Small Car Sample Data
Page : 2

		RESULTS
Total VOC per 1000 vehicle-km	\$	116.87
Fuel	\$	27.38
Lubricants	\$	2.89
Tires	\$	3.80
Crew time	\$	11.46
Passenger time	\$	0.00
Cargo holding	\$	0.00
Maintenance labor	\$	5.19
Maintenance parts	\$	11.92
Depreciation	\$	35.27
Interest	\$	18.96
Overhead	\$	0.00

Data VOC	Input Modify	Save Load	Reports Tables	Files Name	Quit Clear
Compute and Display the Results					

Available Help

Help is available at the Main Screen. You have the following options.

Press	At	To obtain
F1	The Main Screen	Help on help
F3	The Main Screen	Program instructions
F5	The Main Screen, highlighting a particular menu option	Help on the particular menu option
F7	The Main Screen, displaying a particular page	Help on the particular page
F9	The Main Screen	Basic information required to run the program

1 . The Highway Design and Maintenance Standards Model**Volume 1. Description of the HDM-III Model****Volume 2. User's Manual for the HDM-III Model**

**Thawat Watanatada, Chell G. Harral, William D. O. Paterson,
Ashok M. Dhareshwar, Anil Bhandari, and Koji Tsunokawa.
Washington, D.C.: Transportation Department, World Bank, 1987.**

Chapter 3

Main Menu Options

The Main Menu

The Main Menu is located at the bottom of the Main Screen (see Figure 5) and it is used to access all the program's features.

Figure 5 - The Main Menu

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0 F1-Help

Small Car Sample Data INPUT

Page : 2

Selection of Vehicle Type Vehicle Type : 1

1 Small car	(Volkswagen 1300)
2 Medium car	(Chevrolet - Opala)
3 Large car	(Chrysler - Dodge Dart)
4 Utility or pick-up	(Volkswagen Kombi)
5 Bus	(Mercedes-benz G-362)
6 Light gasoline truck	(Ford F-400)
7 Light diesel truck	(Ford F-4000)
8 Medium truck	(Mercedes-benz w/2 axles)
9 Heavy truck	(Mercedes-benz w/3 axles)
10 Articulated truck	(Scania 110/39)

Date	Input	Save	Reports	Files	Quit
VOC	Modify	Load	Tables	Name	Clear
Display the Input Data					

To select an option, highlight the option selected and press the <Enter> key or press the first letter of the option selected.

Input Data for the Current Screen

The Input option allows you to enter information for all variables on a given input page. The program displays at the bottom of the screen the current contents of each input variable and gives you the opportunity to change this value. If you press the <Enter> key, when prompted for a new value, the variable retains its current value.

Use the Input option on page 1 to enter the roadway characteristics. When you enter the horizontal curvature, the program collects the suggested value for superelevation. If you want to use this value, press <Enter> when prompted for the superelevation.

Use the Input option or the Modify option to select a vehicle type on page 2 and use the Input option on pages 3 to 9 to enter the vehicle characteristics after selecting the vehicle type. Note that the Input option is not active while displaying the result pages.

Modify the Data Displayed

The Modify option changes the value of a single variable on a given page. The program prompts for line of the variable you want to modify and displays its current value at the bottom of the screen. Enter the new value for the variable or press the <Enter> key to retain its current value.

When you modify the horizontal curvature in page 1, the program collects the suggested value for superelevation and when you modify the surface type or number of lanes, the program collects the default vehicle characteristics that are a function of surface type or number of lanes (desired speed, BW, FRATIO₀, and FRATIO₁).

Use the Modify option or the Input option to select a vehicle type on page 2 and use the Modify option in pages 3 to 9 to modify the vehicle characteristics after selecting the vehicle type. Note that the Modify option is not active while displaying the result pages.

Save the Input Data

The Save option saves the input data on disk. The program prompts for the name of the file to store the input data and you should provide a legitimate DOS filename. If you press the <Enter> key, when prompted for the filename, the program returns to the Main Menu without taking any action.

The program automatically adds ".VOC" as a default extension for data files, so enter a valid DOS filename without a file extension.

For example:

```
TRUCK  
A:\MYCAR  
C:\VOCDATA\MINIBUS  
D:\PROJECT\VOC\PICKUP
```

Load Input Data from Disk

The Load option loads input data stored on disk. The program prompts for the name of the file that contains the input data and you should provide a legitimate DOS filename. If you press the <Enter> key, when prompted for the filename, the program returns to the Main Menu without taking any action. Note that this option is not active while displaying the result pages.

The program expects ".VOC" as a default extension for data files, so enter a valid DOS filename without a file extension.

Examples:

```
TRUCK
A:\MYCAR
C:\VOCDATA\MINIBUS
D:\PROJECT\VOC\PICKUP
```

Note: Some input data files are included on the VOC program disk (see Software Package Contents). Use these files to tests the program's features.

Compute and Display the Results

The VOC option computes the vehicle speed, the physical quantities of consumption, and the vehicle operating costs. The program displays the results in the same format as it displays the inputs (using "pages" of results).

When you compute the results for the first time, the program displays page 1 of the result pages. Move among the six results pages pressing the PgDn, PgUp, Home or End keys and use the Data option to return to the input data pages. When you compute the results a second time, the program displays the result page displayed when you left the result pages the previous time.

Note that the physical quantities and the vehicle operating costs are given per 1000 vehicle-km.

Display the Input Data

The Data option displays the input data pages. Use this option, after computing the vehicle operating cost with the VOC option, to return to the input data pages.

While displaying the input data or the result pages, press the following keys to move among pages.

- Press PgDn to move to the next page.
- Press PgUp to move to the previous page.
- Press Home to move to the first page.
- Press End to move to the last page.
- Press a number to move to the corresponding page.

Enter a Title for the Reports or Tables

The Name option allows you to enter a title for the reports and tables. The program displays the current title at the bottom of the screen. Edit the title using the arrow keys or press the <Enter> key to retain its current value. After you enter the title, the program displays it at the top of the screen and prints it on each report or table.

Create Reports

The Reports

The Reports option creates the following reports (see Figure 6).

- Input Data Report. One page report with all the main input variables.
- Results Report. One page report with the roadway data, vehicle type, unit costs, and the results.
- Input Data Print-out. Two page print-out of all input variables.
- Results Print-out. Two page print-out of the results and other intermediate values.

Figure 6 - The Reports Menu

```
—| Reports |—————  
  
Your options are:  
  
1) Input Data Report  
2) Results Report  
3) Input Data and Results Reports  
4) Input Data Print-out  
5) Results Print-out  
6) Input Data and Results Print-out  
  
0) Return to the Main Menu  
  
Enter your selection:
```

Destination

You can print the reports or save the reports in ASCII text files (see Figure 7). Print the reports on a printer capable of printing 102 characters per line (12 pitch in an 8.5 inches wide paper). Note that to print the accents correctly in spanish, french, or portuguese the printer must be set to print the IBM US (PC8) Symbols Set or the Epson Extended Graphics Characters.

If you want to import the reports into your word processor, save the reports into ASCII text files. The program prompts for the filename of the ASCII text file to create and you should enter a valid DOS filename.

Figure 7 - Reports Destination Menu

```
—| Destination |—————  
  
Your options are:  
  1) Print the report  
  2) Save the report (ASCII text file)  
  0) Return to the Main Menu  
  
Enter your selection:
```

Create Tables

The Tables

The Tables option creates the following tables (see Figure 8).

- Roughness Sensitivity Table. Table of VOC sensitivity to roughness at three different levels of curvature.
- One Variable Sensitivity Table. Table of VOC sensitivity to any input variable.
- One Variable Sensitivity Chart. Chart of VOC sensitivity to any input variable.
- Two Variables Sensitivity Matrix. Matrix of VOC sensitivity to any two input variables.

Figure 8 - The Tables Menu

```
—| Tables |—————  
  
Your options are:  
  1) Roughness Sensitivity Table  
  2) One Variable Sensitivity Table  
  3) One Variable Sensitivity Chart  
  4) Two Variables Sensitivity Matrix  
  5) Vehicle Fleet Operating Costs Table  
  6) Vehicle Operating Costs Coefficients  
  0) Return to the Main Menu  
  
Enter your selection:
```

- **Vehicle Fleet Operating Costs Table.** Table of total VOC for a given vehicle fleet on a given road.
- **Vehicle Operating Costs Coefficients.** VOC sensitivity to roughness and coefficients relating total VOC to roughness.

The Requirement

Enter the roadway and vehicle characteristics for a vehicle type before creating the tables.

Destination

The Roughness Sensitivity Table, the One Variable Sensitivity Table, the Vehicle Operating Costs Fleet Table, and the Vehicle Operating Costs Coefficients can be displayed, printed or saved on ASCII files. You have the following options (see Figure 9).

- **Display the table.** Use this option to view the table on the screen.
- **Print the table.** Use this option to print the table on a printer capable of printing 102 characters per line.
- **Save the table (ASCII text file).** Use this option to import the table into your word processor.
- **Save the table (delimited ASCII format).** Use this option to import the table into Lotus 1-2-3.

Figure 9 - Tables Destination Menu

```
—| Destination |—————  
  
Your options are:  
  
1) Display the table  
2) Print the table  
3) Save the table (ASCII text file)  
4) Save the table (delimited ASCII format)  
  
0) Return to the Main Menu
```

If you select to save the table (ASCII text or delimited ASCII format), the program prompts for the filename and you should enter a legitimate DOS filename. Note that ASCII text files can have any extension but delimited ASCII files should have a .PRN extension to be imported into Lotus 1-2-3.

If you want to import a table into your word processor, use the import ASCII file option of your word processor. If you want to import a table into Lotus 1-2-3, use the / (F)ile (I)mport (N)umbers option of Lotus 1-2-3. Follow the steps below.

- Create a table and save it in delimited ASCII format.
- Name the table using .PRN for the filename extension.
- Load Lotus 1-2-3.
- Change to the VOC directory with the / (F)ile (D)irectory option.
- Import the table with the / (F)ile (I)mport (N)umbers option.

Roughness Sensitivity Table

This table contains the following information (see Figure 10):

- The roadway characteristics and vehicle type.
- The sensitivity of total VOC and vehicle speed to roughness at three different levels of horizontal curvature.
- The cost breakdown (in percentage of total VOC) of all VOC components.
- The comparison in percentage (C) of the total VOC computed at each roughness level against the total VOC computed at roughness 2.0 IRI.

Note that the vehicle operating costs are given per 1000 vehicle-km.

Figure 10 - Roughness Sensitivity Table

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0

Small Car Sample Data

One Variable Sensitivity Table

The One Variable Sensitivity Table contains the following information (see Figure 11)

- The roadway characteristics and vehicle type.

- The sensitivity of total VOC and vehicle speed to any input variable.
- The cost breakdown (in percentage of total VOC) of all VOC components.
- The comparison in percentage (C) of the total VOC computed at each level of the variable selected against the total VOC computed using a selected comparison value.

Note that the vehicle operating costs are given per 1000 vehicle-km.

Figure 11 - One Variable Sensitivity Table

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0

Small Car Sample Data

Sensitivity Table

Variable : Average roughness (IRI) m/km

Minimum value: 2

Maximum value: 4

Interval : .5

Comparison : 3

Cost Breakdown by Percentage and Total VOC per 1000 vehicle-km

VARIABLE	FUEL	LUBR	TIRE	CREW	PASS	CARG	M.L.	M.P.	DEPR	INTE	OVER	TOTAL	SPEED	C
	%	%	%	%	%	%	%	%	%	%	%	VOC	km/hour	%
2.00	23.7	2.4	3.1	0.9	0.0	0.0	4.3	9.5	30.6	18.4	0.0	115.1	87	-3
2.50	23.4	2.5	3.3	0.8	0.0	0.0	4.4	10.2	30.2	18.2	0.0	116.9	87	-2
3.00	23.1	2.5	3.4	0.7	0.0	0.0	4.6	11.0	29.7	18.0	0.0	118.7	87	0
3.50	22.8	2.6	3.5	0.6	0.0	0.0	4.7	11.8	29.3	15.8	0.0	120.7	87	2
4.00	22.4	2.6	3.6	0.4	0.0	0.0	4.9	12.7	28.8	15.5	0.0	122.8	86	3

When you select this option, the program displays a list of all input variables (see Figure 12). Enter the number of the variable you wish to use and for this variable enter a minimum value, maximum value, an interval between points to compute, and a comparison value.

For example:

Select variable number 1 (Average roughness)

For roughness, enter:

minimum value equal to 2

maximum value equal to 4

interval equal to 0.5

comparison value equal to 3

Note: The program does not check if your inputs are outside a normal range. Therefore, make sure you enter consistent values for the variable selected.

One Variable Sensitivity Chart

This option creates a chart of VOC sensitivity to any input variable (see Figure 13). When you select this option, the program displays a list of all input variables. Enter the variable number of the variable you wish to use and for this variable enter a minimum and maximum value.

Figure 12 - List of Variables

List of Variables						
1	Average roughness (IRI)	23	Wear coefficient of tread	45	CLp	Mp
2	Average positive gradient	24	Average annual utilization	46	CLq	Mp
3	Average negative gradient	25	Average annual utilization	47	CLo	Vc
4	Proportion of uphill trav	26	Hourly utilization ratio	48	FRAT100	LV
5	Average horizontal curvat	27	Average service life	49	FRAT101	VR
6	Average superelevation	28	Age of vehicle in kilomet	50	ARYMAX	YC
7	Altitude of terrain	29	Passengers per vehicle	51	BV	VD
8	Tire weight	30	New vehicle price	52	BETA	Sp
9	Load carried	31	Fuel cost	53	ED	Sp
10	Maximum used driving pore	32	Lubricants cost	54	A0	Sp
11	Maximum used braking pore	33	New Tire cost	55	A1	Fu
12	Desired speed	34	Crew time cost	56	A2	Fu
13	Aerodynamic drag coeffici	35	Passenger delay cost	57	A3	Fu
14	Projected frontal area	36	Maintenance labor cost	58	A4	Fu
15	Calibrated engine speed	37	Cargo delay cost	59	A5	Fu
16	Energy-efficiency factor	38	Annual interest rate	60	A6	Fu
17	Fuel adjustment factor	39	Overhead per vehicle-km	61	A7	Fu
18	Number of tires per vehic	40	KP	Maintenance ps	62	N40
19	Wearable volume of rubber	41	CPo	Maintenance ps	63	RCD Rolling r
20	Retreading cost per new t	42	CPe	Maintenance ps	64	RSL Rolling r
21	Maximum number of recaps	43	QIPe	Maintenance ps	65	Vehicle speed
22	Constant term of tread we	44	CLo	Maintenance ps	66	

For example:

Select variable number 1 (Average roughness)

For roughness, enter:

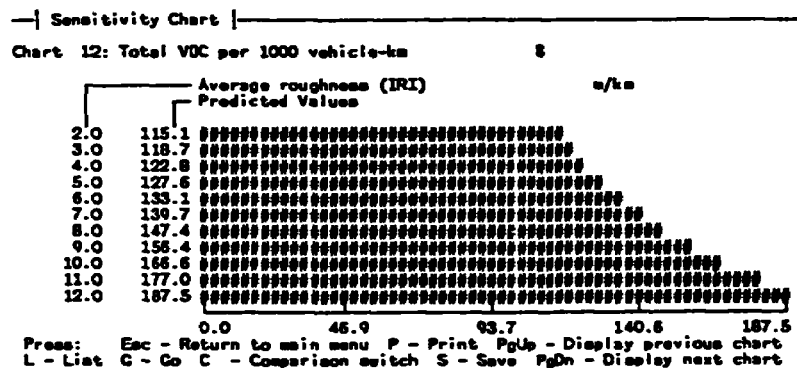
minimum value equal to 2

maximum value equal to 12

Note: The program does not check if your inputs are outside a normal range. Therefore, make sure you enter consistent values for the variable selected.

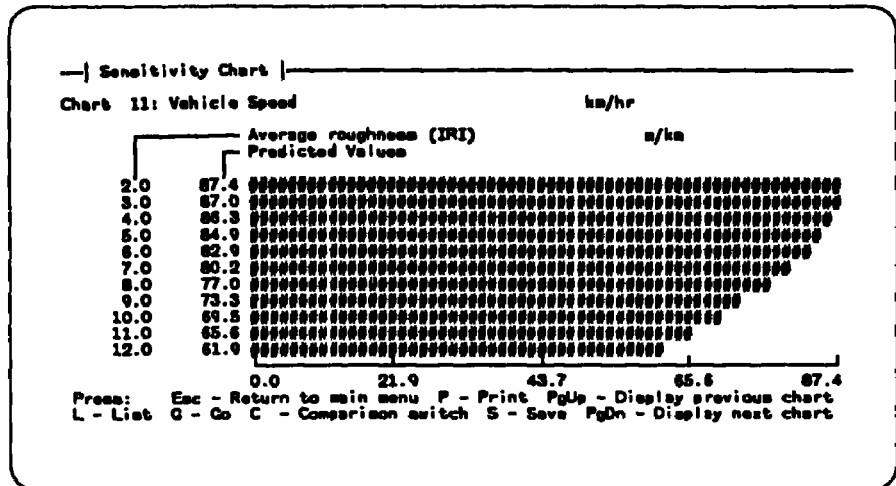
The program computes the results on eleven points between the minimum and maximum values and displays a chart of total VOC as a function of the variable selected and a menu.

Figure 13 - VOC Sensitivity Chart



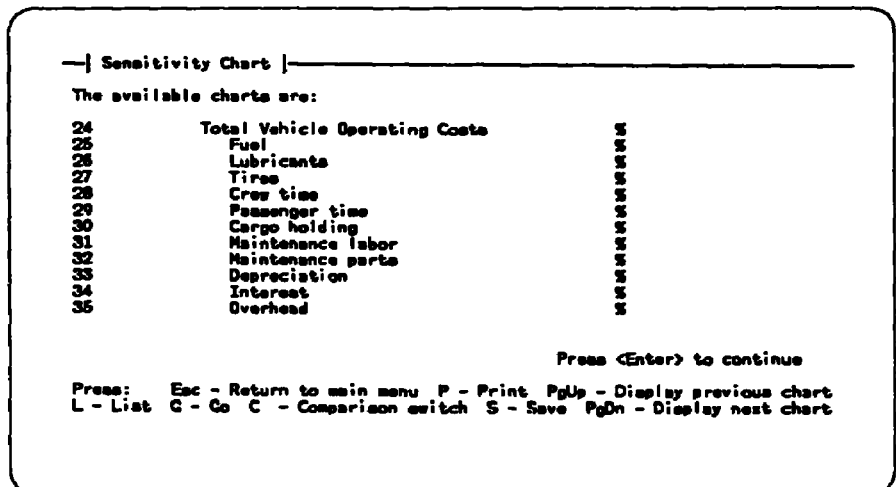
The program also stores the charts for vehicle speed, the physical quantities of consumption, the operating costs of each VOC component, and other intermediate values. To display any of these charts, use the PgUp, PgDn, Home, and End keys (see Figure 14).

Figure 14 - Vehicle Speed Sensitivity Chart



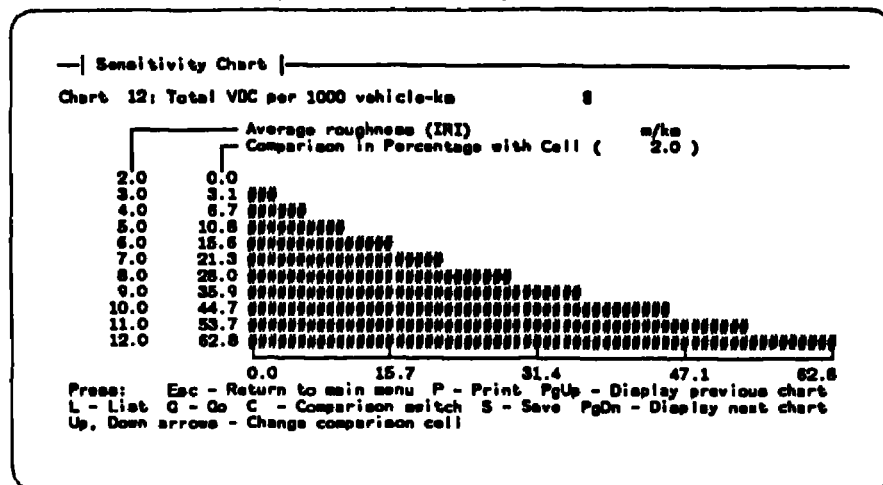
To obtain a list of all available charts, press the letter L (see Figure 15). The program displays the list in six pages.

Figure 15 - List of Charts



To compare the predicted values on any chart, press the letter C (Comparison switch). The program displays the comparisons and adds new options to the Sensitivity Chart Menu (see Figure 16). When you press the letter C for the first time, the program computes the comparison (in percentage) of each predicted value against the predicted value of the minimum value.

Figure 16 - VOC Comparison Chart



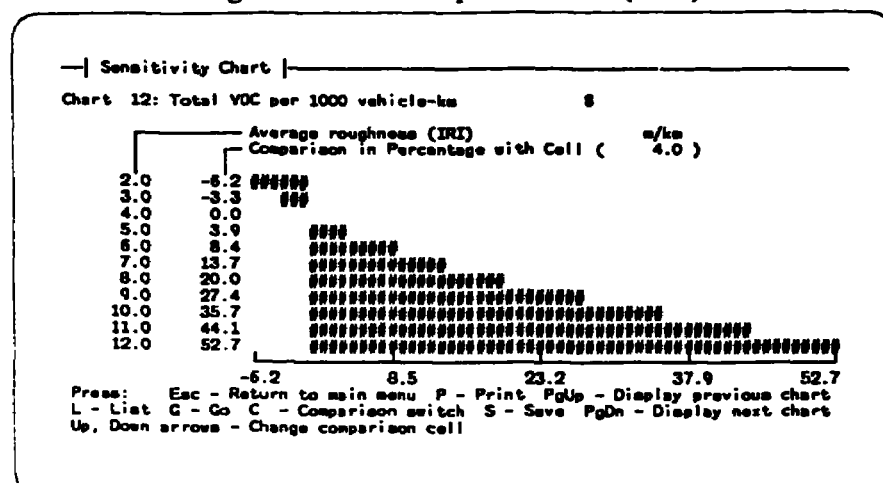
While displaying the comparisons, you can change the comparison line using the Up and Down arrow keys (see Figure 17). To return to the predicted values chart, press the letter C (Comparison switch) again.

To return to the Main Menu, press the Esc key. To print the displayed chart, press the letter P (Print). To save the chart in delimited ASCII format, press the letter S (Save). This file can be later imported into Lotus 1-2-3. To import the file in Lotus 1-2-3, use the / (F)ile (I)mport (N)umbers option of Lotus 1-2-3.

Two Variables Sensitivity Matrix

This option creates a matrix of VOC sensitivity to any two input variables. When you select this option, the program displays a list of all input variables (see Figure 18). Enter the variable number of the first variable you wish

Figure 17 - VOC Comparison Chart (4 IRI)



To compare the predicted values on any matrix, press the letter C (Comparison switch). The program displays the comparisons and adds new options to the Sensitivity Matrix Menu (see Figure 21). When you press the letter C for the first time, the program computes the comparison (in percentage) of each predicted value against the predicted value in column 1, row 1.

While displaying the comparisons, you can change the comparison cell using the arrow keys (see Figure 22). To return to the predicted values, press the letter C (Comparison switch) again.

Figure 22 - VOC Comparison Matrix (40 curv., 4 IRI)

— Sensitivity Matrix —								
Matrix 12: Total VOC per 1000 vehicle-km								
Comparison in Percentage with Cell (40.0 , 4.0)								
	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0
0.0	-6.34	-3.44	-0.11	3.77	8.30	13.63	19.89	27.25
20.0	-6.31	-3.41	-0.08	3.80	8.33	13.65	19.92	27.28
40.0	-6.23	-3.33	0.00	3.87	8.40	13.73	19.99	27.34
60.0	-6.12	-3.22	0.11	3.98	8.51	13.83	20.09	27.44
80.0	-5.97	-3.07	0.25	4.13	8.65	13.97	20.22	27.56
100.0	-5.80	-2.90	0.43	4.30	8.82	14.13	20.37	27.70
120.0	-5.60	-2.70	0.63	4.49	9.01	14.32	20.55	27.86
140.0	-5.38	-2.48	0.85	4.71	9.22	14.52	20.74	28.04

Columns : Average roughness (IRI) m/km
 Rows : Average horizontal curvature deg/km

Press: Esc - Return to main menu P - Print PgUp - Display previous chart
 L - List G - Go C - Comparison switch S - Save PgDn - Display next chart
 Up, Down, Left, and Right arrows - Change comparison cell

To print the displayed matrix, press the letter P (Print). To save the matrix in delimited ASCII format, press the letter S (Save) and to import the matrix into Lotus 1-2-3, use the / (F)ile (I)mport (N)umbers option of Lotus 1-2-3.

To return to the Main Menu, press the Esc key.

Vehicle Fleet Operating Costs Table

This option computes the total VOC of a vehicle fleet using the roadway information defined on page 1 and vehicle characteristics stored in disk files. The preliminary steps required to create this table are the following.

- Enter the roadway and vehicle characteristics for a vehicle type and save the input data into a disk file (see Save the Input Data).
- Repeat the step above for each vehicle type on the fleet, saving the input data under different filenames.

To prepare the table, enter the filename and the Average Daily Traffic (ADT) of each vehicle type on the fleet, using option 1 of the Vehicle Fleet Menu (see Figure 23).

After selecting option 1, use the following keys to enter the filenames and the ADT, move among vehicles, switch among filenames and ADT columns, and to return to the Vehicle Fleet Menu.

Figure 23 - Vehicle Fleet Menu

```

—| Vehicle Fleet Table |—————
Vehicle  Filename                                Average Daily Traffic (ADT)
1
2
3
4
5
6
7
8
9
10
-----
Your options are:
1) Edit filenames and Average Daily Traffic (ADT)
2) Compute the Vehicle Fleet Table
0) Return to the Main Menu

```

Key	Action
<Enter>	Accept change and move to next vehicle.
Up arrow	Move to previous vehicle.
Down arrow	Move to next vehicle.
Tab	Switch between filenames and ADT columns.
Esc	Return to the Vehicle Fleet Menu.

If you enter an invalid DOS filename, the program rejects it, and if you do not enter the filename extension, the program adds the default extension for input data files (.VOC).

Figure 24 - Example of Vehicle Fleet Data

```

—| Vehicle Fleet Table |—————
Vehicle  Filename                                Average Daily Traffic (ADT)
1         car.voc                                700
2         bus.voc                                50
3         medium.voc                             250
4
5
6
7
8
9
10
-----
<Enter> - Accept change
Up arrow - Move to previous line
Down arrow - Move to next line
Tab       - Switch between filenames and Average Daily Traffic (ADT)
Esc       - Return to the vehicle fleet menu

```

An example of vehicle fleet data, using the sample data files supplied with the VOC package, is given in Figure 24

After entering the filenames and the ADT, compute Vehicle Fleet Table, using option 2 of the Vehicle Fleet Menu. The program computes the VOC using the vehicle characteristics stored in the disk files and the roadway information defined on page 1. Change any variable on page 1 and compute the fleet VOC again to obtain the corresponding results. The vehicle fleet table contains the following information (see Figure 25).

- The roadway characteristics.
- The filenames and the ADT for each vehicle.
- The VOC and the speed for each vehicle and the total VOC of the fleet.

Note that in this table the VOC is given per km.

Figure 25 - Vehicle Fleet Table

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0

Small Car Sample Data

Vehicle Fleet Table

Average positive gradient	0.00	Surface type	1
Average negative gradient	0.00	Effective number of lanes	0
Proportion of uphill travel	50.00	Altitude of terrain	0.00
Average roughness (IRI)	2.50		

Vehicle	Filename	Average Daily Traffic
1	car.voc	700.00
2	bus.voc	50.00
3	medium.voc	250.00
TOTAL		1,000.00

Cost Breakdown by Percentage and Total VOC per km

VEHICLE	FUEL	LUBR	TIRE	CREW	PASS	CARG	N.L.	N.P.	DEPR	INTE	OVER	TOTAL	SPEED
	%	%	%	%	%	%	%	%	%	%	%	VOC	km/hour
1	23.4	2.5	3.3	9.8	0.0	0.0	4.4	10.2	30.2	16.2	0.0	81.8	67
2	17.9	1.0	3.9	6.8	27.2	0.0	2.9	11.6	13.1	5.4	10.1	24.8	74
3	30.3	1.8	9.0	12.4	1.2	0.0	4.0	13.4	15.1	5.7	7.0	71.0	71
TOTAL	25.4	2.0	5.6	10.4	4.3	0.0	4.1	11.7	21.8	10.5	4.2	177.6	

Vehicle Operating Costs Coefficients

This option produces a table of VOC sensitivity to roughness and uses this table to compute regression coefficients for the following two alternative equations that relate roughness to total VOC (see Figure 26).

$$\text{Total VOC} = a + b * \text{IRI} + c * \text{IRI}^2$$

$$\text{Total VOC} = \exp(a + b * \text{IRI})$$

Note that in this table and for the above equations, VOC is given per km.

Figure 26 - Vehicle Operating Costs Coefficients

FREE-FLOW VEHICLE OPERATING COSTS MODEL version 4.0														
Small Car Sample Data														
Vehicle Operating Cost Coefficients														
Average positive gradient	0.00	Surface type	1											
Average negative gradient	0.00	Effective number of lanes	0											
Proportion of uphill travel	50.00	Altitude of terrain	0.00											
Average horizontal curvature	0.00	Average superelevation	0.0000											
Small car														
Cost Breakdown by Percentage and Total VOC per vehicle-km														
IRI	FUEL	LUBR	TIRE	CREW	PASS	CARGO	M.L.	M.P.	DEPR	INTE	OVER	TOTAL	SPEED	
m/	%	%	%	%	%	%	%	%	%	%	%	VOC	km/	hour
km												\$		
21	23.7	2.4	3.1	9.9	0.0	0.0	4.3	9.5	30.6	16.4	0.0	0.1151	87	
31	23.1	2.5	3.4	9.7	0.0	0.0	4.6	11.0	29.7	16.0	0.0	0.1187	87	
41	22.4	2.6	3.6	9.4	0.0	0.0	4.9	12.7	28.8	15.5	0.0	0.1228	86	
51	21.6	2.7	3.8	9.2	0.0	0.0	5.2	14.6	27.8	15.1	0.0	0.1276	85	
61	20.6	2.8	4.0	9.1	0.0	0.0	5.5	16.7	26.8	14.6	0.0	0.1331	83	
71	19.4	2.8	4.1	8.9	0.0	0.0	5.8	19.0	25.8	14.2	0.0	0.1397	80	
81	18.2	2.8	4.2	8.8	0.0	0.0	6.0	21.5	24.7	13.7	0.0	0.1474	77	
91	16.9	2.8	4.2	8.7	0.0	0.0	6.2	24.2	23.6	13.3	0.0	0.1564	73	
101	15.7	2.8	4.2	8.6	0.0	0.0	6.4	27.0	22.5	12.9	0.0	0.1666	69	
111	14.6	2.7	4.2	8.6	0.0	0.0	6.6	29.4	21.5	12.5	0.0	0.1770	66	
121	13.6	2.7	4.2	8.6	0.0	0.0	6.8	31.5	20.6	12.2	0.0	0.1875	62	
131	12.7	2.7	4.2	8.7	0.0	0.0	6.7	33.3	19.8	12.0	0.0	0.1981	58	
141	12.0	2.6	4.2	8.7	0.0	0.0	6.7	35.0	19.1	11.8	0.0	0.2099	55	
151	11.3	2.6	4.2	8.8	0.0	0.0	6.7	36.5	18.4	11.6	0.0	0.2197	52	
161	10.7	2.6	4.0	8.8	0.0	0.0	6.7	37.8	17.8	11.5	0.0	0.2303	49	
171	10.2	2.6	3.9	8.9	0.0	0.0	6.7	39.1	17.3	11.4	0.0	0.2408	47	
181	9.9	2.5	3.7	9.0	0.0	0.0	6.6	40.2	16.8	11.3	0.0	0.2515	44	
191	9.7	2.5	3.5	9.0	0.0	0.0	6.6	41.2	16.3	11.1	0.0	0.2629	42	
201	9.6	2.5	3.4	9.1	0.0	0.0	6.5	42.0	15.8	11.0	0.0	0.2743	40	
Equation: $VOC = a + b \cdot IRI + c \cdot IRI^2$														
a	=											.1018502		
b	=											4.317959E-03		
c	=											2.232901E-04		
R2	=											.9979957		
Std Err	=											2.486050E-03		
Equation: $VOC = EXP(a + b \cdot IRI)$														
a	=											-2.300476		
b	=											5.121976E-02		
R2	=											.9963841		
Std Err	=											1.786677E-02		

List Files on Disk

The Files option lists the files stored in a floppy disk or a hard disk directory. The program prompts for the file specifications and you should provide a legitimate DOS filespec (you can include the global filename characters ? and *). If you press the <Enter> key, the program list all files in the current disk and directory.

For example:

Enter	To
<Enter>	List all files in current disk and directory
A:\	List all files in drive A:
*.VOC	List all .VOC files in current disk and directory

A:*.PRN	List all .PRN files in drive A:
C:\VOC*.*	List all files in directory VOC
C:\DATA\Z*.*	List all files that begin with Z in directory DATA
?V??????.*	List all files with the second character V

Set all Input Variables to Zero

The Clear option resets all input variables to zero and erases the title. Make sure to save your input data before using this option.

Quit the Program

The Quit option ends the program. Make sure to save your input data before using this option.

Chapter 4

The HDM-VOC Relationships

This chapter describes the relationships used by the HDM-VOC model. The set of relationships are those derived from the Brazil study by GEIPOT, the Texas Research and Development Foundation, and the World Bank (GEIPOT, 1982; Chesher and Harrison, 1987; Watanatada, *et al.*, 1987). The following sections are a summary and adaptation of the information contained in the following World Bank publications:

- Watanatada, T., A. Dhareshwar, and P.R.S. Rezende-Lima. *The Highway Design and Maintenance Standards Model, Volume II, Vehicle Speeds and Operating Costs: Models for Road Planning and Management*. Washington, D.C.: Transportation Department, World Bank, 1987.
- Watanatada, T. and others. *The Highway Design and Maintenance Standards Model, Volume I, Description of the HDM-III Model*. Washington, D.C.: Transportation Department, World Bank, 1987.
- Chesher, A. and R. Harrison. *The Highway Design and Maintenance Standards Model, Volume I, Vehicle Operating Costs: Evidence from Developing Countries*. Washington, D.C.: Transportation Department, World Bank, 1987.

Refer to these publications for a complete description of the model relationships, information on parameter estimations, model transferability, and model calibration.

The Steps

The steps followed by the model to compute the vehicle operating cost for a given vehicle type are the following:

1. Compute the average operating speed for the vehicle.
2. Compute the amount of resources used per 1000 vehicle-km for the following components:
 - Fuel consumption
 - Lubricant consumption
 - Tire wear
 - Crew time
 - Passenger time
 - Cargo holding
 - Maintenance labor
 - Maintenance parts
 - Depreciation
 - Interest
 - Overhead
3. Apply unit costs to the resource consumption amounts to get the operating cost per 1000 vehicle-km for each component.
4. Sum the operating cost for each component to compute the total vehicle operating cost per 1000 vehicle-km.

Note that on this version of the HDM-VOC model (4.0), the user has the option of specifying the vehicle speed. In previous versions of the VOC model and on the HDM-III model, the vehicle speed is always computed by the model following the Brazil equations.

The following sections describe the relationships used by the model to compute the vehicle speed, resources used, and operating costs.

Vehicle Speed

The prediction of vehicle speed is an aggregate probabilistic limiting velocity approach to steady-state speed prediction. Note the following:

- a) Aggregate implies that the prediction method works with aggregate descriptors of road geometry and surface condition rather than with detailed information about the road.
- b) Steady-state implies that the model does not consider the transitional effects, that is, speed-change cycles along the road.
- c) Probabilistic limiting velocity approach because the predicted speed is a probabilistic minimum of several limiting or constraining speeds.

The Steady-State Speed

The prediction of a vehicle's steady-state speed on a given road segment uses a set of limiting (or "constraining") speeds, corresponding to several different factors that tend to limit the speed. The constraining speeds are a function of such factors as characteristics of the vehicle (for example: engine power, braking capacity, load carried) and of the road (for example: vertical gradient, roughness, curvature). The constraining speeds are:

- **VDRIVE**, the limiting speed based on vertical gradient and engine power.
- **VBRAKE**, the limiting speed based on vertical gradient and braking capacity.
- **VCURVE**, the limiting speed determined by road curvature.
- **VROUGH**, the limiting speed based on road roughness and associated ride severity.
- **VDESIR**, the desired speed without constraints, based on psychological, economic, safety, and other considerations.

For example: For a large car traveling on a paved level segment with curvature equal to 200 degrees/km and roughness = 4.5 IRI, the constraining speeds could be:

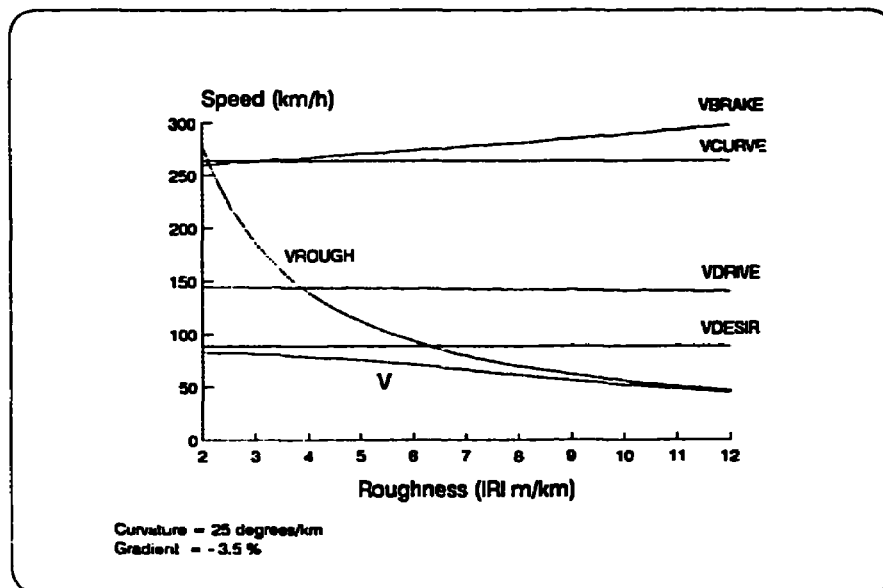
VDRIVE = 148 km/h
 VBRAKE = ∞
 VCURVE = 103 km/h
 VROUGH = 181 km/h
 VDESIR = 98 km/h

giving a predicted steady-state speed. $V_s = 80$ km/h.

The following plots illustrate the constraining speeds and the resulting steady-state speed on a paved segment for a heavy truck carrying a net load of 6,000 kg. Each of the plots shows the constraining speeds and the predicted steady-state speed (V) as we vary one speed-influencing factor and maintain constant the remaining factors. The speed-influencing factors observed are: a) Roughness varying from 2 to 12 IRI m/km, b) Gradient varying from -10 to 10 percent, and c) Curvature varying from 0 to 500 degrees/km.

Figure 27a shows the effect of surface condition on the steady-state

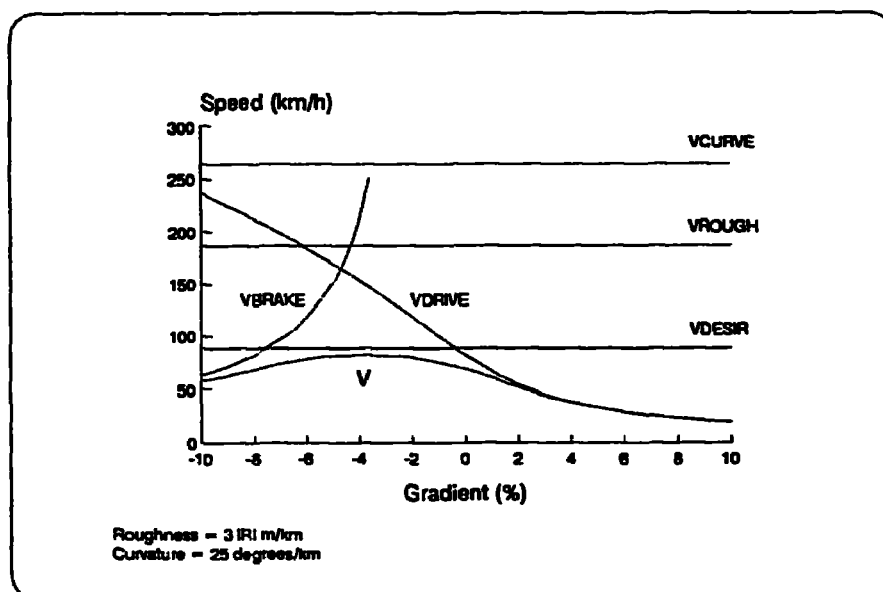
Figure 27a - Surface Condition



speed for a straight and downward-slope segment. At any given point on the roughness axis, the limiting speed with the lowest value is the "binding" speed as it exercises the predominant influence on the resulting steady-state speed at that point; other limiting speeds have only marginal effects. The higher the value of the limiting speed, the more marginal its influence on the predicted steady-state speed. In this instance, over the lower range of road roughness (below 6.5 IRI), the desired speed (VDESIR) becomes the binding speed and on the upper range, VROUGH becomes the binding speed. Note that roughness has no influence over VDESIR and VCURVE, but has a slight influence on the gravity-related constraining speeds, VDRIVE and VBRAKE through the rolling resistance coefficient.

Figure 27b shows the effect of vertical alignment on the steady-state speed for a slightly curved and low roughness segment. In this figure, three different constraining speeds are binding over the -10.0 to +10.0 percent range of the road gradient. On the one extreme, for negative grades steeper

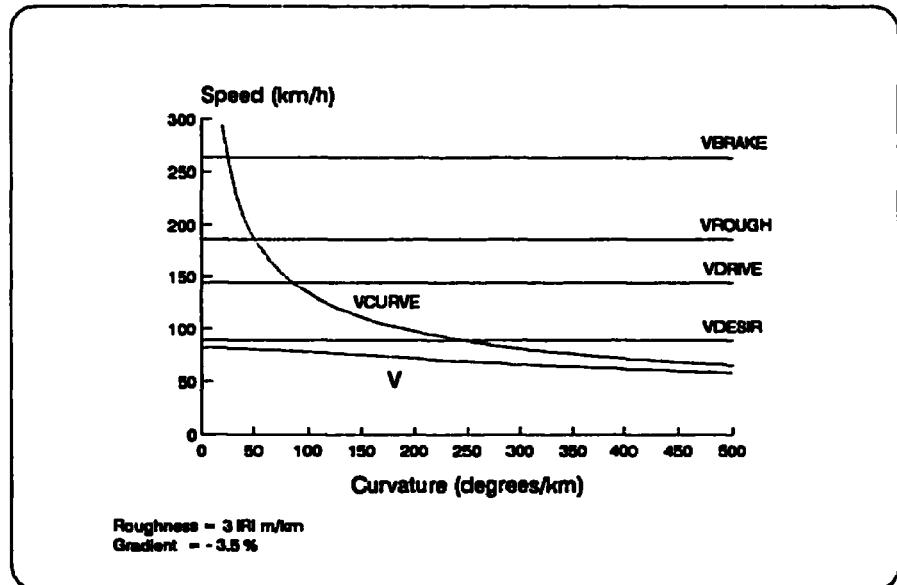
Figure 27b - Vertical Alignment



than 7.5 percent, the limiting speed based on braking capacity (VBRAKE) is binding. At the opposite end, for slightly negative (-0.2 percent) and positive gradients the limiting speed based on engine power (VDRIVE) becomes dominant. In the mid-range the desired speed (VDESIR) determines the steady-state speed. Note that for slightly negative and positive grades, the value of VBRAKE is infinity, that is, it has no influence on the resulting steady-state speed over this range, while road gradient has no influence on VDESIR, VCURVE, and VROUGH.

Figure 27c shows the effect of horizontal alignment on the steady-state speed for a smooth and downward-slope segment. In this case two constraining speeds are binding. The desired speed (VDESIR) is the primary deter-

Figure 27c - Horizontal Alignment



minant over curvature up to 250 degrees/km, beyond which the curvature speed (VCURVE) constraint prevails. Note that VDESIR, VBRAKE, VDRIVE and VROUGH are all independent of horizontal alignment.

The model computes the predicted steady-state speed (V) for the segment using the respective values of the five limiting speeds for each road segment. The theory behind these computations involves treating each of the limiting speeds for a segment as a random variable and the resulting steady-state speed prediction as the average value of the minimum of these random variables. The probability model used is the Weibull distribution which is one of the standard "extreme value" distributions. The formulas are:

$$V_u = E_0 / [(1/V_{DRIVEu})^{1/\beta} + (1/V_{BRAKEu})^{1/\beta} + (1/V_{CURVE})^{1/\beta} + (1/V_{ROUGH})^{1/\beta} + (1/V_{DESIR})^{1/\beta}]^\beta$$

$$V_d = E_0 / [(1/V_{DRIVED})^{1/\beta} + (1/V_{BRAKEd})^{1/\beta} + (1/V_{CURVE})^{1/\beta} + (1/V_{ROUGH})^{1/\beta} + (1/V_{DESIR})^{1/\beta}]^\beta$$

$$V = 3.6 / [(LP / V_u) + (1 - LP) / V_d]$$

V_u is the predicted vehicle speed for the uphill segment, in m/s.

V_d is the predicted vehicle speed for the downhill segment, in m/s.

V is the vehicle speed in km/hour.

LP is the proportion of uphill travel expressed as a fraction. Note that the program collects LP as a percentage.

3.6 is the conversion factor from m/s to km/h.

E_0 is the bias correction factor.

BETA (β) is the Weibull distribution shape parameter.

In the above formulas, the subscripts u and d stand for the uphill and downhill segment, respectively. Note that only the two constraining velocities involving vertical gradient carry these subscripts.

The coefficient BETA (β) determines the shape of the assumed Weibull distribution and is a member of the set of parameters estimated for each type of vehicle. As the estimation involved a logarithmic transformation of the variables, the prediction formulas include the bias correction factor E_0 based on the standard error of residuals in the estimation. Table 1 lists the numerical values of BETA (β) and E_0 , as estimated from the Brazil data set.

If the user decides to specify the vehicle speed, the model performs the following steps to compute the corresponding uphill and downhill segments speeds:

1. Computes a base downhill segment speed and a base uphill segment speed for the given roadway and vehicle characteristics using the same Brazil equations described above.
2. Computes the ratio between the base uphill speed and the base downhill speed.
3. Computes the corresponding uphill speed and the downhill speed by considering the ratio between the uphill speed and downhill speed to be the same as the ratio of the base uphill speed and base downhill speed.

The equations used are the following:

$$VRATIO = VBASEu / VBASEd$$

$$V = VSPEC$$

$$Vu = VSPEC (LP + (1-LP) VRATIO) / 3.6$$

$$Vd = Vu / VRATIO$$

$VBASEu$ is the base uphill speed in m/s.

$VBASEd$ is the base downhill speed in m/s.

$VSPEC$ is the specified vehicle speed in km/hour.

VDRIVEu and VDRIVED

VDRIVE, the speed limited by driving power for a given road segment as determined by power and gradient, derives from the hypothesis that the vehicle is driven at steady-state speed on a smooth, straight road using a high level of power called the driving power, HPDRIVE. Maximum used driving power was found generally to be less than the rated power of the engine, especially for gasoline engine vehicles. Reasons for the difference are largely behavioral (unwillingness of drivers to use full power) and perhaps partly mechanical (operation at less than rated rpm, power lost in the transmission and used by accessories).

VDRIVE relates to HPDRIVE and the gradient through the balance of forces without acceleration:

$$[\text{Drive force}] = [\text{Rolling resistance}] + [\text{Grade resistance}] + [\text{Air resistance}]$$

where the various terms, all measured in newtons, are given by the following expressions:

$$\text{Drive force} = 736 \text{ HPDRIVE} / \text{VDRIVE}$$

$$\text{Rolling resistance} = g \text{ GVW CR}$$

$$\text{Grade resistance} = g \text{ GVW GR}$$

$$\text{Air resistance} = 0.5 \text{ RHO CD AR VDRIVE}^2$$

736 is the number of watts in one metric hp.

GVW is the gross vehicle weight, in kg.

g is the gravitational constant, equal to 9.81 m/s.

CR is the dimensionless coefficient of rolling resistance.

GR is the vertical gradient expressed as a fraction.

RHO is the mass density of air, in kg/m³.

CD is the dimensionless aerodynamic drag coefficient.

AR is the projected frontal area, in m².

Substituting these values in the force balance yields a cubic equation for VDRIVE that always has a single positive root. Thus, given values of HPDRIVE and the other variables listed above, the model computes a unique VDRIVE value. Solving the cubic equation with GR = positive gradient (PG) would yield the value of VDRIVEu, and solving with GR = - negative gradient (NG) would yield the value for VDRIVED. The steps are:

- 1) Compute the rolling resistance coefficient (CR):

The rolling resistance coefficient, CR, was found empirically to be a function of road roughness.

If the vehicle is a car or utility:

$$\text{CR} = 0.0218 + 0.0006071 \text{ RI}$$

If the vehicle is a bus or a truck:

$$\text{CR} = 0.0139 + 0.0002574 \text{ RI}$$

RI is the road roughness expressed in the International Roughness Index units, IRI (m/km).

- 2) Compute the mass density of air (RHO), in kg/m³:

$$\text{RHO} = 1.225 [1 - 2.26 \text{ ALT} / 100000]^{4.255}$$

ALT is the road altitude, defined as the elevation of the road above the mean sea level, in meters.

- 3) Compute the gross vehicle weight of the vehicle (GVW), in kg:

$$\text{GVW} = \text{TARE} + \text{LOAD}$$

TARE is the vehicle tare weight, in kg.

LOAD is the vehicle payload, in kg.

- 4) Compute the driving power-constrained speed for uphill travel, VDRIVEu, in m/s:

The cubic equation is:

$$0.5 \text{ RHO CD AR VDRIVE}_u^3 + \text{GVW } g (\text{CR} + \text{PG}) \text{ VDRIVE}_u - 736 \text{ HPDRIVE} = 0$$

PG is the positive gradient expressed as a fraction. Note that the program collects the positive gradient as a percentage.

First compute the following intermediate values:

$$A = 0.5 \text{ RHO CD AR}$$

$$B = \text{HPDRIVE } 736 / (2 A)$$

$$C_u = \text{GVW } g (\text{CR} + \text{PG}) / (3 A)$$

$$D_u = B^2 + C_u^3$$

The solution for the equation is:

$$\text{VDRIVE}_u = (D_u + B)^{1/3} - (D_u - B)^{1/3}$$

5) Compute the driving power-constrained speed for downhill travel, VDRIVE_d , in m/s:

The cubic equation is:

$$0.5 \text{ RHO CD AR VDRIVE}_d^3 + \text{GVW } g (\text{CR} - \text{NG}) \text{ VDRIVE}_d - 736 \text{ HPDRIVE} = 0$$

NG is the negative gradient expressed as a fraction. Note that the program collects the negative gradient as a percentage.

First compute the following intermediate values:

$$C_d = \text{GVW } g (\text{CR} - \text{NG}) / (3 A)$$

$$D_d = B^2 + C_d^3$$

The solution of the equation is:

If D_d is positive, then:

$$\text{VDRIVE}_d = (D_d + B)^{1/3} - (D_d - B)^{1/3}$$

If D_d is negative or zero, the roots are:

$$r = 2 (-C_d)^{1/2}$$

$$z = 1/3 \text{ arc cos } \{(-2 B) / (C_d r)\}$$

$$v_1 = r \cos(z)$$

$$v_2 = r \cos(z + 2 \pi / 3)$$

$$v_3 = r \cos(z + 4 \pi / 3)$$

since only one of the three roots is positive, set VDRIVE_d to the positive root.

$$\text{VDRIVE}_d = \max \{v_1, v_2, v_3\}$$

VBRAKE_u and VBRAKE_d

VBRAKE, the speed for a given road segment as limited by braking capacity and gradient, derives from the concept of "used braking power," which is a positive quantity, represented by HPBRAKE, in metric horse-

power units. The assumption underlying the concept is that the braking capacity, HPBRAKE, which depends on the vehicle type, limits the steady-state speed acquired on a long, smooth, straight downhill section.

On an uphill segment the braking capacity constraint does not apply. Conceptually, when the brakes are not used the value of VBRAKE is infinity and $1 / \text{VBRAKE}$ is zero. More generally, the constraint is not applicable whenever the vehicle needs positive engine power to move. This would be the case on a downhill segment if the rolling resistance is greater in absolute value than the gradient-resistance; in symbols, whenever $\text{CR} \geq \text{NG}$.

When the constraint applies, VBRAKE relates to HPBRAKE, as before, through the force balance:

$$[\text{Drive force}] = [\text{Rolling resistance}] + [\text{Grade resistance}] + [\text{Air resistance}]$$

However, since the braking capacity constraint is likely to become binding only for steep negative grades with low steady-state speeds, the model ignores without significant error the air resistance. Thus VBRAKE is computed with a first degree equation:

$$\text{VBRAKE}_{\text{u}} = \infty$$

if $\text{CR} \geq \text{NG}$:

$$\text{VBRAKE}_{\text{d}} = \infty$$

if $\text{CR} < \text{NG}$:

$$\text{VBRAKE}_{\text{d}} = 736 \text{ HPBRAKE} / [g \text{ GVW} (\text{CR} - \text{NG})]$$

VCURVE

VCURVE, the curvature-limited speed, is derived from the postulate that when curvature is significant the tendency of the wheels to skid limits the speed. A good indicator of the tendency to skid is the ratio of the side force on the vehicle to the normal force, FRATIO.

For the vehicle traveling at a steady-state speed V , the lateral or side force on the vehicle in the direction parallel to the road surface, LF, in newtons, is given by the following kinematic relationship:

$$\text{LF} = [\text{Centrifugal force}] + [\text{Gravitational force}]$$

$$\text{LF} = (\text{GVW } V^2 / \text{RC}) \cos \text{sp} - (\text{GVW } g) \sin \text{sp}$$

sp is the superelevation angle.

RC is the radius of curvature, in meters.

The force on the vehicle in the direction perpendicular to the road surface, the normal force represented by NF, in newtons, is given by:

$$\text{NF} = \text{GVW } g \cos \text{sp} + (\text{GVW } V^2 / \text{RC}) \sin \text{sp}$$

Since curve superelevation normally does not exceed 20 percent, use the following approximations:

$$\cos \text{sp} \approx 1$$

$$\sin \text{sp} \approx \text{SP}$$

SP is the superelevation expressed as a fraction.

consequently, the equations simplify to:

$$LF = (GVW V^2 / RC) - GVW g SP$$

$$NF = GVW g + (GVW V^2 / RC) SP$$

FRATIO, the "used perceived friction ratio" is given by the ratio of the lateral to the normal force:

$$FRATIO = LF / NF$$

Substituting the LF and NF equations and further simplifying by neglecting the term $(V^2 / g / RC) SP$, produces the equation:

$$FRATIO = (V^2 / g / RC) - SP$$

Solving for V, one has the curvature-limited speed constraint, VCURVE, expressed as:

$$VCURVE = [(FRATIO + SP) g RC]^{0.5}$$

The allowable value of FRATIO was derived as a function of the payload of the vehicle:

$$FRATIO = \max(0.02, FRATIO_0 - FRATIO_1 \text{ LOAD})$$

where $FRATIO_0$ and $FRATIO_1$ are parameters which depend on the vehicle type as well as the surface type of the road. Table 1 lists the values estimated from the Brazil data set for $FRATIO_0$ and $FRATIO_1$.

The radius of curvature, RC, is a simple function of average horizontal curvature:

$$RC = 180000 / [\pi \max(18 / \pi, C)]$$

C = the horizontal curvature, in degrees per km.

Note: For practical purposes the model considers the curvature-constrained speed only when the radius of curvature (RC) is smaller than 10000 meters.

If you do not supply values for superelevation, SP, the model estimates the superelevation from the following formulas:

$$SP = 0.012 C \quad \text{for paved roads}$$

$$SP = 0.017 C \quad \text{for unpaved roads}$$

These formulas are approximations to suggested design standards for typical speeds on these surfaces, and may be unrealistic for actual conditions in particular cases. Therefore, whenever possible you should provide superelevation values based on actual road geometry.

VROUGH

VROUGH, the roughness-limited speed constraint, derives from the "average rectified velocity" measure (ARV) that is recommended as an adequate measure of ride discomfort, or severity. ARV is defined in general for a given vehicle with a rigid rear-axle as the average rate or rear-axle suspension motion, more specifically as the rate of cumulative absolute displacement of the rear-axle relative to the vehicle body (in mm/s). ARV is related to the vehicle speed, V, by means of the following identity:

$$ARV = VARS$$

Table 1 - Defaults Values for Speed Prediction

	Small Car	Medium Car	Large Car	Utility	Bus	Light Gas Truck	Light Diesel Truck	Medium Truck	Heavy Truck	Articulated Truck
Representative vehicle make model	Volkswagen 1300	Chevrolet Opala	Chrysler Dodge Dart	Volkswagen Kombi	Merc. Benz O-362	Ford F-400	Ford F-4000	Merc. Benz 1113 2 axles	Merc. Benz 1113 3 axles	Scania 110/39
Tare weight TARE (kg)	980	1200	1650	1320	8100	3120	3270	5400	8800	14730
Payload LOAD (kg) Suggested values	400	400	400	900	4000					
Drag coefficient CD	0.48	0.50	0.48	0.48	0.86	0.70	0.70	0.85	0.85	0.83
Frontal area AR (m ²)	1.80	2.08	2.20	2.72	6.30	3.25	3.25	5.20	5.20	8.75
HPDRIVE (metric hp)	30	70	85	40	100	80	80	100	100	210
HPBRAKE (metric hp)	17	21	27	30	180	100	100	250	250	500
FRATIO ₀ Paved roads	0.268	0.268	0.268	0.221	0.233	0.253	0.253	0.282	0.282	0.178
FRATIO ₀ Unpaved roads	0.124	0.124	0.124	0.117	0.095	0.099	0.099	0.087	0.087	0.040
FRATIO ₁ Paved roads (10E-4)	0	0	0	0	0	0.128	0.128	0.094	0.094	0.023
FRATIO ₁ Unpaved roads	0	0	0	0	0	0	0	0	0	0
ARVMAX (mm/s)	259.7	259.7	259.7	236.7	212.8	184.0	184.0	177.7	177.7	130.9
VDESIR ₀ (km/h) Paved roads	98.3	98.3	98.3	94.9	83.4	81.8	81.8	88.8	88.8	84.1
VDESIR ₀ (km/h) Unpaved roads	82.2	82.2	82.2	78.3	68.4	71.9	71.9	72.1	72.1	48.6
BW single-lane	0.74	0.74	0.74	0.74	0.78	0.73	0.73	0.73	0.73	0.73
BW more than one	1	1	1	1	1	1	1	1	1	1
BETA (β)	0.274	0.274	0.274	0.308	0.273	0.304	0.304	0.310	0.310	0.244
E _p	1.003	1.003	1.003	1.004	1.012	1.008	1.008	1.013	1.013	1.018

where ARS is the "average rectified slope" measure, defined as the amount of rear-axle suspension motion per unit travel distance (in mm/m or m/km). For modelling purposes ARV and ARS measures are those of the "calibrated" standard Maysmeter-equipped Opala passenger car used in the Brazil study.

The ARS measure is related to IRI, the international roughness index, through the following relationship:

$$ARS = 1.1466 RI$$

RI is the road roughness expressed in the International Roughness Index units, IRI (m/km).

1.1466 is a constant for unit conversion.

The constraining speed due to ride severity, $VROUGH$, is governed by the maximum practical ARV, called $ARVMAX$, as follow:

$$VROUGH = ARVMAX / 1.1466 / RI$$

where $ARVMAX$ is an estimated parameter. Table 1 lists the values of $ARVMAX$, as estimated from the Brazil data set .

VDESIR

VDESIR is the desired speed constraint, i.e. the speed at which a vehicle is assumed to be operated without the constraints based on the vertical grade, curvature, and roughness. The desired speed results from the driver's response to psychological, safety, economic, and other considerations.

The Brazil study considers, for each surface type (i.e. paved or unpaved), VDESIR to be a constant for each vehicle type. However, for narrow roads (that is, those with effective number of lanes equal to one or single-lane roads), the model assumes VDESIR to be lower. The following formulas were adopted, based on an analysis of speed data from India.

$$VDESIR = VDESIR_0 BW$$

$VDESIR_0$ is the unmodified user-specified value of the desired speed, in km/h.

BW is the width effect parameter applicable to single-lane roads.

Table 1 lists the originally estimated values of $VDESIR_0$, as estimated from the Brazil data set, and the values of BW.

Fuel Consumption

The program expresses the fuel consumption per 1000 vehicle-km (FL) as the number of liters consumed per 1000 vehicle-km. The fuel consumption cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = FL \text{ fuel cost per liter}$$

The fuel consumption prediction model uses of the concept of time-rate fuel consumption or unit fuel consumption, represented by UFC (in ml/s). Basic principles of internal combustion engine suggest that, under idealized environmental conditions, the unit fuel consumption is a function of power output (HP, in metric hp) and engine speed (RPM, in rpm).

For a vehicle operating on a given road section of specified geometry alignment, the average fuel consumption, FL, in liters/1000 vehicle-km is given by:

$$FL = 1000 \alpha_1 \alpha_2 (UFC_u LP / V_u + UFC_d (1-LP) / V_d)$$

UFC_u is the predicted unit fuel consumption for the uphill segment, in ml/s.

UFC_d is the predicted unit fuel consumption for the downhill segment, in ml/s.

LP is the proportion of uphill travel expressed as a fraction.

α_1 is the relative energy-efficiency factor.

α_2 is the fuel adjustment factor.

V_u, V_d are the estimated speeds in m/s.

Since the test vehicles used in the Brazil study are makes and models typical in the mid-1970s, a "relative energy-efficiency factor," represented by α_1 , has been introduced to allow to incorporate changes in vehicle technology. This factor has a value of 1.0 for makes and models close to the ones employed in the Brazil study. However, you may specify lower values for newer, more fuel-efficient vehicles. For passenger cars, the following energy-efficiency factors are recommended for late-1980s vehicles and are the defaults of the HDM-VOC model:

Small car	0.7
Medium car	0.4
Larger car	0.4

To account for the differences between experimental conditions and real life driving conditions, a "fuel adjustment factor", represented by α_2 has been introduced. The model uses as default, the values determined by calibrating the mechanistic fuel prediction model to the Brazil road user cost survey data. It is 1.16 for cars and utilities, and 1.15 for buses and trucks.

While it is not possible to deduce the precise form of the UFC function from theoretical considerations, the function is known to be convex in both arguments. In the Brazil study, a quadratic form was employed, with separate coefficients for positive and negative power regimes. The experiment basically involved running the test vehicles on 51 selected test sections of constant slope under different loads and speeds varying in the range 10-120 km/h.

The predicted unit fuel consumption is given separately for the uphill (UFC_u) and downhill (UFC_d) road segments, as follows:

$$UFC_u = (UFC_0 + a_3 HP_u + a_4 HP_u \text{ RPM} + a_5 HP_u^2) 10E-5$$

if $HP_d > 0$:

Table 2 - Default Values for Fuel and Lubricants Consumption

	Small Car	Medium Car	Large Car	Utility	Bus	Light Gas Truck	Light Diesel Truck	Medium Truck	Heavy Truck	Articulated Truck
Fuel Consumption										
CRPM (rpm)	3500	3000	3300	3300	2300	3300	2800	1800	1800	1700
a0	-8201	23453	-23705	8014	-7278	-48381	-41803	-22955	-22955	-30950
a1	33.4	40.8	100.8	37.8	83.5	127.1	71.8	85.0	85.0	158.1
a2	0	0.01214	0	0	0	0	0	0	0	0
a3	5830	7775	2784	3848	4323	5887	5129	3758	3758	4002
a4	0	0	0.938	1.388	0	0	0	0	0	0
a5	0	0	13.91	0	8.64	43.70	0	18.12	18.12	4.41
a6	4480	8552	4580	3604	2479	3843	2853	2394	2394	4435
a7	0	0	0	0	11.50	0	0	13.78	13.78	28.08
NH0	-10	-12	-15	-12	-50	-50	-30	-85	-85	-85
Q1	0.7	0.4	0.4	1	1	1	1	1	1	1
Q2	1.16	1.18	1.18	1.18	1.15	1.15	1.15	1.15	1.15	1.15
Lubricants Consumption										
COo	1.55	1.55	1.55	1.55	3.07	2.20	2.20	3.07	3.07	5.15

$$\text{UFCd} = (\text{UFC}_0 + a_3 \text{HPd} + a_4 \text{HPd RPM} + a_5 \text{HPd}^2) 10\text{E-}5$$

if $\text{NH}_0 \leq \text{HPd} < 0$:

$$\text{UFCd} = (\text{UFC}_0 + a_6 \text{HPd} + a_7 \text{HPd}^2) 10\text{E-}5$$

if $\text{HPd} < \text{NH}_0$:

$$\text{UFCd} = (\text{UFC}_0 + a_6 \text{NH}_0 + a_7 \text{NH}_0^2) 10\text{E-}5$$

UFC_0 is the idling component obtained at idling speed and expressed as follows:

$$\text{UFC}_0 = a_0 + a_1 \text{RPM} + a_2 \text{RPM}^2$$

RPM is the engine speed in rpm. The Brazil study found that a satisfactory prediction of fuel consumption could be obtained by using a constant calibrated engine speed (CRPM) instead of the actual engine speed, and that a good estimate of CRPM is given by the following formula:

$$\text{RPM} = \text{CRPM} \approx 0.75 \text{MRPM}$$

MRPM is the maximum rated engine speed, in rpm.

CRPM is the user-specified calibrated engine speed, in rpm.

New research for this publication has shown that for passenger cars, the fuel consumption prediction can be improved if RPM is a function of the vehicle speed when the vehicle is at top gear. Therefore, for passenger cars, this version of the HDM-VOC model (4.0) gives you the option of varying the engine speed for passenger cars using the following formulas:

$$\text{Top gear} \quad \text{RPM} = \text{MRPM } V / V_{\text{max}}$$

$$\text{Less than top gear} \quad \text{RPM} = \text{MRPM } V_{\text{top}} / V_{\text{max}}$$

MRPM is the maximum rated engine speed that is equal to $\text{CRPM} / 0.75$.

V is the vehicle speed in km/hour.

V_{max} is the maximum vehicle speed equal to V_{DRIVED} in km/hour.

V_{top} is the speed at the start of top gear (45 km/hr for small cars and 55 km/hr for medium and large cars)

HPu , HPd are the vehicle powers on the uphill and downhill road segments, in metric hp, given by:

$$\text{HPu} = [(\text{CR} + \text{PG}) \text{GVW } g V_{\text{u}} + 0.5 \text{RHO } \text{CD} \text{AR } V_{\text{u}}^3] / 736$$

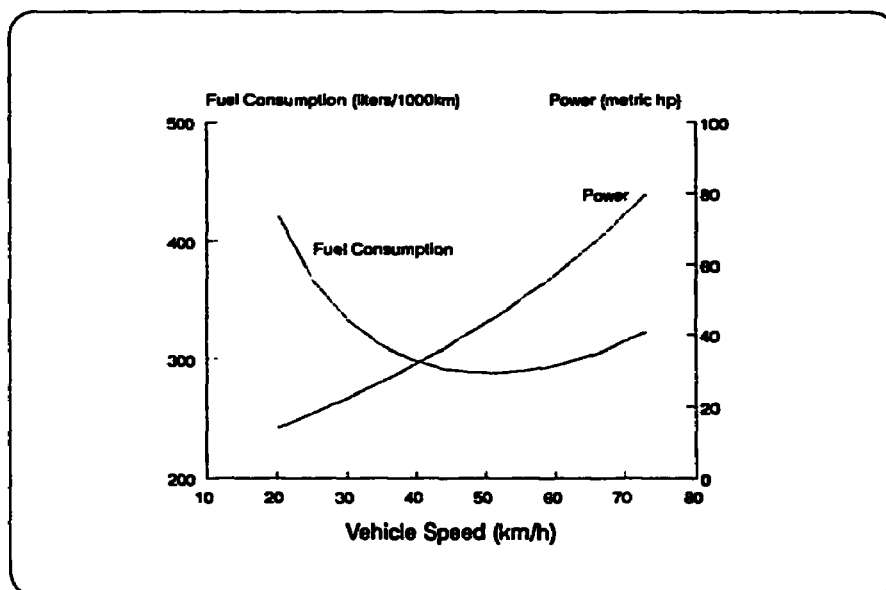
$$\text{HPd} = [(\text{CR} - \text{NG}) \text{GVW } g V_{\text{d}} + 0.5 \text{RHO } \text{CD} \text{AR } V_{\text{d}}^3] / 736$$

The coefficients a_0 through a_7 and NH_0 (lower limit on negative power) are the parameters of the mechanistic fuel prediction model estimated using data from controlled experiments.

Table 2 lists the default values for CRPM, a_0 through a_7 and NH_0 for the representative vehicles used in the Brazil study.

Figure 28 shows the effect of vehicle speed on vehicle power (HP) and fuel consumption (FL) for a heavy truck on a level tangent good condition road. The figure shows that as the speed increases, the power rises, partly due to increased air resistance and partly due to the need to overcome resistance forces at a faster rate; however, the fuel consumption drops initially to a minimum before rising.

Figure 28 - Fuel Consumption



Lubricant Consumption

The program expresses the lubricant consumption per 1000 vehicle-km (AOIL) as the number of liters consumed per 1000 vehicle-km. The lubricant consumption cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{AOIL} \times \text{lubricant cost per liter}$$

Lubricants consumption was not part of the Brazil study. For completeness, the model uses the following relationship where lubricants consumption is a function of roughness. The relationship is as modified by Chesher and Harrison (1987) from those obtained from the India study (CRRI, 1982):

$$\text{AOIL} = \text{CO}_0 + 0.151 \text{ RI}$$

CO_o is the constant term of the lubricants relationship.
CO_o depends on the vehicle type. Table 2 lists the default values for CO_o.

RI is the road roughness expressed in the International Roughness Index units, IRI (m/km).

Tire Wear

The program expresses the tire wear per 1000 vehicle-km (EQNT) in "cost equivalent" or simply "equivalent" new tires per 1000 vehicle-km. The tire wear cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 vehicle-km} = \text{EQNT new tire cost}$$

The model employs two relationships obtained in the Brazil study for predicting tire wear: one for cars and utilities, and another for trucks and buses. Because the tire data for cars and utilities obtained in the Brazil study were inadequate, the relationships constructed with the data for these vehicle types is relatively crude. On the other hand the more comprehensive data for trucks and buses permitted a more elaborate analysis on mechanistic principles and idealized uphill and downhill road segments as in the speed and fuel relationships. The relationships are:

a) For passenger cars (small, medium and large) and utilities the tire wear (EQNT) is given by:

$$\text{EQNT} = \text{NT} (0.0114 + 0.001781 \text{ RI}) \quad \text{for } 0 < \text{RI} \leq 15$$

$$\text{EQNT} = \text{NT} 0.0388 \quad \text{for } \text{RI} > 15$$

NT is the number of tires per vehicle. Table 3 lists the default values for NT.

RI is the road roughness expressed in the International Roughness Index units, IRI (in m/km).

b) For light (gasoline and diesel), medium, heavy and articulated trucks and large buses the tire wear (EQNT) is given by:

$$\text{EQNT} = \text{CTV} / \text{CN}$$

CTV is the tire wear cost per 1000 vehicle-km.

CN is the cost of a new tire.

The tire wear cost per 1000 vehicle-km (CTV) is expressed by:

$$\text{CTV} = \text{NT} (\text{CN} + \text{CRT NR}) / \text{DISTOT}$$

NT is the number of tires per vehicle.

CN is the cost of a new tire.

CRT is the cost of one retreading.

NR is the number of retreadings.

DISTOT is the total distance of travel provided by the tire carcass through its new tread and retreads, in 1000 km.

The tire wear (EQNT) can be expressed as:

$$\text{EQNT} = \text{NT} (1 + 0.01 \text{ RREC NR}) / \text{DISTOT}$$

RREC is the ratio of cost of one retreading to the cost of one new tire, in percent. Table 3 list the default values for the RREC.

The number of retreadings, NR, is expressed as:

$$NR = NR0 \exp(-0.03224 RI - 0.00118 \min(C, 300)) - 1$$

NR0 is the base number of retreads. Table 3 lists the default values for NR0.

C is the horizontal curvature, in degrees per km. The effect of curvature is limited to a maximum value of 300 degrees per km.

The total travel distance per tire carcass, DISTOT, is given by:

$$DISTOT = 1 / TWN + NR / TWR$$

TWN is the tread wear of new treads expressed as the fraction of tread worn per 1000 tire-km.

TWR is the tread wear of retreads expressed as the fraction of tread worn per 1000 tire-km.

and assuming that TWN and TWR are equal, then:

$$TWN = TWR = TWT / VOL$$

TWT is the predicted volume of rubber loss, in $dm^3/1000$ tire-km.

VOL is the average volume of rubber per tire for a given vehicle axle-wheel configuration and nominal tire size, in dm^3 . Table 3 lists the default values for VOL.

TWT is given by the expression:

$$TWT = Cotc + Ctcte CFT^2 / NFT$$

Cotc is the constant term of the tread wear model.

Ctcte is the wear coefficient of the tread wear model.

The parameters Cotc and Ctcte are specific, not to the vehicle class, but mainly to the type of tire (conventional or radial ply), and secondarily to the make of the tire. Table 3 lists the default values which apply to conventional (bias ply) type of tires of the Pirelli make.

NFT is the average force per tire in the direction perpen-

Table 3 - Default Values for Tire Wear Prediction

	Small Car	Medium Car	Large Car	Utili- ty	Bus	Light Gas Truck	Light Diesel Truck	Medium Truck	Heavy Truck	Articu- lated Truck
NT	4	4	4	4	6	6	6	6	10	18
RREC (%)	-	-	-	-	15	15	15	15	15	15
NR0	-	-	-	-	3.39	1.93	1.93	3.39	3.39	4.57
VOL (dm^3)	-	-	-	-	6.85	4.30	4.30	7.60	7.30	8.30
Cotc	-	-	-	-	0.184	0.184	0.184	0.184	0.184	0.184
Ctcte (10E-3)	-	-	-	-	12.78	12.78	12.78	12.78	12.78	12.78

dicular to the road surface, in newtons, given by:

$$NFT = GVW g / NT$$

CFT^2 is the average squared circumferential force per tire, given by:

$$CFT^2 = 0.5 (CFu^2 + CFd^2)$$

CFu is the average circumferential force per tire (in the direction tangential to the road surface) on the uphill road segment, in newtons.

CFd is the average circumferential force per tire (in the direction tangential to the road surface) on the downhill road segment, in newtons.

The circumferential force Cfu and CFd are computed as the vehicle drive force divided by the number of tires of the vehicle:

$$CFu = [(CR + PG) GVW g + 0.5 RHO CD AR V_u^2] / NT$$

$$CFd = [(CR - NG) GVW g + 0.5 RHO CD AR V_d^2] / NT$$

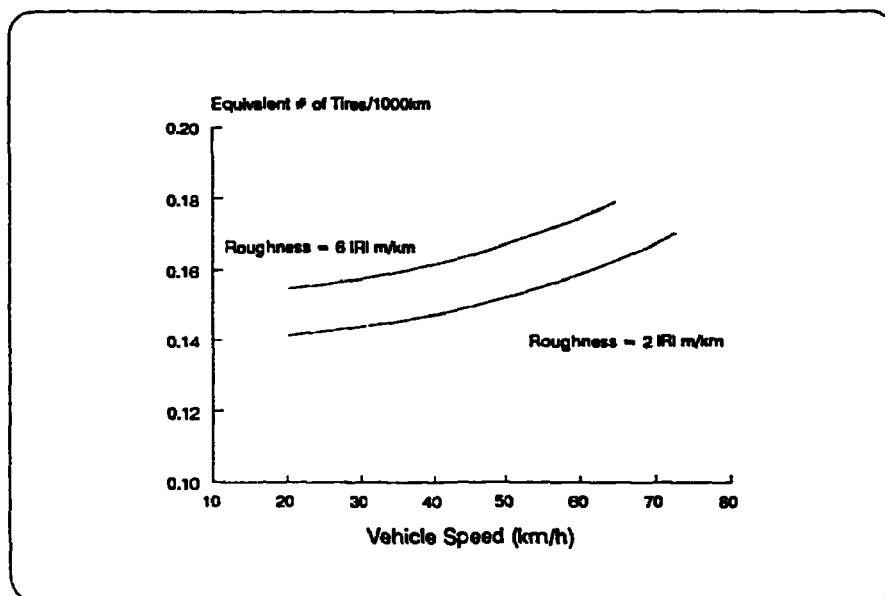
Finally, the tire wear (EQNT) is expressed as:

$$EQNT = NT [(1 + 0.01 NR) TWT / (1 + NR) / VOL + 0.0027]$$

0.0027 is a correction term for the prediction bias due to model nonlinearity.

Figure 29 shows tire wear consumption as a function of vehicle speed for a heavy truck on a tangent level paved road.

Figure 29 - Tire Wear Consumption



Crew Time

The program expresses the crew requirements per 1000 vehicle-km (CRH) as the number of crew-hours spent traveling per 1000 vehicle-km. The crew cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{CRH} \times \text{crew cost per hour}$$

CRH is given by:

$$\text{CRH} = 1000 / V$$

V is the computed vehicle speed, in km/h.

Passenger Time

The program expresses the passenger delays per 1000 vehicle-km (PXH) as the number of passenger-hours spent traveling per 1000 vehicle-km. The passenger delay cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{PXH} \times \text{passenger time cost per hour}$$

PXH is given by:

$$\text{PXH} = 1000 \text{ PAX} / V$$

PAX is the user-specified average number of passengers per vehicle.

V is the computed vehicle speed, in km/h.

Cargo Holding

The program expresses the cargo holding per 1000 vehicle-km (VCH) as the number of vehicle-hours spent in transit per 1000 vehicle-km. The cargo holding costs per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{VCH} \times \text{cargo holding cost per hour}$$

VCH is given by:

$$\text{VCH} = 1000 / V$$

V is the computed vehicle speed, in km/h.

Maintenance Parts

The program expresses the maintenance parts consumption per 1000 vehicle-km (PC) as a percentage of the average new vehicle cost. The maintenance parts cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{PC} / 100 \times \text{new vehicle price cost}$$

The maintenance parts consumption is related to roughness and vehicle age (Chesher and Harrison, 1987). The effects of these two factors are multiplicative. Holding the age constant, the relationship between maintenance parts consumption (PC) and roughness is generally exponential, especially for relatively low values of roughness. However, the exponential relation tends to overpredict PC at higher values. Therefore, the recommended equation is a composite of exponential and linear -- exponential up to a transitional value of roughness, QIPo, which is different for different vehicle types, and

then linear for higher values. The linear extension is tangent to the exponential relationship at QIPo. Since the Brazil relation for truck parts consumption was found to be linear over all values of roughness encountered in practice, QIPo is set to zero for all trucks. The maintenance parts consumption (PC) is given by:

For $RI \leq QIPo$:

$$PC = 100 CKM^{KP} CPo \exp(CPq RI 13)$$

For $RI > QIPo$:

$$100 CKM^{KP} (a0 + a1 RI 13)$$

CKM is the average age of the vehicle group in km, defined as the average number of kilometers the vehicles have been driven since they were built.

KP is the age exponent, a fixed model parameter.

CPo is the constant coefficient in the exponential relationship between spare parts consumption and roughness.

CPq is the roughness coefficient in the exponential relationship between spare parts consumption and roughness.

QIPo is the transitional value of roughness, in IRI, beyond which the relationship between spare parts consumption and roughness is linear.

RI is the road roughness expressed in the International Roughness Index units, IRI (m/km).

a0 and a1 are coefficients of the linear-tangential extension of the exponential relationships and may be expressed as functions of model parameters.

$$a0 = CPo \exp(CPq QIPo) (1 - CPq QIPo)$$

$$a1 = CPo CPq \exp(CPq QIPo)$$

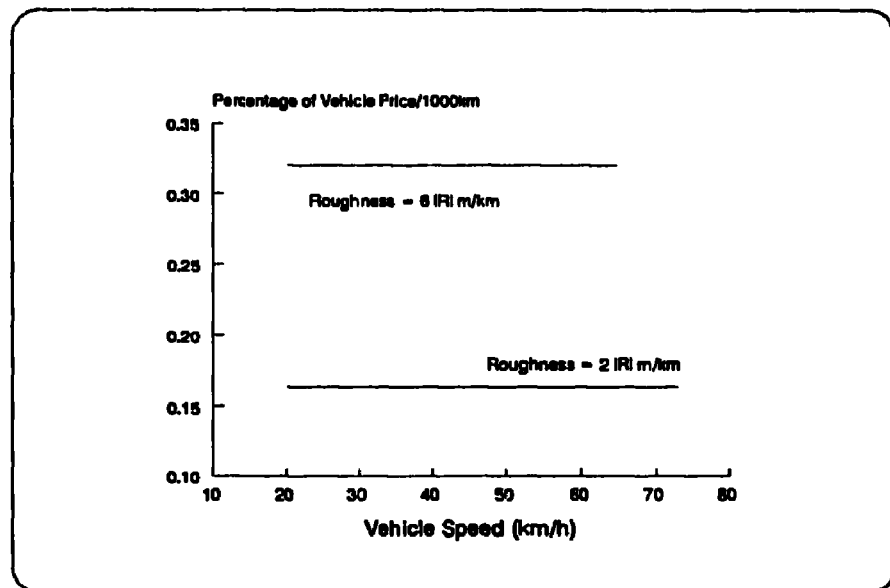
The prediction of PC requires four parameters, namely KP, CPo, CPq and QIPo. Table 4 lists the default values, as estimated from the Brazil data set.

Table 4 - Default Values for Maintenance Predictions

	Small Car	Medium Car	Large Car	Utili- ty	Bus	Light Gas Truck	Light Diesel Truck	Medium Truck	Heavy Truck	Articu- lated Truck
Maintenance Parts										
KP	0.308	0.308	0.308	0.308	0.483	0.371	0.371	0.371	0.371	0.371
CPo (10E-6)	32.48	32.48	32.48	32.48	1.77	1.49	1.49	1.49	8.81	13.84
CPq (10E-3)	13.70	13.70	13.70	13.70	3.56	251.79	251.79	251.79	35.31	15.85
QIPo	9.23	9.23	9.23	9.23	14.62	0	0	0	0	0
Maintenance Labor										
CLo	77.14	77.14	77.14	77.14	293.44	242.03	242.03	242.03	301.48	852.51
CLp	0.547	0.547	0.547	0.547	0.517	0.519	0.519	0.519	0.519	0.519
CLq	0	0	0	0	0.0055	0	0	0	0	0

Figure 30 shows maintenance parts consumption as a function of vehicle speed for a heavy truck on a tangent level paved road. Note that the vehicle speed has no effect on maintenance parts consumption.

Figure 30 - Maintenance Parts Consumption



Maintenance Labor

The program expresses the maintenance labor requirements per 1000 vehicle-km (LH) as the number of maintenance labor-hours required per 1000 vehicle-km. The maintenance labor cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{LH labor cost per hour}$$

Maintenance labor hours relates primarily to maintenance parts requirements, and in some cases, to roughness. When significant, the latter has been found to be exponential and the two effects are multiplicative. The relationship in its general form is written as:

$$\text{LH} = \text{CLO} (\text{PC}/100)^{\text{CLP}} \exp(\text{CLQ RI } 13)$$

PC is the standardized parts cost per 1000 vehicle-km expressed as a fraction of new vehicle price.

CLO is the constant coefficient in the relationship between labor hours and parts costs.

CLP is the exponent of parts cost in the relationship between labor hours and parts costs.

CLQ is the roughness coefficient in the exponential relationship between labor hours and roughness.

RI is the road roughness expressed in the International Roughness Index units, IRI (m/km).

The prediction of LH requires three parameters, namely CLo, CLp, and CLq. Table 4 lists the default values, as estimated from the Brazil data set.

Depreciation

The program expresses the depreciation per 1000 vehicle-km (DEP) as a percentage of the average new vehicle cost. The depreciation cost per 1000 vehicle-km is given by:

$$\text{Cost per 1000 veh-km} = \text{DEP} / 100 \text{ new vehicle price cost}$$

A vehicle is a medium-term capital asset; its purchase costs represents an investment which yields services over several years. The market value of the asset declines with both the passage of time and, usually to a much smaller degree, with the amount and type of usage.

It is this loss of market value (as distinct from some physical or accounting concept) that represent vehicle depreciation. The vehicle depreciation per km is a function of the average annual depreciation (ADEP) and the vehicle annual utilization (AKM).

$$\text{DEP} = 1000 \text{ ADEP} / \text{AKM}$$

ADEP is the average annual depreciation, expressed as a percentage of the average new vehicle cost, given by:

$$\text{ADEP} = (1 / \text{LIFE}) 100$$

LIFE is the average vehicle service life, in years.

AKM is the average number of kilometers driven per vehicle per year.

Figure 31 shows depreciation and interest as a function of vehicle speed for a heavy truck on a tangent level good condition road.

Vehicle Service Life (LIFE)

There are two methods available for computing the vehicle service life: the Constant Vehicle Life Method, and the de Weille's Varying Vehicle Life Method.

Constant Vehicle Life Method

This method uses a straight-line depreciation and assumes the life, LIFE, to be constant irrespective of vehicle speed and equal a user-specified value.

$$\text{LIFE} = \text{LIFE}_0$$

LIFE₀ is the user-specified baseline average vehicle service life, in years.

de Weille's Varying Vehicle Life Method

This method, suggested by de Weille (1966), also uses a straight-line depreciation over a predetermined vehicle service life that decreases somewhat as vehicle speed increases, so lifetime kilometerage increases in less proportion than speed.

$$\text{LIFE} = \text{minimum} \{ 1.5 \text{ LIFE}_0 ; (V_0 / V + 2) \text{ LIFE}_0 / 3 \}$$

V_0 is the baseline average vehicle speed, in km/h, given by:

$$V_0 = \text{AKM}_0 / \text{HRD}_0$$

AKM_0 is the user-specified baseline average number of kilometers driven per vehicle per year.

HRD_0 is the user-specified baseline number of hours driven per vehicle per year.

V is the computed vehicle speed, in km/h.

LIFE_0 is the user-specified baseline average vehicle service life, in years.

Note: The model imposes the maximum limit of 1.5 LIFE_0 to prevent computing unrealistically long vehicle lives.

Vehicle Annual Utilization (AKM)

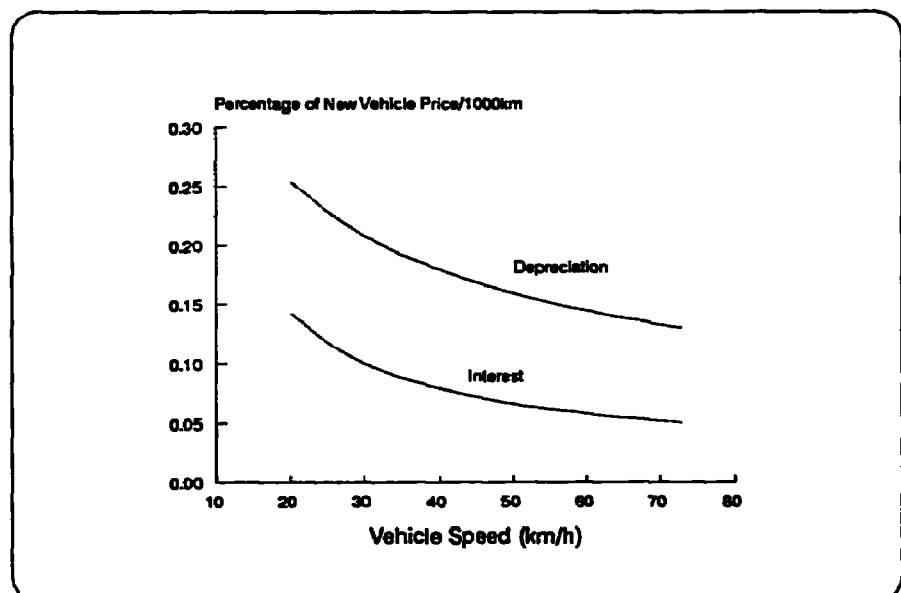
The model uses the "adjusted utilization" method to compute the annual utilization. Two other methods: the "constant annual kilometerage" method and the "constant annual hourly utilization" method are particular cases of the "adjusted utilization" method.

Adjusted Utilization Method

The "adjusted utilization" method assumes each vehicle to operate on the section under consideration as a fixed route over the analysis year, with the total time, per round trip, TT , given by:

$$TT = TN + TD$$

Figure 31 - Depreciation and Interest



TN = the time spent on non-driving activities as part of the round trip tour, including loading and unloading, refueling, layovers, etc., in hours per trip.

TD = the driving time on the section, in hours per trip.

$$TD = RL / V$$

RL is the round trip driving distance or route length, in km.

V is the vehicle speed, in km/h.

The model assumes vehicle operators try to maximize vehicle productivity by making as many trips as possible within the vehicle availability constraint. Let **HAV** represent the vehicle availability, defined as the total amount of time the vehicle is available for vehicle operation. In general, **HAV** is equal to the total number of hours per year less the time allowed for crew rest, infeasibility of vehicle operation (e.g. holidays or hours labor does not normally work), vehicle repairs, etc. The model assumes **HAV** to be independent of vehicle speed and route characteristics. Under this assumption the kilometerage driven per year is derived as:

$$AKM = (\text{number of round trips per year}) * (\text{route length})$$

$$AKM = (HAV / TT) RL$$

$$AKM = [HAV / (TN + RL / V)] RL$$

$$AKM = HAV / (TN / RL + 1 / V)$$

The term **TN / RL**, the number of non-driving hours per vehicle-km of travel, is expressed as follows:

$$TN / RL = (HAV - HRD_0) / AKM_0$$

AKM₀ is the user-specified baseline average number of kilometers driven per vehicle per year.

HRD₀ is the user-specified baseline number of hours driven per vehicle per year.

and substituting this expression into the above expression for **AKM** yields:

$$AKM = HAV / ((HAV - HRD_0) / AKM_0 + 1 / V)$$

Thus if the values of **HAV**, **HRD₀** and **AKM₀** are available, the model predicts the annual kilometerage driven, **AKM**, as a function of the predicted operating speed, **V**.

The user provides directly the baseline parameters **HRD₀** and **AKM₀**. The **HAV** parameter is derived from the following formula:

$$HURATIO = HRD_0 / HAV$$

where **HURATIO** is the "hourly utilization ratio" for the baseline case, defined as the ratio of the annual number of hours driven to the number of hours available for operation. Substituting this formula in the expression for **AKM** above yields the general formula for predicting vehicle utilization.

$$AKM = AKM_0 HRD_0 / [HRD_0 (1 - HURATIO) + AKM_0 HURATIO / V]$$

AKM₀ is the user-specified baseline average number of kilometers driven per vehicle per year.

HRD₀ is the user-specified number of hours driven per vehicle per year.

HURATIO is the user-specified hourly utilization ratio.

V is the computed speed of the vehicle, in km/h.

Based on the data from the Brazil study, Watanatada, et al. (1987) estimated typical values of hourly utilization ratio for various classes of vehicles. The results led to the following default values of HURATIO.

<u>Vehicle Type</u>	<u>Hourly Utilization Ratio</u>
Cars	0.60
Utilities	0.80
Buses	0.75
Trucks	0.85

These default values are based on the operating characteristics of typical vehicles in Brazil. However, since hourly utilization ratios are expected to vary considerably across countries, you should provide values appropriate to the local operating conditions.

Constant Annual Kilometerage Method.

The "constant annual kilometerage" method is obtained when HURATIO equals to zero and the formula becomes:

$$AKM = AKM_0$$

The assumption of constant annual kilometerage is appropriate for non-commercial vehicles such as private passenger cars, of which the trip distances and frequencies are usually relatively insensitive to changes in average travel speed. However, commercial vehicles tend to be used for more frequent or longer trips if time for a given length trip is reduced.

Constant Annual Hourly Utilization Method.

The "constant annual hourly utilization" method is obtained when HURATIO equals to one and the formula becomes:

$$AKM = HRD_0 V$$

The constant annual hourly utilization method assumes that the average annual number of hours driven per vehicle is constant. Note that this method tends to overpredict time-related benefits. As the average speed increases the number of trips a commercial vehicle makes in a year tend to rise. However, in addition to the driving time the total time needed to complete each trip also includes a large proportion of non-driving activities such as loading, unloading, vehicle repairs, and layovers. This means that the number of trips per year does not increase in direct proportion to speed. The effect is particularly pronounced for short trips with many stops for pickups and deliveries.

Interest

The program expresses the interest charge per 1000 vehicle-km (INT) as a percentage of the average new vehicle cost. The interest cost per 1000 vehicle-km is given by:

Cost per 1000 veh-km = INT / 100 new vehicle price cost

Since depreciation occurs gradually, at any given point in time there is a residual (undepreciated) amount of capital tied up to the vehicle, which normally could be invested elsewhere, so an annual interest charge is incurred.

The model takes the annual interest as the average of the residual vehicle value, decreasing in a linear fashion from full purchase price at the end of year 0 to zero at the end of year LIFE.

INT = 1000 AINT / AKM

AINT is average annual interest on the vehicle, in percent.

AINT = AINV / 2

AINV is the user-specified annual interest charge on the purchase cost of a new vehicle, in percent.

AKM is the average number of kilometers driven per vehicle per year.

Note: Refer to the Vehicle Annual Utilization topic in the Depreciation section of this chapter for information on the computation of AKM.

Overhead

The program expresses the overhead per 1000 vehicle-km (OVER) as a lump sum overhead cost per vehicle-km. The overhead cost per 1000 vehicle-km is given by:

Cost per 1000 veh-km = OVER / 1000

OVER is the user-specified overhead cost per vehicle-km.

Chapter 5

The Input Data

Surface Type

The model provides two options for road surface type: (i) Paved and (ii) Unpaved. Enter 1 to select a paved road, and 0 to select an unpaved road.

The paved roads include primarily asphalt concrete roads and surface treatment roads, and the unpaved roads include compacted gravel and earth roads. The surface type affects directly the following predictions:

- VCURVE, the curvature-limited constraint speed
- VDESIR, the desired constraint speed

Note that the model follows the steps below:

- 1 - Computes the constraint speeds (VDRIVE, VBRAKE, VCURVE, VROUGH, VDESIR).
- 2 - Computes the predicted vehicle speed (V) from the constraint speeds.
- 3 - Computes the resources used for each vehicle operating costs component (i.e., liters of fuel, hours of labor, depreciation, etc.).
- 4 - Applies the unit costs to the resource consumption amounts to obtain the vehicle operating costs.

The vehicle operating costs components listed below are a function of the predicted vehicle speed (V) and the predicted vehicle speed is a function of the constraint speeds (VDRIVE, VBRAKE, VCURVE, VROUGH, VDESIR). Therefore, an input variable that affects any constraint speed will affect directly the predicted vehicle speed and indirectly the following vehicle operating cost components:

- Fuel consumption
- Tire wear
- Crew time
- Passenger time
- Cargo holding
- Depreciation
- Interest

Roughness

The road roughness is defined as the deviations of a surface from a true planar surface with characteristics that affect vehicle dynamics, ride quality, dynamic loads and drainage. Enter the average road roughness in IRI units (International Roughness Index, in m/km). If you have roughness in QI units (roughness measured by a quarter-car index scale), convert it into IRI units using the formula:

$$\text{IRI} = \text{QI} / 13$$

If you have roughness in BI units (roughness measured by Bump Integrator trailer at 32 km/h), convert it into IRI units using the formula:

$$\text{IRI} = \text{BI} / 715$$

If you have roughness in other units, convert it into IRI units using an appropriate calibration method. Refer to the following publication for more information about the International Roughness Index and its relationship to other roughness units.

Sayers, M.W., T.D. Gillespie and W.D.O. Paterson. *Guidelines for Conducting and Calibrating Road Roughness Measurements*. Technical Paper No. 46, The World Bank, Washington, DC, 1986.

If a roughness value is not available in any of the above units, translate your subjective assessment of the road roughness into IRI units by using the five-point scale given below (since these guidelines can only provide very broad approximations, you are urged to work with actual roughness measures, if possible):

Quantitative Evaluation	Roughness IRI (m/km)	
	Paved Road	Unpaved Road
Smooth	2	4
Reasonably smooth	4	8
Medium rough	6	12
Rough	8	15
Very rough	10	20

The roughness affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed

- VBRAKE, the braking power-limited constraint speed
- VROUGH, the roughness-limited constraint speed
- Fuel consumption
- Lubricant consumption
- Tire wear
- Maintenance parts
- Maintenance labor

Vertical Profile

You can identify three distinct types of journeys on a road between two points, say A and B. These are:

- (i) one-way journey from A to B;
- (ii) one-way journey from B to A; and
- (iii) round trip journey either from A to B and back to A, or from B to A and back to B.

Of the three, the first two are basic in the sense that you may obtain predictions for the round-trip journey from the predictions for the two one-way journeys by appropriate averages. Homogeneous sections of the road between A and B which would have a positive grade in (i) will have a negative grade in (ii), and vice versa. The road studied in (iii) is conceptually identical to a road which is twice in length and has the homogeneous sections of both (i) and (ii).

To obtain the desired predictions for each journey type, the model requires three aggregate attributes of vertical geometry of the road:

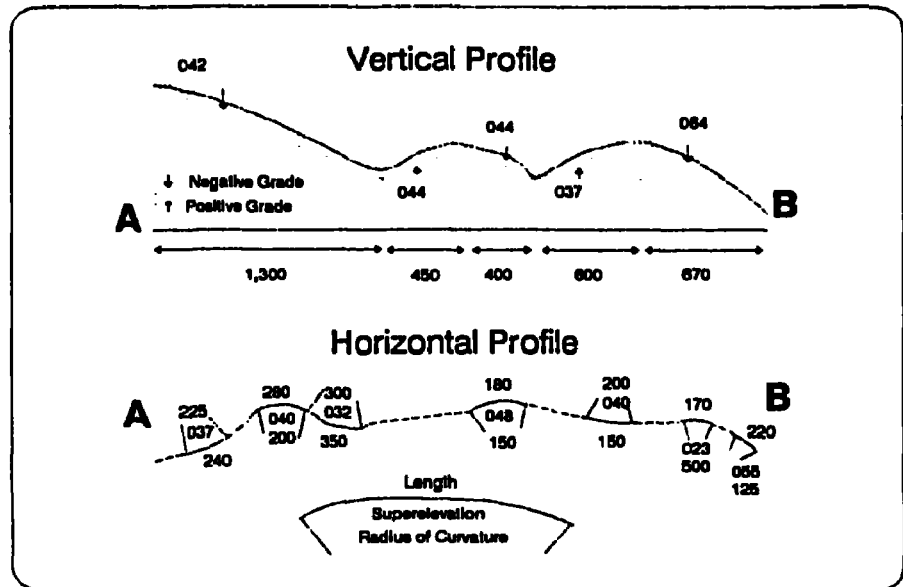
- Positive gradient (PG, in percentage) defined as the ratio of the sum of all ascents (or rises) along a road by the length of the sections constituting uphill travel.
- Negative gradient (NG, in percentage) defined as the ratio of the sum of absolute values of all descents (or falls) along a road by the length of the sections constituting downhill travel.
- Proportion of uphill travel (LP, in percentage) defined as the ratio of the total length of road sections with positive grade by the total length of the road.

However, the aggregate information on vertical geometry obtained for either journey type (i) or (ii) is also sufficient for the other type and also for the round trip journey. For most applications, predictions for a round trip are adequate. The only significant exception is the case of a truck with very different load levels in the two opposite directions. In this case, obtain predictions separately for (i) and (ii).

Follow the steps below to compute the vertical geometric aggregates from a detailed geometric profile:

- 1 - Start with a detailed vertical profile of the road as shown in Figure 32.

Figure 32 - Sample of Horizontal and Vertical Profile



2 - Divide the roadway into sections with crests and troughs as boundary points. Determine the lengths (l_s) and average gradients (as a fraction and with signs retained) of the sections (g_s) and form a tabular profile of vertical geometry. Figure 33 shows that and gives a numerical example of the computation of vertical aggregates for the road defined in Figure 32 from A to B.

3 - Determine the "positive gradient" (p_s) of each section s (column d):

If the gradient of section s is positive, i.e., $g_s \geq 0$, then:

$$p_s = g_s$$

If the gradient of section s is negative, i.e., $g_s < 0$, then:

$$p_s = 0$$

4 - Determine the "negative gradient" (n_s) of each section s (column e):

If the gradient of section s is positive, i.e., $g_s \geq 0$, then:

$$n_s = 0$$

If the gradient of section s is negative, i.e., $g_s < 0$, then:

$$n_s = |g_s|, \text{ where } |g_s| \text{ is the absolute value of } g_s$$

5 - Determine the "rise" of each section. Multiply columns b and d to get pl_s (column f):

$$pl_s = p_s l_s$$

6 - Determine the "fall" of each section. Multiply columns b and e to get nl_s (column g):

$$nl_s = n_s l_s$$

Figure 33 - Computation of Vertical Aggregates

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Section	Length (m)	Gradient (fraction)	Positive Gradient (fraction)	Negative Gradient (fraction)	Rise (m)	Fall (m)	Uphill Travel (m)
1	1,300	-0.042	0	0.042	0	84.80	0
2	450	0.044	0.044	0	19.80	0	450
3	400	-0.044	0	0.044	0	17.60	0
4	800	0.037	0.037	0	29.60	0	800
5	870	-0.004	0	0.004	0	42.88	0
	3,420				42.00	115.08	1,050
	<u>L</u>				<u>PL</u>	<u>NL</u>	<u>P</u>

From point A to B

Positive Gradient (PG) = $42.00 / 1,050 \times 100 = 4.0 \%$

Negative Gradient (NG) = $115.08 / (3,420 - 1,050) \times 100 = 4.9 \%$

Uphill Travel (LP) = $1,050 / 3,420 \times 100 = 30.7 \%$

7 - Specify the segments with positive gradient (uphill travel) (column h). Enter the length l_s of the section if the section has a positive gradient; enter zero if the section has a negative gradient:

$$p_s = l_s \quad \text{if } g_s \geq 0$$

$$p_s = 0 \quad \text{if } g_s < 0$$

8 - Form the totals of columns b, f, g and h as L, PL, NL and P, respectively.

9 - Compute the average vertical geometric characteristics from the formulas below:

Average Geometric Characteristics	Symbol	One-way Trip		Round Trip
		A to B	B to A	
Average positive gradient	PG	$PL / P \times 100$	$NL / (L - P) \times 100$	$(PL + NL) / L \times 100$
Average negative gradient	NG	$NL / (L - P) \times 100$	$PL / P \times 100$	$(PL + NL) / L \times 100$
Proportion of uphill travel	LP	$P / L \times 100$	$(L - P) / L \times 100$	50

The recommended range for positive gradient (PG) and negative gradient (NG) is from 0 to 12 percent. The range for the proportion of uphill travel (LP) is from 0 to 100 percent.

Note that the HDM program computes the vehicle operating costs only for round trip journeys and derives the aggregate vertical geometric information from the average rise plus fall (RF) value of the road. Recalling that the rise and fall (RF, in m/km) is the sum of absolute values (in m) of all the ascents and descents along the road divided by the length of the road (in km), we have the following relation:

<u>VCL Program</u>	<u>HDM Program</u>
PG	RF / 10
NG	RF / 10
LP	50

The vertical profile affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed
- VBRAKE, the braking power-limited constraint speed
- Fuel consumption
- Tire wear

Horizontal Profile

Two measures that are independent of direction of travel represent the horizontal profile:

- Average horizontal curvature (C), defined as the weighted average of the curvatures of the curvy sections of the road, the weights being the proportion of the lengths of curvy sections. Its units are degrees/km. The horizontal curvature of a curvy section is the angle (in degrees) subtended at the center by a unit arc-length of the curve (in km). Note that the curvature of a curvy section is an inverse function of the radius of curvature:

$$c_s = 180,000 / \pi r c_s$$

where $r c_s$ is the radius of curvature, in meters. Further, the angle subtended by an arc of a circle at the center is equal to the external angle made by the tangents to the circle at the ends of the arc. Thus the curvature also expresses the absolute angular deviation of the two tangent lines at the end-points of the curve by the arc-length.

- Average superelevation (SP), defined as the weighted average of the superelevations of the curvy sections of the road, the weights being the proportion of the lengths of curvy sections. It is a dimensionless quantity. The superelevation of a curvy section is the vertical distance between the heights of the inner and outer edges of the road divided by the road width.

Figure 34 - Computation of Horizontal Aggregates

(a)	(b)	(c)	(d)	(e)	(f)	(g)
Curvy Section	Length (m)	Radius of Curvature (m)	Curvature (deg/km)	Superelevation (fraction)	cl _s	sl _s
1	240	220	204.78	0.037	61.147	8.53
2	280	200	206.82	0.040	64.304	11.20
3	350	300	191.08	0.038	64.879	11.08
4	180	180	242.17	0.048	64.791	8.70
5	180	200	206.82	0.040	42.983	6.96
6	170	800	96.84	0.023	16.943	3.97
7	220	120	466.80	0.068	104.892	12.10
Road Length = 3,420 m					437.197	61.98
					K	S
Horizontal Curvature (C) =			437.197 / 3,420		≈ 127.8	
Superelevation (SP) =			61.98 / 3,420		≈ 0.018	

Follow the steps below to compute the horizontal geometric aggregates from a detailed geometric profile:

1 - Start with a detailed horizontal profile of the road as typified in Figure 32.

2 - Divide the road into sections with uniform curvature using the end points of the curves as boundary points. Determine the lengths (l_s), curvatures (c_s) and superelevation (s_s) of the curvy sections and form a tabular profile of horizontal geometry. Figure 34 shows that and gives a numerical example of the computation of horizontal aggregates for the road defined in Figure 32.

3 - Multiply columns b and d to get cl_s (column f):

$$cl_s = c_s l_s$$

4 - Multiply columns b and e to get sl_s (column g):

$$sl_s = s_s l_s$$

5 - Form the totals of columns f and g as K and S respectively.

6 - Compute the total length of the road (L), in km.

7 - Compute the average horizontal geometric characteristics from the formulas below:

Average Geometric Characteristics	Symbol	One-way Trip		Round Trip
		A to B	B to A	
Average Curvature	C	K/L	K/L	K/L
Average Superelevation	SP	S/L	S/L	S/L

If you don't know the superelevation, either on a detailed basis or on an average basis, the model estimates a value for the average superelevation as a function of the average horizontal curvature. If you don't enter the superelevation, the model uses the following formulas obtained from a sample of roads in Brazil:

$$\begin{array}{ll} SP = 0.00012 C & \text{for paved roads} \\ SP = 0.00017 C & \text{for unpaved roads} \end{array}$$

The recommended range for horizontal curvature (C) is from 0 to 1200 degrees/km and for superelevation (SP) is from 0 to 0.20.

The horizontal curvature and superelevation affect directly the following prediction:

- VDRIVE, the curvature-limited constraint speed

Altitude of Terrain

The model uses the altitude of terrain (the average elevation of the road above the mean sea level, in meters) to compute the air resistance to the vehicle motion. The recommended range for altitude (ALT) is from 0 to 5000 meters.

The altitude of terrain affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed
- Fuel consumption
- Tire wear

Effective Number of Lanes

The model provides two options for the effective number of lanes: (i) One lane and (ii) More than one lane. Enter 1 to select a single-lane road, and 0 to select a more than one lane road.

The model makes a distinction between single-lane roads and other roads. If the carriageway width is less than 4.0 m designate the road as single-lane (vehicles traveling in two opposite directions share both wheel paths). If the road is wider than 5.5 m, designate it as having more than one lane (vehicles traveling in two opposite directions either share one wheel path or have distinct wheel paths). Designate roads with width between 4.0 and 5.5 m based on other factors such as, shoulder width and condition, daily traffic, and traffic composition.

The effective number of lanes affects directly the following prediction:

- VDESIR, the desired constraint speed

Vehicle Type

You can select the vehicle type among the vehicle classes listed in Table 5. Table 5 also lists the representative makes and models as employed in the Brazil study and the main vehicle characteristics.

Table 5 - Vehicle Classes and Standard Characteristics

	Small Car	Medium Medium Car	Large Car	Util- ity	Bus	Light Gas Truck	Light Diesel Truck	Medium Truck	Heavy Truck	Articu- lated Truck
Representative vehicle make model	Volk- swagen 1300	Chev- rolet Opala	Chrys- ler Dodge Dart	Volk- swagen Kombi	Merc. Benz O-362	Ford F-400	Ford F-4000	Merc. Benz 1113 2 axes	Merc. Benz 1113 3 axes	Scania 110/ 30
Vehicle code	1	2	3	4	5	6	7	8	9	10
Weight (kg): Tare weight (TARE)	980	1200	1850	1320	8100	3120	3270	5400	8800	14730
Load carried (LOAD)	400	400	400	800	4000					
Driving power (metric hp): Maximum used (HPDRIVE)	30	70	85	40	100	80	80	100	100	210
Maximum rated (HPRATED)	48	148	198	60	147	188	102	147	147	285
Braking power (metric hp): Maximum used (HPBRAKE)	17	21	27	30	160	100	100	250	250	500
Engine speed (rpm): Calibrated (CRPM)	3500	3000	3300	3300	2300	3300	2800	1800	1800	1700
Maximum rated (MRPM)	4800	4000	4400	4800	2800	4400	3000	2800	2800	2200
Frontal area (m ²)	1.80	2.08	2.20	2.72	6.30	3.25	3.25	5.20	5.20	5.75
Aerodynamic drag	0.45	0.50	0.45	0.48	0.85	0.70	0.70	0.85	0.85	0.83
Tires: Number	4	4	4	4	6	6	0	6	10	18
Nominal diameter (mm)					1000	900	900	1000	1000	1100
Wear rubber volume (dm)					8.85	4.3	4.3	7.8	7.3	8.39

Tare Weight

The model used the tare weight (TARE) to compute the gross vehicle weight (GVW) using the formula:

$$GVW = TARE + LOAD$$

TARE is the vehicle tare weight, in kg.

LOAD is the vehicle payload, in kg.

The model provides default values for tare weight (see Table 1) and the recommended range for gross vehicle weight (GVW) is given below:

Vehicle	Recommended Gross Vehicle Weight Range (kg)
Cars	8,000 - 2,000
Utilities	1,1000 - 2,500
Buses	7,500 - 12,000
Light trucks	3,000 - 6,500

Medium trucks	5,000 - 16,000
Heavy trucks	6,000 - 22,000
Articulated trucks	13,000 - 45,000

The tare weight affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed
- VBRAKE, the braking power-limited constraint speed
- VCURVE, the curvature-limited constraint speed
- Fuel consumption
- Tire wear

Payload

The model uses the payload (LOAD) to compute the gross vehicle weight (GVW) and to estimate the tendency to skid ratio (FRATIO) used in the calculation of VCURVE.

The model doesn't provide default values for payload. If the vehicle is a car, a bus or a utility, the payload represents the weight of the passengers and some light load. Suggested values for payload are given below.

Vehicle	Suggested Payload (kg)
Cars	400
Utilities	900
Buses	4,000

If the vehicle is a truck, enter the value of load carried after considering factors such as the loading practice and the maximum rated tonnage for the vehicle. The order of magnitude involved for each type of truck is given below:

Loading Condition	Magnitude of Payload (kg)			
	Light Truck	Medium Truck	Heavy Truck	Articulated Truck
Unloaded	0	0	0	0
Partially loaded	1,800	4,500	6,000	13,000
Fully loaded	3,600	9,000	12,000	26,000

The recommended range for payload (LOAD) is given below:

Vehicle	Recommended Payload Range (kg)
Cars	0 - 400
Utilities	0 - 1,400
Buses	0 - 4,500
Light trucks	0 - 3,500

Medium trucks	0 - 11,000
Heavy trucks	0 - 16,000
Articulated trucks	0 - 32,000

The payload affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed
- VBRAKE, the braking power-limited constraint speed
- VCURVE, the curvature-limited constraint speed
- Fuel consumption
- Tire wear

Maximum Used Driving Power

The model uses the maximum driving power (HPDRIVE) to compute the driving power-limiting constraint speed (VDRIVE). The model provides default values for maximum driving power (see Table 1, Page 39) and the recommended input range is given below:

Vehicle	Recommended Maximum Used Driving Power (Metric HP)
Cars	25 - 100
Utilities	35 - 100
Buses	80 - 120
Light trucks	50 - 100
Medium trucks	80 - 120
Heavy trucks	80 - 120
Articulated trucks	180 - 230

You can estimate the maximum driving power (HPDRIVE) from the maximum rated power of a vehicle (HPRATED), that is available from the vehicle manufacturer. Based on the test vehicles data from the Brazil study, separate relationships were developed for gasoline and diesel vehicles:

For gasoline vehicles:

$$\text{HPDRIVE} = 2.0 \text{ HPRATED}^{0.7}$$

For diesel vehicles:

$$\text{HPDRIVE} = 0.7 \text{ HPRATED}$$

where HPRATED is the SAE maximum rated power of the vehicle. Note that since HPRATED is usually quoted under standard atmospheric conditions, the value of HPRATED should be adjusted where the operating atmospheric conditions depart from the standard conditions (e.g., in high-altitude driving or driving in severely cold weather).

The maximum driving power affects directly the following prediction:

- VDRIVE, the driving power-limited constraint speed

Maximum Used Braking Power

The model uses the maximum braking power (HPBRAKE) to compute the braking power-limiting constraint speed (VBRAKE). The model provides default values for maximum braking power (see Table 1, Page 39) and the recommended input range is given below:

Vehicle	Recommended Maximum Used Braking Power (Metric HP)
Cars	15 - 30
Utilities	20 - 35
Buses	140 - 180
Light trucks	90 - 120
Medium trucks	230 - 270
Heavy trucks	230 - 270
Articulated trucks	460 - 540

You can estimate the maximum braking power (HPBRAKE) from the manufacturer's rated gross vehicle weight (GVWRATED). Based on the test vehicles data from the Brazil study, use the following simple formula:

$$\text{HPBRAKE} = 14 \text{ GVWRATED or } 15 \text{ GVWRATED}$$

where GVWRATED is the manufacture's rated gross vehicle weight. This formula is based on the assumption that vehicle designers strive to match the vehicle's braking capacity with its design weight.

The maximum braking power affects directly the following prediction:

- VBRAKE, the braking power-limited constraint speed

Desired Speed

The desired speed constraint (VDESIR) is the desired vehicle speed without the effect of road severity factors. On a straight, flat and smooth road, although the driving, braking, curve and ride severity speed constraints do not exist, the vehicle still does not normally travel at the speed afforded by its own maximum or even used power. Rather, its speed is usually governed by subjective considerations of such factors as fuel economy, vehicle wear, safety or blanket speed limits. Since it was not possible to separate these effects in the study data, they were combined in the parameter "desired speed constraint," VDESIR.

The model uses the user-specified desired speed (VDESIR₀) to compute the desired speed constraint (VDESIR). Based on observed speed data from Brazil, it was found satisfactory to assume that the desired speed constraint (VDESIR) for a vehicle class depends only on the surface type of the homogeneous section. However, in the extension to the steady-state speed prediction model based on Indian data, (VDESIR) depends also on the width class of the homogeneous section. Thus the desired speed constraint (VDESIR) is given by the following formula:

$$\text{VDESIR} = \text{VDESIR}_0 \text{ BW}$$

BW is the width effect parameter applicable to single-lane roads.

VDESIR₀ is the user-specified desired speed, in km/h.

The model provides default values for BW and for VDESIR₀. The default values for VDESIR₀ are a function of the surface type (see Table 1, Page 39).

The desired speed affects directly the following prediction:

- VDESIR, the desired speed-limited constraint speed

Aerodynamic Drag Coefficient

The model uses the aerodynamic drag coefficient (CD) to compute the air resistance to the vehicle motion. The drag coefficient represents three sources of air resistance: (i) Form drag, (ii) Skin friction and (iii) Interior friction.

The recommended range for the aerodynamic drag coefficient is from 0.3 to 1.0 (dimensionless) and typical values for different types of vehicles are given below:

Vehicle	Typical Values of Aerodynamic Drag Coefficient
Cars	0.3 - 0.6
Buses	0.6 - 0.7
Trucks	0.8 - 1.0

The aerodynamic drag coefficient affects directly the following predictions:

- VDRIVE, the driving power-limited constraint speed
- Fuel consumption
- Tire wear

Projected Frontal Area

The model uses the projected frontal area (AR) to compute the air resistance to the vehicle motion.

The recommended range for projected frontal area is given below:

Vehicle	Recommended Projected Frontal Area (m ²)
Cars	1.5 - 2.4
Utilities	2.3 - 3.2
Buses	6.0 - 7.0
Light trucks	3.0 - 5.0
Medium trucks	5.0 - 8.0
Heavy trucks	5.0 - 8.0
Articulated trucks	5.5 - 10.0

The projected frontal area affects the following predictions:

- VDRIVE, the driving power-limited constraint speed
- Fuel consumption
- Tire wear

Calibrated Engine Speed

The model uses the calibrated engine speed (CRPM) to compute the fuel consumption. You can estimate the calibrated engine speed from the maximum rated engine speed (MRPM), that is available from the vehicle manufacturer. Based on the test vehicles data from the Brazil study, the following relationship was developed:

$$\text{CRPM} = 0.75 \text{ MRPM}$$

where MRPM is the maximum rated engine speed, in rpm.

The fuel consumption is a function of the engine speed and the engine speed is a function of the gear speed. The problem is that for a combination of vehicle speed and power there can be more than one feasible gear and the choice of gear depends on the behavior of individual drivers. The approach used by the model is to make a assumption of constant or nominal engine speed and to determine or "calibrate" it using the collected fuel consumption test data.

The calibrated engine speed affects directly the following prediction:

- Fuel consumption

Energy-Efficiency Factor

The sample of test vehicles for the Brazil study was chosen before the two major oil crises, in the early and late seventies, that stimulated an unprecedented change in vehicle technology to improve fuel economy. To allow you incorporate changes in vehicle technology, a "relative energy-efficiency factor," denoted by α_1 , has been introduced.

This factor has a default value of 1.0 for makes and models close to the ones employed in the Brazil study. You may specify lower values for newer, more fuel-efficient makes and models. Some typical values are given below:

Vehicle	Test Vehicle	Relative Energy Efficiency Factor (α_1)		
		Comparable Design	Modern Design	Possible Range
Small car	VW-1300	1.00	0.85	0.70-1.00
Medium car	Chevrolet Opala	1.00	0.85	0.70-1.00
Large car	Dodge Dart	1.00	0.95	0.80-1.00
Utility	VW-Kombi	1.00	0.95	0.80-1.00
Bus	Mercedes -326	1.00	0.95	0.80-1.00
Light gas. truck	Ford 400	1.00	0.95	0.80-1.00
Light diesel truck	Ford 4000	1.00	0.95	0.80-1.00
Medium truck	Mercedes 1113 (2ax)	1.00	0.95	0.80-1.00
Heavy truck	Mercedes 1113 (3ax)	1.00	0.95	0.80-1.00
Articulated truck	Scania 110/39	1.00	0.80	0.65-1.00

The energy-efficiency factor affects directly the following prediction:

- Fuel consumption

Fuel Adjustment Factor

The fuel consumption data employed in the development and validation of the fuel consumption prediction model were obtained under rather idealized controlled conditions in favor of fuel efficiency. Predictions by the model were found to be generally lower than values experienced by vehicle operators in the same geographic region but under actual conditions. Therefore, an adjustment factor, denoted by α_2 , was developed to bring the predictions closer to vehicle operators' values.

The default values of the adjustment factor, α_2 , were obtained from calibrating the mechanistic fuel prediction model to the road user cost survey data in Brazil. They are 1.16 for cars and utilities, and 1.15 for trucks and large buses.

The fuel adjustment factor affects directly the following prediction:

- Fuel consumption

Tire Wear Information

The model uses the following variables for tire wear prediction:

- Number of tires per vehicle
- Wearable volume of rubber per tire (dm^3)
- Retreading cost per new tire cost ratio (fraction)
- Maximum number of recaps
- Constant term of tread wear model (dm^3/m)
- Wear coefficient of tread wear model ($10^{-3} \text{ dm}^3/\text{kJ}$)

The model provides default values for all tire wear parameters for the representative makes and models of the Brazil study (see Table 3, Page 43). Note that the default value for retreading cost per new tire cost ratio (0.15), based in the Brazil case, is quite low in comparison with many countries.

The recommended range for wearable volume of rubber per tire is given below:

Vehicle	Recommended Wearable Volume of Rubber per Tire (dm^3)
Buses	5.6 - 8.0
Light trucks	2.0 - 3.5
Medium trucks	6.5 - 9.3
Heavy trucks	6.3 - 8.8
Articulated trucks	6.0 - 8.5

The model uses the constant term of the tread wear model and the wear coefficient of the tread wear model to predict the volume of rubber loss, in $\text{dm}^3/1000 \text{ tire-km}$.

The tire wear information affects directly the following prediction:

- Tire wear

Average Annual Utilization in Kilometers

The average annual utilization in km (AKM) is the number of kilometers driven per vehicle per year. The model uses the user-specified base average annual utilization in km (AKM₀) to compute the predicted vehicle annual utilization (AKM) which is a function of the predicted vehicle speed. The model doesn't provide default values for annual utilization in km.

The average annual utilization in km affects directly the following predictions:

- Depreciation
- Interest

Average Annual Utilization in Hours

The average annual utilization in hours (HRD₀) is the number of hours driven per vehicle per year. The model uses the user-specified base average annual utilization in hours (HRD₀) to compute the predicted vehicle annual utilization (AKM). The model doesn't provide default values for annual utilization in hours.

The average annual utilization in hours affects directly the following predictions:

- Depreciation
- Interest

Hourly Utilization Ratio

The hourly utilization ratio (HURATIO) is the ratio of the annual number of hours driven to the number of hours available for operation. The model uses the hourly utilization ratio to compute the predicted vehicle annual utilization (AKM). The model provides default values for the hourly utilization ratio (see Page 52).

The hourly utilization ratio affects directly the following predictions:

- Depreciation
- Interest

Average Service Life

The model uses the base user-specified average service life (LIFE₀) to compute the predicted service life (LIFE) which can be a function of the predicted vehicle speed. The model doesn't provide default values for the base average service life.

The average service life affects directly the following prediction:

- Depreciation

Use Constant Service Life?

The model has provides options for computing the service life (LIFE). Enter 1 to use a constant service life which is equal to the base user-specified average service life (LIFE₀), and enter 0 to compute the service life as a function of the predicted vehicle speed, the user-specified service life (LIFE₀) and the base vehicle utilization.

The service life computation method affects directly the following prediction:

- Depreciation

Age of Vehicle in Kilometers

The model uses the average age of the vehicle group in km (CKM), defined as the average number of kilometers the vehicles belonging to the particular vehicle class have been driven since they were built, to predict the maintenance parts and labor costs. The model doesn't provide default values for CKM. A convenient formula to arrive at a good estimate of CKM is:

$$CKM = \min (0.5 \text{ LIFE}_0 \text{ AKM}_0, CKM1)$$

LIFE₀ is the user-specified base average vehicle service life.

AKM₀ is the user-specified base average number of kilometers driven per year.

CKM1 is a ceiling on average vehicle age in km given below:

Vehicle	CKM1
Car and utility	3,000,000
Bus	1,000,000
Light truck	600,000
Heavy truck	600,000
Articulated truck	600,000

The average age of vehicle in km affects directly the following predictions:

- Maintenance parts
- Maintenance labor

Passengers per Vehicle

The model uses the number of passenger per vehicle (PAX) to compute the passenger time costs. The model doesn't provide default values for number of passengers per vehicle.

The number of passenger per vehicle affects directly the following prediction:

- Passenger time

Unit Costs

You may specify unit costs in either financial or economic terms. The model computes the vehicle operating costs in the corresponding term. Financial costs represent the actual costs incurred by transport operators in owning and operating the vehicles over the road. Economic costs represent the real costs to the economy of that ownership and operation, where adjustments are made to allow for market price distortions such as taxes, foreign exchange restrictions, labor wage laws, etc, and where the implicit costs of passengers' time and cargo holding are accounted for.

Note that you can enter the unit costs in any currency, but be aware that you may have some problems in the format of reports and tables if the magnitude of your input currency is much different from US dollars. A suggestion is to use thousands or millions of the currency unit.

The model does not provide default values for unit costs. The unit costs required are the following:

New Vehicle Price

The new vehicle price (cost per new vehicle) affects directly the following predictions:

- Maintenance Parts
- Depreciation
- Interest

Fuel Cost

The gas or diesel cost (cost per liter) affects directly the following prediction:

- Fuel cost

Lubricants Cost

The lubricant cost (cost per liter) affects directly the following prediction:

- Lubricant cost

New Tire Cost

The new tire cost (cost per new tire) affects directly the following prediction:

- Tire wear

Crew Time Cost

The crew time cost (cost per crew-hour of vehicle operation) affects directly the following prediction:

- Crew cost

Passenger Delay Cost

The passenger delay cost (cost per passenger-hour delayed) affects directly the following prediction:

- Passenger delay cost

Maintenance Labor Cost

The maintenance labor cost (cost per labor-hour of vehicle repairs and maintenance) affects directly the following prediction:

- Maintenance labor

Cargo Delay Cost

The cargo delay cost (cost per vehicle-hour delayed) affects directly the following prediction:

- Cargo delay cost

Annual Interest Rate

The annual interest rate (annual interest charge on purchase of new vehicle, %/year) affects directly the following prediction:

- Interest

Overhead per vehicle-km

The overhead per vehicle-km (lump sum overhead cost per vehicle, in input currency per vehicle-km) affects directly the following prediction:

- Overhead

Maintenance Parts Parameters

The model uses the following parameters to predict the maintenance parts costs:

- KP is the age exponent.
- CPo is the constant coefficient in the exponential relationship between spare parts consumption and roughness.
- CPq is the roughness coefficient in the exponential relationship between spare parts consumption and roughness.
- QIPo is the transitional value of roughness.

The model provides default values for these parameters (see Table 4, Page 48).

Maintenance Labor Parameters

The model uses the following parameters to predict the maintenance labor costs:

- CLo is the constant coefficient in the relationship between labor hours and part costs.

- CL_p is the exponent of part costs in the relationship between labor hours and part costs.
- CL_q is the roughness coefficient in the exponential relationship between labor hours and part costs.

The model provides default values for these parameters (see Table 4, Page 48).

Lubricant Parameters

The model uses the following parameter to predict the lubricant consumption:

- CO₀ is the constant term of the lubricants relationship.

The model provides default values for this parameter (see Table 2, Page 41).

Vehicle Speed Parameters

The model uses the following parameters to predict the vehicle speed:

- FRATIO₀ is the perceived friction ratio (dimensionless).
- FRATIO₁ is load parameter for adjusting perceived friction ratio (tons-1).
- ARVMAX is the maximum average rectified velocity of suspension motion (m/s).
- BW is the width parameter for adjusting the desired speed (dimensionless).
- BETA is the Weibull shape parameter for speed distribution (dimensionless).
- E₀ is the bias correction factor.

The model provides default values for these parameters (see Table 1, Page 39).

Fuel Parameters

The model uses the following parameters to predict the fuel consumption:

- A₀ through A₇ are coefficients used in the prediction of the unit fuel consumption.
- NH₀ is the lower limit on negative power.

The model provides default values for these parameters (see Table 2, Page 41).

Additional Options

Rolling Resistance Coefficient

You may specify the relationship between the rolling resistance coefficient and roughness. You may enter the constant value (a) and the slope (b) for the following equation:

$$CR = a + b IRI$$

The default values for a and b are from the Brazil study.

Vary Engine Speed for Passenger Cars

You may vary the engine speed as a function of the vehicle speed for passenger cars to improve the fuel consumption prediction. The default is to vary the engine speed. Note that the HDM-III model does not have this option. Therefore, to obtain the same results as the HDM-III model you should not vary the engine speed.

Specify Vehicle Speed

You may specify the vehicle speed, bypassing the speed prediction model. The default is to compute the vehicle speed.

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