

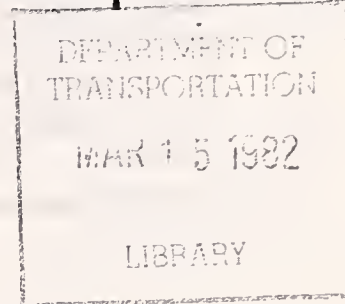
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A Computer Program (HEVSIM) for Heavy Duty Vehicle Fuel Economy and Performance Simulation

Volume 1: Description and Analysis

Richard E. Buck



**Transportation Systems Center
Cambridge MA 02142**

**September 1981
Final Report**

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16. Abstract This report presents a description of a vehicle simulation program, which can determine the fuel economy and performance of a specified motor vehicle over a defined route as it executes a given driving schedule. Vehicle input accommodated by HEVSIM include accessories, engine, rear axle, converter, transmission, tires, aerodynamic drag coefficient, and shift logic. The report consists of three volumes. Volume I presents a description of the numerical approach and equations, Volume II is a user's manual, and Volume III contains the program listings.					
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PREFACE

The vehicle performance simulation computer program, HEVSIM, was developed at the Transportation System Center of the U.S. Department of Transportation as an engineering tool for studies required in support of the DOT/SAE Truck and Bus Fuel Economy Program and the Transit Bus Energy and Propulsion Technology Program.

Several years ago under the Automotive Energy Efficiency Program, this computer simulation program was initiated for automotive applications. The program has been revised to accept heavy duty vehicle component data specifications and has been greatly enhanced to accept heavy duty vehicle operational modes.

The Transportation Systems Center wishes to acknowledge the expertise of Leonard Somers, System Development Corporation, who provided valuable assistance in the development of this program.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³

TEMPERATURE (exact)

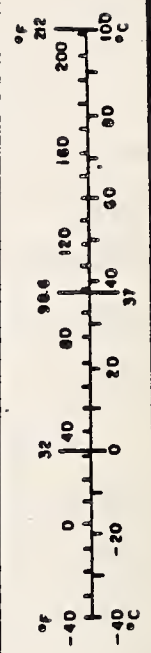
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C
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Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F
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¹ in 1 2.54 exactly. For other exact conversions and more detailed tables, see NBS Misc. Publ. 288, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10.285.

CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION.....	1
2	SIMULATION TECHNIQUE.....	3
2.1	Continuous Simulation Method.....	3
2.2	Modes of Operation.....	4
2.2.1	Constant Acceleration Mode.....	6
2.2.2	Constant Velocity Mode.....	6
2.2.3	Constant Throttle Mode.....	8
2.3	Computation of Energy Losses.....	8
2.4	Transmission Shift Logic.....	9
2.5	Driving Schedule and Route.....	10
2.6	Computational Procedure.....	12
2.6.1	Overview of Equations.....	12
2.6.2	Analysis.....	12

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Engine Map Regions as seen by the HEVSIM Engine Routine.....	5
2	Flow Chart of Control Logic.....	7

SYMBOLS

a	Acceleration, ft/sec ²
b	Grade, %
BVG	Bevel gear between engine and torque converter
C _d	Aerodynamic drag coefficient
e _i	Gear efficiency for ith gear, %
e _r	Differential efficiency %
e _t	Tire efficiency, %
F _{ACCEL}	Inertia force due to acceleration, lb
F _{AERO}	Aerodynamic drag force, lb
F _{GRADE}	Force due to route grade, lb
F _{roll}	Force due to tire rolling resistance, lb
F _w	Force acting at wheel hub, lb
g _i	Gear ratio for ith gear
HP	Horsepower
I ₁	Moment of inertia of torque converter pump, ft-lb-sec ²
I ₂	Moment of inertia of torque converter, ft-lb-sec ²
I _A	Moment of inertia of accessories, ft-lb-sec ²
I _E	Moment of inertia of engine flywheel, ft-lb-sec ²
I _p	Moment of inertia of prop shaft, ft-lb-sec ²
I _w	Moment of inertia of a wheel and tire assembly, ft-lb-sec ²
IGIN ₂	Moment of inertia for ith gear (input mode), ft-lb-sec ²
IGOUT ₂	Moment of inertia for ith gear (output mode), ft-lb-sec ²
K _o	Transmission output capacity factor
N ₁	Torque converter input speed, RPM

SYMBOLS (Continued)

N_E	Engine speed ($\approx N_1$), RPM
N_P	Propshaft speed, RPM
N_W	Wheel speed, RPM
R	Wheel radius, ft
RAR	Rear axle ratio
r_s	Fuel rate, lb/hr
SR	Torque converter speed ratio
T_1	Torque convertor input torque, lb-ft
T_2	Torque converter output torque, lb-ft
T_A	Accessory torque, lb-ft
T_E	Engine torque, lb-ft
T_F	Front end rotating inertia torque, lb-ft
T_{GS_i}	Gear i spin loss, lb-ft
T_R	Rotating inertia torque of rear end, lb-ft
TRS	Rear axle spin loss, lb-ft
T_W	Torque at wheel hub, lb-ft
TR	Torque converter torque ratio
t	time, sec
W	Weight, lb
z_1	Rolling resistance force linear term, lb/1000 lbs W
z_2	Rolling resistance force velocity dependent term, lb/1000 lb per mph
z_3	Constant in aerodynamic force equation
z_4	Yaw angle sensitivity coefficient
ϕ	Angle of wind relative to vehicle

1. INTRODUCTION

HEVSIM is a numerical vehicle performance simulator which can determine the fuel economy and performance of a specified motor vehicle as it executes a given driving schedule. The program is versatile in that it is capable of simulating buses and trucks while maintaining consistency of input data format and operating procedures. A simulation exercise may be conducted from a remote terminal interactively or in batch. Alternatively, the program may be submitted in batch via a card deck.

HEVSIM provides the user with a convenient way to evaluate the individual vehicle components (e.g. engine, torque converter, drag coefficient, weight, etc.) and to determine their effects on the fuel consumption of the vehicle. Also, detailed analyses and monitoring, both qualitative and quantitative, of the variously proposed driving schedules may be made.

This document describes HEVSIM in three volumes. Volume I presents a description of the numerical approach and equations, Volume II is a user's manual and Volume III contains the appendices. Sample cases are provided in the user's manual, while the program listing is included in the appendices.

2. SIMULATION TECHNIQUE

2.1 CONTINUOUS SIMULATION METHOD

HEVSIM utilizes the method of continuous incremental time-step simulation to model performance and fuel economy characteristics for trucks or buses. This method was picked because the state of the vehicle being modeled is constantly changing, and none of the other simulation techniques (such as mathematical model or discrete event simulation) would be appropriate.

The continuous incremental approach is quite straightforward. A time-step Δt is defined by the user, and the initial condition of the vehicle are set by the program. Then, at the end of time Δt , the desired velocity and acceleration of the overall vehicle are computed using the appropriate driving schedule data. The torque and RPM at the wheels are then known, and these quantities are transmitted back to the engine by way of the differential, gear box, and torque converter (automatic transmission), or clutch mechanism (manual transmission). After the determination of this "required" engine torque and rpm, a table look-up with a linear interpolator is used to determine the fuel flow rate and throttle position.

Since the desired forces at the wheels do not "know" in advance whether or not the engine will be able to respond satisfactorily to their demand, a control structure must exist which assures that all required engine states will be within the range of the specified engine input data, or that they will be "on the engine map." If the control logic senses that such a demand is too great, the demand is reduced accordingly. In some situations where the engine is unable to absorb energy quickly enough (motoring), as in coast down, the brakes may be applied. As a guide to desired performance, the control logic uses the driving schedule and route data which specify, among other things, the mode of operation required.

The engine map routine performs one of the most critical calculations in HEVSIM; it interpolates the input engine data to find the instantaneous fuel flow rate. It also determines whether or not the "demand" from the wheels may be satisfied by the engine without further consideration by the control logic.

As may be seen in Figure 1, the engine routine views the map as a set of nine regions. Region 1 is the actual input engine map data. Regions 2 thru 9 are "off-the-map" regions, and the control logic may have to take some corrective action. Region 2 contains points with valid load demands but which are below minimum engine speed. In this case the torque and fuel flow rates from the lowest two engine speeds are projected down to the desired speed. (Note that if the result is less than the idle speed of the engine, the control logic will pin the engine at idle speed and converter spin loss [or clutch slip] will account for the energy difference.) Region 3 contains points with valid load demands but which are above the maximum engine speed that was fed into the model. In this case, the torque and fuel flow rates from the highest two speeds are projected up to the desired speed.

Regions 5, 8, and 9 are areas in which the engine is overtaxed and is beyond 100 percent WOT (wide-open-throttle). These are definitely areas in which the control logic must adjust the demand at the wheels by reducing the required acceleration. Regions 4, 6, and 7 are areas in which the engine's absorption capability (motoring torque) is insufficient to absorb all the energy coming back from the wheels (as in a coast-down condition). In these areas the control logic must apply the brakes.

2.2 MODES OF OPERATION

The desired performance criteria, as specified by the driving schedule, is the factor which determines the mode of operation of the vehicle. HEVSIM has three primary modes of operation: constant acceleration, constant velocity, and constant throttle setting. These modes are actually segment types which make up the driving schedule. The basic idea is that the control logic tries to maintain one of the operational modes specified in each segment of the

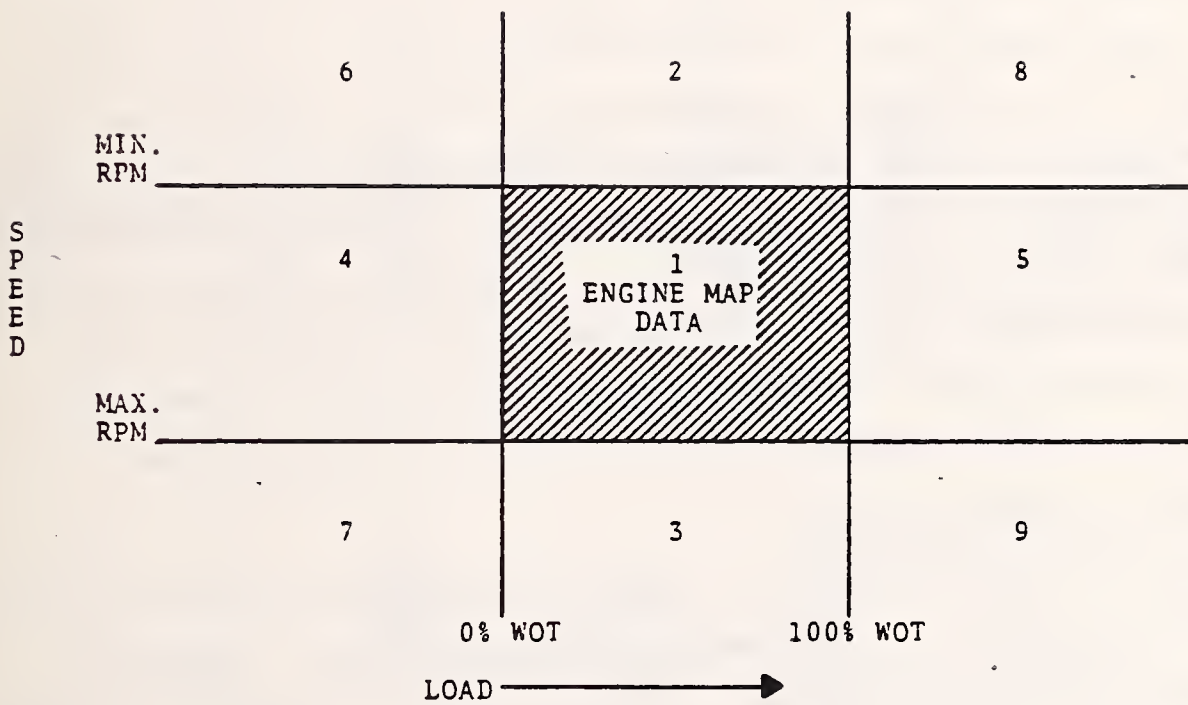


FIGURE 1. ENGINE MAP REGIONS AS SEEN BY THE HEVSIM ENGINE ROUTINE

schedule by adjusting the demand on the engine accordingly. In a very real sense, the control logic is "driving" the vehicle. The interactions between these modes of operation and the adjustment of the demand on the engine are shown in Figure 2. In each segment of the driving schedule, checks are made to determine which type of operational mode is currently being followed. The control logic then adjusts either the acceleration or throttle until the specified condition is satisfied.

2.2.1 Constant Acceleration Mode

In this mode HEVSIM attempts to reach and maintain a constant rate of acceleration (or deceleration). Should this condition require the engine to produce a torque greater than its maximum allowable value, a lesser acceleration would be attempted, and the 100 percent WOT point would be used. For negative accelerations (coast-down conditions), the 0 percent WOT torque is the minimum torque allowed. This torque is negative since it reflects motor-ing of the engine. Should the computed torque value at the engine be less than 0 percent WOT, the brakes would absorb the difference.

Note that a vehicle may or may not be able to achieve a given positive acceleration rate, due to the maximum horsepower curve of the engine. However, any negative acceleration rate is possible since it simply requires additional braking to be negotiated.

2.2.2 Constant Velocity Mode

This mode is similar to the constant acceleration mode in that it attempts to maintain an acceleration rate of zero. However there are some differences in the control logic. Since it is not certain that the velocity at the beginning of the segment is equal to the desired velocity, a few time-steps are computed to urge the vehicle to reach this velocity and to allow certain transient phenomena, such as shifting into a new gear or computing rotating inertia effects, to die out. When this steady-state is reached, the rest of the segment is computed in one large time-step to conserve computer time.

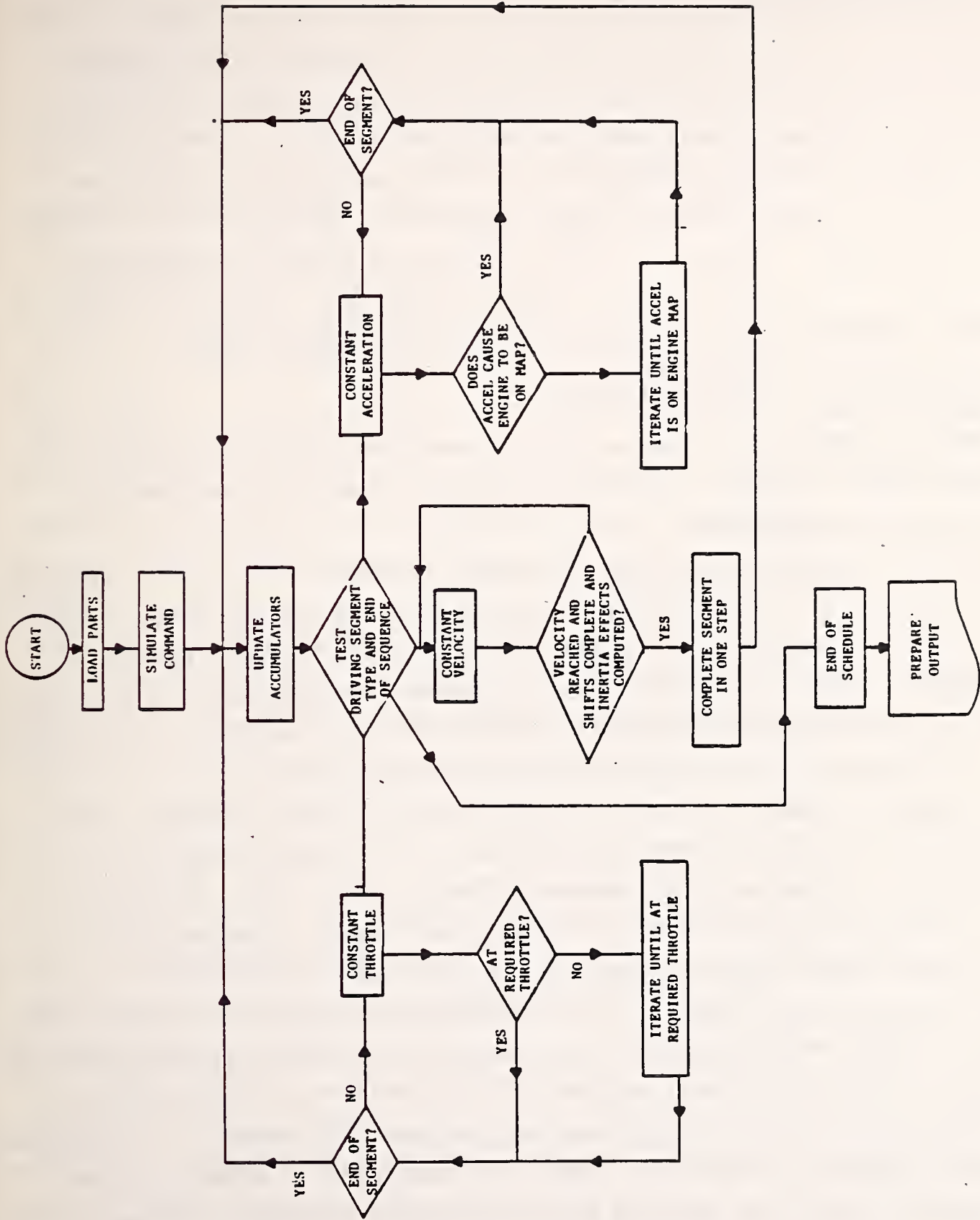


FIGURE 2. FLOW CHART OF CONTROL LOGIC

2.2.3 Constant Throttle Mode

The throttle position is defined as the percent of "throw" (maximum torque minus minimum torque) at a particular engine RPM. As such, the actual torque at 0 percent WOT is usually a negative number, which indicates motoring: it does not make a "quantum jump" from one to the other, thus preserving the continuous nature of the simulation. Again, as with the other modes of operation, the acceleration at the wheels is the parameter varied in order to maintain a constant percent throttle for any engine RPM.

2.3 COMPUTATION OF ENERGY LOSSES

Energy gains and losses are monitored by HEVSIM in terms of horsepower-hours (HP-HR). There are four types of "devices" for which losses are computed.

The first of these is the "in-line" device. This is a vehicle component which is actually part of the path of energy flow (drive-train) from the engine to the wheels. The tires, differential, gear box, and torque converter (or clutch mechanism) fall into this category. The loss for an in-line device simply consists of energy-out minus energy-in over the time-step being used.

The second type of loss is that of the "state" device. This is a device which has a loss associated with it as a function of RPM, such as the engine accessories' load. The losses are computed by taking the difference between the power required before and after the time-step and applying it for that duration.

The third type of loss is associated with certain "reversible" processes. The word "device" here ceases to be meaningful since the loss being referred to only exists if the states of the vehicle before and after the complete simulation are different. For example, should the vehicle start from 0 MPH and complete the simulation traveling at 55 MPH, a loss to kinetic energy would be obvious. If, however, the final speed was also 0 MPH, the net loss to kinetic energy would be zero. Other losses of this type include the rotating inertia losses and potential energy (grade). Note that it is possible to end up with a negative loss here (e.g. start-

ing at the top of a hill and ending at the bottom). Such a situation would be treated by the program as an energy "gain" and handled separately so that it would not be confused with energy output from the engine.

The final type of loss concerns those devices which have "inherent" losses. Engine motoring and the brakes are two such situations in which any associated power acting across a time-step is inherently considered to be irrevocably lost energy.

2.4 TRANSMISSION SHIFT LOGIC

When simulating a vehicle with a manual transmission, HEVSIM expects to see a maximum engine or vehicle speed in the shift logic data. If, for example during a simulation, the engine attempts to exceed this maximum engine speed, the control logic will authorize an upshift to the next higher gear. During an upshift the vehicle is allowed to coast, acted upon only by aerodynamic drag, rolling resistance, and gravity (grade). The engine, meanwhile, is disengaged from the drivetrain and is allowed to spin down by using the motoring torques to absorb the rotating energy of the engine, flywheel, and accessories. When the two speeds on either side of the clutch plates match, the engine is engaged to the drivetrain.

The user specifies the downshift engine or vehicle speeds for all gears so that when the downshift is performed the engine speed will be below the engine upshift speed. This requires the tailoring of each engine and transmission shift logic individually. Whenever HEVSIM detects the engine speed dropping below the downshift point for the gear engaged at that time, the control logic will authorize a downshift to the next lower gear. During a downshift, the same forces act on the overall vehicle as it is allowed to coast. However, the engine is throttled up to provide the energy necessary to increase the flywheel RPM to the new speed in the new gear. Again, when the speeds across the clutch plates match, the engine is re-engaged.

If a vehicle is in top gear when the maximum engine speed is reached, the program relies on the engine map to limit the available horsepower (governor droop should be built into the map for heavy duty trucks with diesel engines.) If the vehicle is in gear 1 when a downshift is requested, no action is taken,

The major problem with any shift logic, whether manual or automatic, is to prevent "stutter," i.e., switching back and forth from one gear to another. In order to counteract this possibility, HEVSIM will prevent a shift from occurring if the projected speed following an upshift is below the downshift speed for the new gear, or if the projected speed following a downshift is above the upshift speed for the new gear. Should this condition occur, the program would assume that a shift at that point would not be advisable, and would set the throttle to a value that would simply maintain the engine at the shift speed. This would continue until another new condition was requested (e.g., a change in grade).

The HEVSIM output record provides shift frequency data which may be used as an aid in determining the validity of the shift logic. The user should check the number of shifts being performed, and modify the shift logic if this number seems high by separating the shift lines more, particularly on the wide-open throttle end.

2.5 DRIVING SCHEDULE AND ROUTE

The driving schedule specifies vehicle motion according to one of the following segment types: constant vehicle acceleration, constant speed, or constant percent of full throttle. The calculation procedure for each of these segment types has been previously described, and will not be repeated here. There are other important considerations, however, which should be noted concerning the driving schedule and route.

Sudden changes in acceleration must be avoided when specifying driving schedule data. Such changes can result in unrealistic and artificially high torque demands. This problem can be circumvented by inserting a zero acceleration segment between two radically different accelerations that change in sign. In this

manner the peaks and valleys of sequential acceleration segments in a driving schedule are smoothed to negotiable profiles.

Specification of an unrealistic constant acceleration is permissible, but the program would only allow maximum engine horsepower to be delivered. The calculation procedure would then be similar to the case where 100 percent WOT is specified.

The end conditions for a segment may be specified by the attainment of any one of five criteria. One should be cautious of the possible consequences if only one end condition is specified. Such an example would be specification of an unattainable terminal speed for an underpowered vehicle. A simulation may be terminated by completion of either the driving schedule or route, whichever endpoint is reached first. A typical example is a general purpose route of 500 miles of level road, which may be used in conjunction with a driving schedule of any length 500 miles or less absolute distance.

A detailed route description may be prescribed, although the driving schedule may be relatively simple. For example, a route which incorporates many grades and changing wind velocities may be used with a driving schedule made up of 55 MPH initial conditions and 55 for an absolute distance equal to or greater than the total distance of the route. The simulation would attempt to follow the route by adjusting the accelerations as necessary to try to maintain the specified speed, in this case 55 MPH. Throughout such a simulation, there may not be sufficient engine power to maintain constant speed on uphill sections of the route: the brakes would be applied to augment engine braking, if necessary, on a downhill milepost interval to prevent exceeding the speed limit.

The driving schedule and route input formats were designed to provide simulation of essentially any road course. More often than not, a problem lies in providing the required data to make it possible for a vehicle to perform as desired.

2.6 COMPUTATIONAL PROCEDURE

This section will present a description of the mathematical formulation of vehicle performance within HEVSIM. A program listing is included in Volume III, Appendix 1.

2.6.1 Overview of Equations

Since HEVSIM uses the "deterministic" method of computing vehicle performance (i.e. the engine state is determined by demand at the wheels), the primary considerations are velocity and acceleration of the overall vehicle. HEVSIM uses standard Newtonian mechanics to compute gross vehicle motion. Therefore, the force acting on the vehicle at any given time is equal to the D'Alembert (inertial) force plus the sum of all the external forces. These external forces are aerodynamic drag, rolling resistance, and gravity (grade). After converting this force at the road level to a torque at the wheel hub, HEVSIM transmits this back to the engine by way of the differential, gear box, and torque converter (or clutch mechanism). Along the way the accessory torques and the torques due to rotating inertia changes are added in as well.

2.6.2 Analysis

The equations used to compute back from the wheels are simple and straightforward. At the wheels:

$$v_f = v_i + \frac{a_i \Delta t}{1.467} \quad (1)$$

where:

v_i is initial velocity (MPH) at the beginning of Δt ;

a_i is initial acceleration (ft/sec^2) at the beginning of Δt ;

v_f is the final velocity (MPH) at the end of Δt and Δt is the time step.

The rolling resistance force F_{ROLL} is given by:

$$F_{\text{ROLL}} = (Z_1 + Z_2 v_f)W/1000 \quad (2)$$

where:

Z_1 and Z_2 are input constants; and
W is the vehicle weight.

The aerodynamic drag force F_{AERO} is:

$$F_{AERO} = Z_3 C_D A (v_f + v_w)^2 \{1. + Z_4 \tan^{-1} [v_n / (v_f + v_w)]\} \quad (3)$$

where:

$Z_3 = \rho(1.467)^2 / 2g$ is an input constant,

C_D is the drag coefficient;

A is the frontal area;

v_w is the wind velocity component parallel to the direction of the vehicle; and

v_n is the wind velocity component normal to the direction of the vehicle. Additional comments on equation (3) are included in Section 6.

The inverse tangent function computes the yaw angle, which is the angle of the air motion (including wind) as seen by the vehicle. The coefficient Z_4 is a measure of how sensitive the drag coefficient is to the yaw angle. For yaw angles of up to 30 degrees, considering bluff bodies such as trucks and buses, this sensitivity factor appears to have a value of about 0.02 per degree of yaw up to about 30 degrees yaw.^{1,2} HEVSIM accepts this coefficient on the vehicle input information data card as the C_d sensitivity coefficient.

The angle of wind direction PHI referenced to the vehicle direction ($\phi = 0$. for headwinds; ; $\phi = 180$. for tailwinds) and wind velocity VWIND are inputted using MODIFY PHI and MODIFY WIND cards, respectively. Default values are wind velocity VWIND and

-
1. "The Aerodynamics of Basic Shapes for Road Vehicles," The Motor Industry Research Association, Report No. 1969/2, 1969.
 2. "Truck Aerodynamics," H. Flynn and P. Kyropoulos, SAE Transactions 1962, Vol. 70, C. 1962m p. 297-308.

direction PHI, both equal to zero. The user is cautioned that this wind modification features is an approximation and may not be reasonable in all cases due to different vehicle designs. This modification should not be used for vehicles which cannot be approximated as bluff bodies, and it should be restricted to yaw angles only up to about 30 degrees.

The inertial force due to acceleration F_{ACCEL} is:

$$F_{ACCEL} = \frac{a_i W}{32.17}, \quad (4)$$

and the force due to route grade F_{GRADE} is:

$$F_{GRADE} = bW/100. \quad (5)$$

where b is percent grade being traveled.

The force acting at the wheel hub (F_w) is then given by:

$$F_w = (F_{ROLL} + F_{AERO} + F_{ACCEL} + F_{GRADE})/e_t \quad (6)$$

where e_t is the tire efficiency.

We find the rear end rotating inertia torque T_R using the following equation:

$$T_R = \frac{2\pi}{60} \{ (TI)I_w + (RAR)^2 e_r [(I_p + IGOUT_i) + g_i^2 e_i (I_2 + IGIN_i)] \} \left\{ \frac{\Delta N_w}{\Delta t} \right\} \quad (7)$$

where:

TI is the number of wheels;

e_r and e_i are the efficiencies of the differential and the i^{th} gear, respectively;

$IGOUT_i$ is the output moment of inertia for the i^{th} gear;

$IGIN_i$ is the input moment of inertia for the i^{th} gear;

I_w , I_p and I_2 are the moments of inertia for a wheel, the propshaft and the torque converter turbine, respectively;

g_i is the gear ratio for the i^{th} gear;

RAR is the rear axle ratio;

and ΔN_w is the change in RPM's at the wheels, i.e.

$$\Delta N_w = (N_w)_f - (N_w)_i \quad (8)$$

$$\text{where } (N_w)_t = \frac{60}{2\pi} \times \frac{V_t}{R} \times 1.467 \quad (9)$$

for any time t ;

R is the rolling radius of the wheel (ft);

and V_t is the vehicle speed (MPH).

We may now compute the total torque at the wheel hub (T_w)

as follows from equations (6) and (7):

$$T_w = R F_w + T_R \quad (10)$$

Proceeding back through the differential we obtain the propshaft state as:

$$N_p = (\text{RAR}) N_w \quad (11)$$

$$\text{and } T_p = \frac{T_w}{(\text{RAR}) e_r} + T_{RS} \quad (12)$$

where T_{RS} is the rear axle spin loss interpolated from rear axle tabular input.

The input to the gear box then follows from:

$$N_2 = g_i N_p \quad (13)$$

$$\text{and } T_2 = \frac{T_p}{g_i e_i} + T_{GS_i} \quad (14)$$

where T_{GS_i} is the gear spin loss for gear i interpolated from tabular input.

The output capacity factor (K_o) of the torque converter, where

$$K_o = \frac{N_2}{\sqrt{T_2}}, \quad (15)$$

provides us with a means of interpolating the torque converter tables to obtain the speed ratio (SR) and torque ratio (TR).

The input to the torque converter is then given by:

$$N_1 = N_2 / (\text{SR}) \quad (16)$$

and $T_1 = T_2 / (\text{TR}). \quad (17)$

A bevel gear (BVG) connects the engine to the torque converter in most transit buses. The engine speeds and torque is therefore a function of the BVG ratio and efficiency:

$$N_E = \frac{N_1}{\text{BVG}} \quad (18)$$

$$T_E = T_1 (\text{BVG}_{\text{eff}}). \quad (19)$$

If BVG ratio and efficiency are set to unity, then the BVG is in effect removed from the HEVSIM program.

The accessory speed (N_A) is a function of the pulley system or gearing speed ratio (ASR) between the engine and the accessory. (The accessory speed ratios can be different for each accessory.)

The accessory speed is given by:

$$N_A = N_e (\text{ASR}) \quad (20)$$

The accessory torque and inertia are reflected to the engine by the ASR and $(\text{ASR})^2$ respectively. Final torque and inertia are also modified by the value of the individual accessory duty cycle.

The front-end rotating inertia torque (T_F) is given by the equation:

$$T_F = \frac{2\pi}{60} \left(I_E + \frac{I_A}{(ASR)^2} + \frac{I_1}{(BV)^2} \right) \frac{\Delta N_E}{\Delta t} \quad (21)$$

where:

I_E , I_A and I_1 are the moments of inertia for the engine flywheel, each accessory and the torque converter pump, respectively;

and ΔN_E is the change in RPM's at the engine, i.e.

$$\Delta N_E = (N_E)_f - (N_E)_i. \quad (22)$$

We can now find the torque at the engine (T_E) from:

$$T_E = T_1(BVG) + T_A(ASR) + T_F. \quad (23)$$

Given T_E and N_E we can interpolate the engine map to obtain fuel rate, manifold vacuum and throttle position.

Horsepower at any point Z, of course, is given simply by:

$$HP_Z = T_Z \times N_Z / 5252 \quad (24)$$

where the torque is in lb.-ft. and the speed is in RPM.

The instantaneous fuel economy in MPG is computed from:

$$(FE)_f = v_f / r_f \quad (25)$$

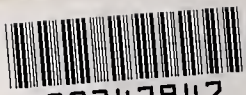
where r_f is the fuel rate from the engine map.

The cumulative fuel economy is given by total miles driven divided by total gallons consumed.

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