# 3.0 MAJOR ACCOMPLISHMENTS AND EXPERIMENTAL RESULTS

The following sections discuss briefly the most significant accomplishments and experimental findings of this project. If the reader desires more information on a particular subject, references are made to later sections of this report.

## 3.1 COMPUTER PROGRAM FOR PREDICTION OF VEHICLE PERFORMANCE ON HIGHWAYS (HPP)

This project culminated in the development of a computer program that predicts the fuel consumption and air pollutant emission of vehicles when operated on highways of arbitrary length and geometric design. The algorithm considers the effects of realistic driving patterns involving accelerations and decelerations and of operating on roads that have positive and negative grades, and can evaluate the added propulsive demands of horizontal curves. If vehicle data include information on vehicle exhaust emissions in appropriate formats, the program can also estimate the exhaust emissions resulting from the above kinds of vehicle operation. The algorithm operates efficiently and economically; it simulates vehicle operation in piecewise fashion over short increments of road (typically about 50 m/increment), and processes about 2 to 3 mi (3.22 to 4.83 km) of road travel by one vehicle/second of computer operation. The method was implemented on personal computers. The computer program incorporates the necessary level of automotive engineering insights, and the highway designer need input only highway geometry and vehicle speed vs. distance. Alternative configurations of any particular highway can be entered sequentially and vehicles "driven" over each with little interaction by the user. The differences (in fuel consumption and emissions," if data are available) between the optional configurations can provide objective, realistic comparisons of the relative operating costs to the driving public of the alternative highway designs or traffic flows or both as desired.

The computation method is described in detail in Appendix A.

## 3.2 EFFECT OF ROAD GRADE

In the first vehicle tests under this project, total driveshaft torque was measured in a series of replicate runs on a 4-mi (6.4-km) section of private/ road at speeds of 15 to 60 mi/h (24 to 96 km/h) and on grades up to +8 percent. A linear correlation between driveshaft torque and road grade was found that showed a standard deviation of 2.2 percent. When vehicle-specific factors were used to calculate the increment of torque for a given grade change, the experimental data agreed with calculated values within 1.2 percent. This quality of agreement between experimental data and calculated values corroborated general experience in automotive engineering. It was considered to have demonstrated sufficiently that the effect of road grade on driveshaft torque could be calculated for typical operating conditions. Thus, it would not be necessary to measure this characteristic of additional vehicles for which performance data bases were to be prepared.

Attempts to identify an effect of horizontal curvature on torque in this set of test data were unsuccessful. It was concluded that a more sensitive test of this phenomenon, in which the desired effect was isolated as much as possible from perturbing influences (such as grade), was required.

For additional information, see Appendix D, Section D.2.

## 3.3 EFFECT OF HORIZONTAL CURVATURE

At the outset of this project, the FHWA's early requirements were to demonstrate (a) whether the effects of highway geometrical features on vehicle propulsive demand could be measured, (b) whether such effects could be calculated reliably for vehicles without having to test each vehicle on the road, (c) whether vehicle operation on various highway geometries could be simulated adequately on a large-roll research-grade chassis dynamometer, and (d) whether such simulation was necessary. While these questions were answered quickly for the effects of road grades, the influence of horizontal curvature was more difficult to quantify. It was necessary to develop special test methods and equipment with greater sensitivity and to eliminate sudden transients in road geometrical configuration before adequately quantitative data could be obtained.

A suitable method of quantifying the effect of horizontal road curvature (without superelevation) on driveshaft torque was developed. Three concentric circles with radii of 100, 200, and 300 ft (30.5, 61, and 91.5 m) were marked out with road-marking tape on a portland cement concrete-paved plane area that was inclined at about 0.8 percent (for drainage). A common starting point for all circles, at the high point of the surface, was marked with a radial strip of tape. The test vehicle was driven around each circle in continuous laps at nominally constant speed while data were recorded for six laps. This procedure was repeated for a total of five speeds on each of the three circles, for each of three cars. The five speeds on each circle were chosen to produce lateral accelerations of approximately 0.1, 0.2, 0.3, 0.4, and 0.5 G. (Lateral acceleration = speed squared/radius of curvature.)

Analysis of the data showed that the dependent variable was the increment of driveshaft torque, i.e., the difference between torque on a curve at a given speed and torque on a straight, level road at the same constant speed; this parameter was termed the "curve-torque increment." Similarly, the independent variable was found to be lateral acceleration, which conveniently incorporated both the curve radius and speed on the curve into one parameter. The curve-torque increment showed extremely good correlation with a quadratic function of lateral acceleration, was independent of speed per se, and—for radial-ply tires—appeared to be independent of curve radius. Bias-ply tires on one car also showed clear dependence on curve radius. The self-consistency of each set of data for a given car and tire set was much better than normally is encountered in measurements on operating vehicles.

The curve-torque increment was divided by the straight-road torque at the same speed to "normalize" the quantity i.e., to reduce or eliminate the explicit restriction of the relationship to an individual vehicle or type of vehicle. This normalization introduced a modest dependence on curve radius and increased the dispersion of the data points. However, when all normalized data for each car individually were used to calculate a single regression curve for that car, and the three regression curves were compared, a reasonable degree of agreement between the curves was apparent. Another regression of data points calculated from each of the three curves produced a single composite regression curve that represented an approximate description of any of the three cars.

This composite regression curve of normalized curve-torque increment vs. lateral acceleration is proposed for general use in estimating the effect of horizontal curvature on any vehicle that has not been curve-tested but for which the straight-road, tractive force, or driveshaft torque relationship to constant speed is known.

Subsequent to much of the curve testing and analysis, and independent of that work, a theoretical analysis of "cornering drag" vs. curvature and speed was published (3). This study, developed admittedly with almost no experimental data to support it, found precisely the same parameters to be active as are described above. The relationships also were in agreement. The theory explained the divergence of normalized curve-torque increment data, i.e., it showed there is a dependence on curve radius; further, the theory demonstrates there also is a dependence on the cornering compliance of the tires. Therefore, there is theoretical opposition to the validity of the single "universal" normalized curve-torque increment relation postulated above to be applied to all passenger cars if no other data exist. However, for the purposes of this project, the availability of at least one empirically based approximate description of the effect of horizontal curvature is preferable to having no relationship simply because the cornering compliance of unknown makes of tires is unavailable.

Thus, this project validated experimentally a simple analytic expression relating added propulsive requirement on curves to a function of both speed and curve radius, viz., to lateral acceleration. The relationship was shown to be smooth, stable, and repeatable.

The software needed for the input of modules that defines horizontal curvature vs. distance along the road is a direct parallel of that for grade vs. distance. Hence, the computation routine for calculations of curve-torque increment is known. The software for grades was copied and modified slightly for horizontal curvature.

For additional information, see Appendix A, Section A.3.2; Appendix C-Sections C.1.2, C.1.3, and C.2.2; and Appendix D, Section D.2.3.

## 3.4 DETERMINATION OF ROAD LOAD FROM CONSTANT-SPEED TORQUES

The term "road load" as used in this report and project has a specific meaning; it refers to the total propulsive requirement, in terms of either driveshaft torque or tractive force of the drive tires, as a function of vehicle speed on a level, straight road at any constant speed and in the absence of any ambient wind (i.e., wind speed relative to the ground). Road load, as used here, excludes any power demands on the engine by engine auxiliaries, air conditioning, etc. Road load, an important characteristic or property of any vehicle, typically is described by a mathematical expression always containing a term independent of speed and another term that is dependent on the second power of speed; the expression may or may not contain another term dependent on the first power of speed, based on the mathematical technique by which the regression is performed.

Determination of road load was essential in this project. First, the road load relationship was an important component of the vehicle data bases that would be constructed to support the analytical algorithm for estimating vehicle fuel consumption on highways. Second, road load was required in analysis of the curve-torque phenomenon to provide the base quantity to subtract from total on-curve torque.

For uninstrumented vehicles, road load most often is determined by the coastdown technique (4, 5). However, roads and airport runways in New England lack the requisite straight length (typically, 2 mi or 3 km) with grade that is essentially constant (+0.1 percent) and of small magnitude (+1 percent or less). Coastdown tests under this project did not produce satisfactory data.

Since the test vehicles already were equipped to measure and record driveshaft torque, an alternative technique was to run the vehicles in both directions at several different, nearly constant speeds over a modest length of straight road that was adequately constant in grade. The central 6000-ft (1.8-km) portion of the Bangor runway, with a slope of 0.6 percent, proved quite satisfactory. Test speeds usually were approximately 25, 40, 55 and 70 mi/h (40, 64, 88, and 113 km/h). Regressions of mean torque against a quadratic function of mean speed were performed simply with a programmable calculator; the correlations were consistently excellent. The resultant equation provides data on both the rolling friction (speed-independent and speed-linear terms) and aerodynamic drag (speed squared term) characteristics of the vehicle.

During these tests, a limited number of tests was conducted at speeds of less than 25 mi/h (40 km/h) on the circle-test pad over distances of less than 1000 ft (300 m). The results of these shorter-length tests indicated that torque-instrumented vehicles such as these also could be used for another type of measurement: comparison of the rolling friction characteristic of different pavements. This could be done as described in Section 3.5 below.

### 3.5 PAVEMENT FRICTION COMPARISON WITH TORQUE-INSTRUMENTED VEHICLE

The sections of pavement on which friction is to be measured should have as little slope as feasible and should have contiguous approach segments that permit approach from both directions at the speeds at which measurements are to be made. The measurement sections preferably should be straight, or at least have curvatures low enough to generate lateral accelerations of less than about 0.05 G at the highest intended test speed. Test length need not be more than few hundred feet, but more length should promote better data. The approaches need not be as straight as the test section, but should not have substantial transients that would hinder stable operation on the test section. Replicate series of torque measurements, taking data points every few feet of travel, should be made on the test section in pairs at each of several speeds spanning as wide a range as possible, with consecutive runs made in opposite directions at each speed (see Appendix B, Section B.4.2). Similar measurements should be made on each type of pavement surface to be evaluated.

Regressions of the data will produce coefficients of both rolling friction and aerodynamic drag. Since the tests all were performed with the same vehicle, the aerodynamic coefficient should be essentially the same in all tests (except for normal experimental variation). The only reason for variation in the rolling friction coefficients should be the differences in the pavements driven on.

It must be noted that the absolute values of rolling resistance on each kind of pavement will be specific to the particular vehicle, tires used including tire pressure, moisture condition on road, and length of time the vehicle has been in operation. (Until engine and tires are warmed up, rolling resistance is higher. Water, snow, or ice on pavement will keep tires much cooler) .

A variety of vehicles should produce somewhat diverse rolling resistance values on a given pavement. However, pending evaluation of this application of the technique, it is reasonable to expect that the relative effects of several types of pavement on each of a variety of vehicles should produce approximately comparable relative changes in rolling resistance for each of the vehicles. Therefore, friction measurements with only a single test vehicle should give a reasonably valid assessment of the relative behavior of the different pavements for traffic in general.

### 3.6 INFLUENCE OF DRIVER VARIANCE ON HIGHWAY FUEL ECONOMY

An experiment was conducted with 10 drivers selected at random from the VNTSC employee staff and consisted of 5 women and 5 men of various ages, plus a "control" driver who was the experiment conductor. The 10 drivers were not told that their driving habits were the subject of the experiment; they were given to understand they were evaluating some prototype road-test equipment. The test road was a rural section of a limited-access, divided highway used for this test only during low-traffic times; it had a uniform posted speed limit of 55 mi/h (88 km/h). The test vehicle was one of the instrumented cars with automatic transmission; the data logger recorded speed, torque, and fuel flow continuously throughout the test drives at 1 sample per second. Each driver made six runs, three as he or she "would normally drive" and three while keeping speed as constant as possible at 55 mi/h (88 km/h); two runs were made on each of three different days.

The experiment was conducted at highway speeds because a literature search showed no previous work had been performed at this level, while a considerable amount of testing had been done at urban conditions. The literature indicated a general consensus that, at highway speeds, fuel economy drops as average speed increases, is dependent mainly on the speed driven, and is largely independent of the driver (6).

The results of this experiment refuted this usual assumption. The fuel economy observed was found to be driver-dependent beyond the effect attributable to speed chosen by that driver. The maximum range of fuel economy values was about 4.5 times that which should have resulted from the spread of speeds involved. For all drivers at all speeds from 52 to 57 mi/h (84 to 92 km/h), there was no statistical correlation between fuel economy and speed; however, there was a very strong statistical indication that fuel economy was associated with the driver.

## 3.7 EFFECT OF TRACTIVE FORCE LEVEL ON ENERGY DISSIPATION IN TIRES AND AXLE

Whenever chassis dynamometer testing is performed on a vehicle equipped to measure driveshaft torque, the torque or tractive force (positive or negative) observed at the dynamometer roll surface always is smaller in magnitude than the value corresponding to torque measured in the driveshaft. This "torque loss" results from friction in the bearings of the drive axle and from energy dissipation both within the drive tires and between the tires and the dynamometer rolls. The sum of the last two quantities usually is termed the "rolling friction" of the tires, and generally is assumed to comprise nearly the total amount of torque loss. Rolling friction is measured routinely by tire manufacturers and researchers at zero transmitted torque; their test equipment generally is not equipped to apply or measure a significant amount of drive or braking torque. Consequently, very few data have been published on the effect of drive torque level on energy dissipation, i.e., on rolling friction under significant drive torque output.

During performance mapping of one of the test vehicles on the large-roll chassis dynamometer, the torque loss was analyzed for nearly every test point. When the torque loss was plotted against total drive torque as the independent variable (or, alternatively, loss in tractive force against total tractive force), the relationship could be described quite well by a quadratic function of total torque (or force). The relationship appeared to be essentially independent of speed over the range from 15 to ll7 km/h (9 to 73 mi/h). Thus, this was the simplest manner in which to express the phenomenon; had it been expressed in terms of power, a speed-dependency would have been introduced that would have complicated the evaluation. The effect of speed was, in fact, introduced implicitly by the higher drive torque or tractive force required to maintain higher speeds.

The magnitude of the torque loss, in relation to total torque, tended to be about 6 to 7 percent of total torque over most of the normal operating range of the vehicle. At very high torques corresponding to low gear and heavy throttle, the loss increased to more than 10 percent. As drive torque approached zero, the torque loss reached a minimum but still significant value—equivalent to the normal "rolling friction" measurement; the ratio of loss to total torque, of course, became meaningless as the denominator approached zero. At negative drive torques, the loss began to increase again.

For additional information, see Appendix C, Section C.1.5.

## 3.8 EXPERIMENTAL VEHICLE DATA BASES

Data bases of experimental fuel economy (measured on a chassis dynamometer) were produced for three cars; one of the three included associated data on exhaust emissions. Test conditions spanned the normal operational ranges of speed and torque. Fuel economy data for the first vehicle (plus an earlier one used in the pilot study, for which the test conditions did not include large negative torques) could be represented quite well, over essentially the entire highway range of speed and torque, by a simple, second-order equation in torque alone. This was true, also, for the last two vehicles tested, at medium to high torque levels in all gears; but, from low positive to negative torques, a separate equation of the same form for each individual transmission gear furnished better descriptions of the data. It may be significant that the earlier two cars both had automatic transmissions with torque converters, while the latter two had manual transmissions.

Some analysis of the above data was performed using multiple independent variables (such as speed, torque, and transmission gear, sometimes plus products of these quantities). However, provision of sufficient data to support adequately such detailed analyses would have required testing at two to three times as many torque and speed levels. The objectives of this project could be met satisfactorily with the smaller number of test points used, and with the simple equations in torque only, sometimes using a separate function for each gear. This smaller amount of data reduced the costs of vehicle testing and of data analysis and utilization.

The exhaust emissions data for the one car also were represented by simple analytic functions. While the scatter in these data was much greater than was observed for fuel economy results, this is consistent with auto industry experience.

## 3.9 SYNTHESIS OF FUEL ECONOMY (AND AIR CONTAMINANT EMISSION) DATA FOR VEHICLES NOT TESTED

The experimental data base described in Section 3.8 contained information on only three cars; this did not provide much variety for use with the HPP. Only the data base for one vehicle tested was used for a Vehicle Data Base Module (VDBM)(Pontiac Le Mans). VDBM modules could have been made for other vehicles tested. This was not done. Methods have been devised by which fuel economy and air contaminant emission data might be synthesized for other vehicles that had not been actually tested. These procedures include VEHSIM described in Section 2.0. Other vehicle data can be used if the information required is placed into a VDBM as prescribed in the instructions for the HPP that are provided. If any data required for a VDBM, namely fuel consumption rate or carbon monoxide, hydrocarbon, or nitrogen oxide air contaminant emission rates are not included, the missing data is identified as a zero and no answers will be available for that vehicle for that factor. Precautions should be exercised if a vehicle with no input for part of a VDBM is used as part of a "fleet" in the HPP so the proper interpretation of results will be made.

## 3.10 FRICTION MEASUREMENTS BEFORE AND AFTER RESURFACING A HIGHWAY

A minimal effort was made under this project to evaluate the use of a torque-instrumented vehicle for road surface-friction measurements. At the time when one test vehicle was undergoing field tests on Bangor airport, a section of Interstate I-95 running through Bangor was being prepared for resurfacing; the condition of the surface had become seriously degraded. The Maine State Department of Transportation (MeDOT) suggested that the instrumented car be used to measure running friction on that portion of road before and after resurfacing, to see how much difference would be observed.

A single record run was made on a 5-mi (8-km) length of the high-speed (left-hand) lane of the southbound portion of I-95; data were recorded 10 times per second. Approximately 1 year later, the same test vehicle was returned to Bangor and three replicate runs were made over the same portion of road. MeDOT provided highway construction drawings showing the elevations along the test route. Limited observations and analyses of results showed that observations of total load could indicate variations of road roughness after accounting for inertia, gravity, curvature, and aerodynamic loads. Others have seen this implicitly by observing fuel usage as the road surface varied or measurement of loads as a function of tire-road interface conditions. Despite the potential for using dedicated vehicles measuring driveshaft torque to evaluate road roughness, the procedure was not adopted because direct means of simultaneously measuring linear acceleration and therefore gravity loads (accurate measurements of grade or slope) were not successful. Since this work was completed, Sierra Research for California Air Resources Board (CARB) and University of California at Riverside for National Cooperative Highway Research Program (NCHRP) project 25-11 were able to make continuous measurements of grade simultaneously with driveshaft torque measurements. (Linear accelerometer and use of Global Position Monitoring (GPS), respectively.)

## 3.11 FUEL CONSUMPTION DURING ACCELS AND DECELS ON CHASSIS DYNAMOMETER

Fuel consumption of one test vehicle was measured during transient accelerations (accels) and decelerations (decels) on a large-roll chassis dynamometer. The intent was to obtain empirical data on such consumption against which to test estimated values for the same maneuvers generated by the vehicle/highway performance prediction computer program. Operating problems with the dynamometer precluded further tests of this type, and resource limitations prevented running of computer simulations to compare against the empirical data.

The experiment was conducted with the 1980 Chevette. To enhance repeatability of the test, the cycle was driven completely in top (fourth) gear of the manual transmission, and acceleration rates consequently were limited to modest values. During acceleration, speed was increased from 30 to 50 mi/h at 1.0 mi/h/s, and from 50 to 60 mi/h at 0.67 mi/h/s; in the deceleration, speed was reduced from 60 to 30 mi/h at 1.33 mi/h/s. (In SI units, these were: accel from 48 to 80 km/h at 1.6 (km/h)/s, and from 80 to 97 km/h at 1 (km/h)/s; decel from 97 to 48 km/h at 2.1 (km/h)/s). Exhaust gases were collected between 35 and 55 mi/h (56 and 88 km/h) during accels and decels and accumulated in two separate sample bags. Throttle position had to be changed continuously during both halves of the cycle to maintain the accel/decel rates. Three series of runs were made, and consisted of 20, 22, and 24 cycles in order to accumulate enough exhaust gas for analysis. Note that fuel consumption was not measured by a fuel flowmeter because these devices tend to lag behind fluctuations in power and produce erroneous results for sharp, short-duration transients.

The composite fuel economy values observed for the consecutive series were: accelerations, 18.8, 19.7, and 20.9 mi/gal (8.0, 8.4, and 8.9 km/L); decelerations, 79.8, 91.2, and 87.2 mi/gal (33.9, 38.9, and 37.1 km/L). The acceleration results suggest that the driver's technique was continuing to improve with increasing experience in driving this new test cycle.

# 4.0 CONCLUSIONS

## 4.1 EFFECTS OF HIGHWAY GEOMETRIC FEATURES ON VEHICLE PERFORMANCE

This project has documented by empirical data that the effects of major geometrical features of highways on propulsive demand on vehicles are significant, can be measured, and can be predicted, i.e., calculated without measurement. The effect of grades is linearly related to the slope of the road. The increase in demand on curves was found to be a smooth and repeatable function of lateral acceleration; and lateral acceleration provides a convenient single parameter that expresses the interrelated influences of radius of curvature and speed on the curve. These empirical effects of horizontal curvature were consistent with a theoretical analysis of the phenomena that were developed independently of this project.

Experimental data have been used to construct data bases of operational parameters of modern (1975-1981) automobiles; these data bases relate such parameters to driveshaft torque (and, in some cases, to transmission gear) by simple analytic functions of no higher than second order. Thus, it has been shown that the fuel consumption of an automobile can be calculated with adequate accuracy for such real-road maneuvers as accelerations, decelerations, and travel on positive and negative grades and on horizontal curves. Further, if test data on exhaust emissions are available, the effects of such maneuvers on these parameters can be calculated in a similar manner. While emissions computations provide a lesser degree of accuracy than for fuel consumption, they still afford an objective comparison of the effects of different geometries that is based on sound automotive engineering principles. Such computations ought to be better approximations of real conditions than estimates based on long runs at various constant average speeds over totally flat straight terrain.

The combinations of maneuvers experienced by vehicles operating on highways of arbitrary configurations can be simulated adequately by decomposing combined maneuvers into a series of quasi-steady-state operations on short lengths (usually only a few meters in length) of road. Fuel consumption (and emissions) can be calculated for each increment of road and summed over the entire length of highway. Alternative geometrical configurations can be evaluated quickly and objectively to compare their relative effects on fuel consumption. Road segments where the intended combination of speed and grade cannot be met by one or more types of vehicles in the design fleet are quickly identified for appropriate design action.

## 4.2 VEHICLE/HIGHWAY PERFORMANCE PREDICTOR (HPP) SIMULATION

A computer program has been developed that can calculate fuel consumption and exhaust emissions of automobiles when operated with realistic accelerations and decelerations on highways that have grades and curves. This software incorporates the essentials of automotive engineering principles that address vehicle response to combinations of applied loads; the intent is to provide a valid approximation of actual fuel consumption on the specific highway. The quality of the approximation is further improved when the algorithm is used to compare fuel consumption on two or more alternative configurations of the same road. This is the intended principal application of this method. The improvement in approximation is obtained because any errors in absolute magnitude of fuel consumption on one highway layout likely will be largely canceled out by similar errors on the other designs; thus, the relative magnitudes of the calculated fuel consumption should tend to reflect quite well the relative effects of the different configurations.

The computation method is convenient to use, runs very rapidly (typically, it analyzes 2 to 3 km road/s of computation time), and has been developed for use on personal computers. The computer program described above, the HPP, was first made operational on the VNTSC mainframe computer with three slightly different versions; later, an interactive version for personal computers was developed that allows additions of other vehicle data bases. The computational procedure, the vehicle highway performance predictor algorithm (HPP), could contribute significantly to analyses of the merits of proposed or planned upgrading of existing highways, to design of new or relocated highways where fuel consumption rates and exhaust emissions are important, and to develop and evaluate traffic management.

## APPENDIX A
## THE VEHICLE/HIGHWAY PERFORMANCE PREDICTOR (HPP) ALGORITHM

### A.1 DESCRIPTION OF OPERATION, PROTOTYPE VERSION

This appendix describes the operations of the prototype Vehicle/Highway Performance Predictor (HPP) algorithm. First, the unit operations performed on each increment of road length are outlined. The results from each increment are summed over the entire length of highway. The procedure for tracking position on the highway is presented. Reasons for computerization of the HPP are given. Finally, a brief overview of the entire algorithm is sketched, and a logic diagram demonstrates how all the component operations relate to each other.

### A.1.1. UNIT OPERATIONS ON ROAD ELEMENT FOR ONE VEHICLE

#### A.1.1.1 Road Elements

The HPP subdivides the total road length into elements of distance, each of which must have a constant grade (positive, negative, or zero), and a limited change in speed over its full length. Elements generally average about 50 m ( 0.050 km) in length; however, an element may be of arbitrary, much greater length if speed, curvature, and grade are constant. If curvature, speed, or grade change within the nominal 50-m length, the element is subdivided further into two or more smaller elements that meet the constancy constraints.

To illustrate this process briefly, consider the example shown in figure 1. The input speed profile calls for a constant acceleration of 2.083 (km/h)/s from a starting speed of 20 km/h to a final speed of 40 km/h. For this example, it is assumed that the maximum speed change per road element is 5 km/h. Consequently, this acceleration will be distributed over four road elements.

The length of each element is calculated from the classical constant-acceleration relationship:

$$V_2^2 = V_1^2 + 2\ ax$$

This equation is transposed to solve for distance:

$$x = (V_2^2 - V_1^2)/(2a)$$

The elapsed time per element is calculated by another constant acceleration equation:

$$V_2 = V_1 + at$$

which is transposed to solve for time:

$$t = (V_2 - V_1)/a$$

For the example cited, the results are listed in table1 and plotted in figure 1. It is clear that element length varies, that speed is non-linear vs. distance, and that the linear-average speed for each of these short elements is very nearly equal to the actual instantaneous speed at mid-element. (The significance of this last point will be apparent in the Road Load section below.)

Table 1. Example of speed and elapsed time vs. distance at constant acceleration over four road elements.

Start = 20 km/h

End = 40 km/h

Acceleration = 2.083 (km/h)/s= 1.295 mi/h/s = 7500 (km/h)/h

$x=(V_2^2 - V_1^2)/(2a)$ $\quad$ $t = (V_2 - V_1)/a$

| Element No. | Distance, m | | Speed, km/h | | Elapsed Time, sec | | Element Linear-Average Speed, km/h |
|---|---|---|---|---|---|---|---|
| | Element | Sum at End | Start | End | Element | Sum at End | |
| 1 | 15.0 | 15.0 | 20 | 25 | 2.4 | 2.4 | 22.5 |
| 2 | 18.33 | 33.33 | 25 | 30 | 2.4 | 4.8 | 27.5 |
| 3 | 21.67 | 55.00 | 30 | 35 | 2.4 | 7.2 | 32.5 |
| 4 | 25.0 | 80.00 | 35 | 40 | 2.4 | 9.6 | 37.5 |

For each element of road, the following operations are performed if applicable; any process not pertinent to a given element is bypassed.

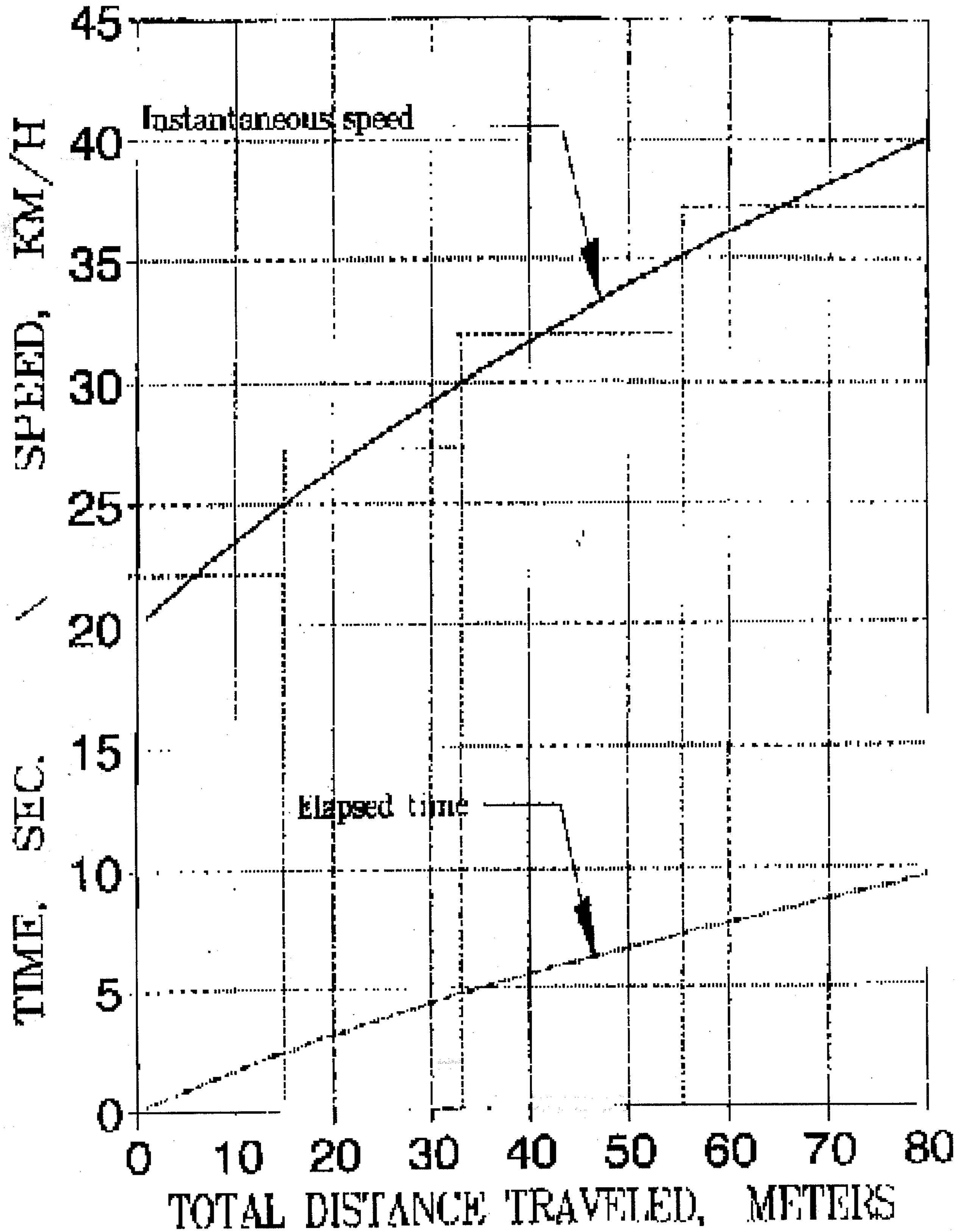


Figure 1. Example of speed and elapsed time vs. distance.

### A.1.1.2 Speed

Vehicle speed at the start of each element is equated to the speed leaving the preceding element (for the first element of the road, the user is required to enter the starting speed). Speed leaving the element is determined from the speed module specifications (see Section A.2.2 below) and the limitation in speed change over one element. Average speed on the element is the linear average of entering and leaving speeds; this average speed is used only to calculate the basic road-load tractive force for the element (see following section), and is not used to compute cumulative distance or time.

### A.1.1.3 Road Load

As described earlier, the term "road load" has been restricted throughout this project to refer exclusively to total propulsive demand (tractive force at the wheels, or driveshaft torque) at a given constant speed on a level, straight road in the absence of any wind (air motion relative to the road surface). It defines the basic propulsive requirement of the vehicle before any perturbing influences are considered. It does not consider the peripheral power demands imposed on the engine by vehicle accessories (except that the effect of peripheral loads active when the vehicle was being performance-mapped are included implicitly in the fuel economy data).

For a given vehicle, the vehicle data base contains an equation that defines the road load tractive force as a function only of vehicle speed. On any element of road, the change in speed is sufficiently small that speed can be considered to be constant (at element average speed) for computation of road load.

Thus, road load is calculated by entering element average speed into the road load equation. This yields the first component of total tractive force for the particular road element.

### A.1.1.4 Acceleration

The acceleration on a given element is derived from the input speed vs. distance specification. The HPP obtains from the pertinent VDBM (described later in Section A.2.4) the vehicle effective inertia weight; this includes an increment of inertia weight corresponding to the rotational inertia of the tires and wheels.

The force (positive or negative) required to produce the specified acceleration then is calculated. This yields the acceleration component of total tractive force for the element.

### A.1.1.5 Grade

For the HPP, highway grade vs. distance is entered in terms of grade in percent (m of rise per 100 m horizontal distance) and distance in km. The tractive force increment is calculated from the vehicle weight (w) (obtained from the vehicle data module) and the grade:

$$F_G = W\,(\text{Grade, \%})/100$$

To be mathematically rigorous, the relationship would use the sine of the road elevation angle. However, for grades up to 4 percent (greater than normally encountered on most modern highways), the error from using grade is less than 0.08 percent of the correct value of this force component. And, for grades up to 14 percent, the error still is less than 1 percent. Consequently, this convenience imposes no significant error.

A.1.1.6 Curvature

For the HPP, the highway radius of curvature in meters is entered. Based on vehicle speed, the lateral acceleration can then be determined. The load due to curvature is then found to be proportional to the road load for a straight road determined for given vehicle (s) and speeds according to the equation shown in figure 10; namely, $\Delta$ T (curve) = T(straight) 1.349 $A_{Lat} + (3.37\ A_{Lat})^2$. The force or load due to curvature can be derived based on discussion in Sections A.1.1.7, Driveshaft Torque and C .2.1, Derived Tractive Force for Three Vehicles.

A.1.1.7 Driveshaft Torque

In accordance with original guidelines for this project, vehicle operating parameters such as fuel economy and exhaust emissions were related to driveshaft torque as the independent parameter. Correlations with this single independent variable for the first two vehicles tested were surprisingly good and afforded great simplicity and computational economy. Subsequently, road speed was added as a second variable in recognition of the fact that these power-dependent parameters should, in general, be dependent on more than just torque. The degree of correlation improved somewhat, for some vehicles, with this addition. Both of these independent variables also were the actual parameters that were measured in test operations.

The four tractive force components (road load, acceleration, grade, and curves) are summed to obtain the net tractive force on the road segment. The HPP then obtains from the vehicle data module the effective rolling radius of the drive wheels and the final drive ratio of the drive axle, if applicable. (In the case of an FWD vehicle, driveshaft torque usually is accessible only in the half-shafts between differential and wheels, and hence already is outboard of the differential. For these cases, the drive ratio is set equal to 1.0.)

The driveshaft torque corresponding to the net tractive force is calculated from the equation:

$$T_s = (\Delta F_i) * R_{wheel} / (\text{Drive ratio})$$

This calculation neglects two sources of energy dissipation: friction in the final drive gears (for RWD vehicles) and loss(es) in the drive axle(s) that are functions of the total tractive force transferred by the drive tires. The final drive efficiency generally is assumed to range around 97 percent at moderate to high torques; at low torques, efficiency falls off sharply, but the absolute magnitude of power loss at low torques tends to be small.

The second loss, the force-transfer loss in drive tires and axle, is a parameter about which very little data have been published. When rolling friction of tires is measured, either by manufacturers or by others, the standard practice is to run the tire on an unpowered axle in free rotation. Under this project, the force-transfer loss was measured for only one pair of tires on one vehicle (see Section C.4). It would be risky to generalize the observed relationship to other vehicles without further investigation. Therefore, this correction to driveshaft torque is neglected for most of the vehicles in the present data base.

However, the 1980 Pontiac was the vehicle for which this parameter was measured. Here, the driveshaft torque calculated above is used in a quadratic equation to compute a correction increment; this increment is added to the above shaft torque to obtain the final net shaft torque.

A.1.1.8 Fuel Consumption

For many highway-related calculations, fuel consumption is a more convenient parameter to use than the more familiar fuel economy. However, when experimental data are being regressed to establish a mathematical relationship, fuel economy proves to be considerably more tractable. Accordingly, an expression for fuel economy is developed and then used as a reciprocal:

Fuel consumption = 1/(fuel economy)

To determine fuel consumption for the road element being analyzed, the HPP delivers the net driveshaft torque and speed to the VDBM and requests the corresponding fuel consumption rate and exhaust emissions rates. The VDBM is configured to perform the calculations internally, in the manner of a subroutine, and to return the requested outputs. Thus, if a given parameter for separate vehicles can be best represented by equations of different form (e.g., a power equation for one and a polynomial for another), these differences in data format are transparent to the HPP. Further, if the data module for a given vehicle has no information on exhaust emissions, the module simply returns zero for these parameters.

The HPP receives the requested fuel economy (and emissions rates, if available) in terms of units/km of distance traveled. Each of these rates is multiplied by the length of the road element in question to produce an increment of fuel used (or emissions generated).

A.1.1.9 Performance Limits

Although performance parameters are included in the VDBM, the current version of HPP does not include checking to determine if performance limits have been exceeded.

The above description completes the unit operations on any given road element. It is evident that no great mathematical complexity is involved. Also, an intimate knowledge of automotive engineering relationships by the highway designer is unnecessary; as much of that technical specialty as is required has been built into the procedures of the HPP and especially into the VDBM. The net output of the procedure, for a single element of road, is either one or four numbers: always, liters of fuel used; and, if emissions data are available, grams of hydrocarbons (H.C.), grams of carbon monoxide (CO), and grams of oxides of nitrogen (NOx) emitted.

A.1.2 SUMMATIONS OVER ENTIRE ROAD LENGTH

The unit operations described above in Section A.1.1 determine a realistic estimate of the amount of fuel consumed (and emissions produced, if data are available) on a piece of road only a few meters in length, for a single iteration. The process can be repeated as many times as necessary to "travel" the entire highway. The increments of fuel and emissions are summed in individual accumulators to compile a running total of each parameter along the highway.

A.1.3 HIGHWAY GEOMETRY PROCESSOR (HGP)

The iterative process described above, when performed on a highway length measured in kilometers (or miles), requires a "navigator" to keep track of position along the highway, of the starting and ending speeds for each element, length and road grade for the element, or duration of stationary idle. The HGP allows the speed vs.

distance specification to be changed independently of the grade vs. distance specification. When such a substitution is made, the lengths of many road elements will have to be modified, and their positions along the highway will shift.

All of these operations are quite simple, but the amount of "bookkeeping" very quickly becomes oppressive and subject to human error.

## A.1.4 COMPUTERIZATION OF ALGORITHM

### A.1.4.1 Rationale

As noted above, the procedure for calculating the effects of highway geometry and vehicle operation on vehicle fuel economy and emissions is quite simple. However, it requires a very large number of iterations and much recordkeeping. When either the speed or grade profile is changed, the entire process must be repeated. When different vehicles are operated over the same speed and grade profiles, all calculations must be repeated again.

The resultant information is far more specific to a particular highway than other calculation procedures we are aware of. One important advantage is that the effects of road grades and curves are considered; many earlier programs operate only on a flat world. Also, the influence of speed transients is included; many other programs operate with piecewise-discontinuous, constant average speeds but do not consider the substantial effects involved in achieving the different speeds. At best with the earlier models, the designer would be required to calculate average numbers of speed changes and stop/starts per mile, lockup tables of correction factors, and hand-calculate a number of corrections.

Information on relative fuel consumption of alternative highway geometries can be valuable to a highway designer, but only if achieving it does not encroach seriously on highway design time. The designer's primary responsibility still is the design and cost estimation of highway construction.

The entire computation procedure is ideally suited for operation on a digital computer. Once the highway geometries and speed profiles are entered into data files, essentially no interaction by the user is required. The vehicle data would be stored in data modules. New vehicle data modules could be added at any future time without requiring any changes in computation software.

Consequently, it was decided to develop a prototype computer program to evaluate the procedure and to identify any problem areas that might not have been foreseen.

### A.1.4.2 Implementation

The HPP program was first written in FORTRAN IV language for a minicomputer. Subsequently the HPP was transferred to a mainframe computer. Then, the HPP program was rewritten in Visual Basic language and adapted to personal computers. The software and instructions for installation of the Highway Performance Software have been placed on a CD ROM.

## A.1.5 OVERVIEW OF COMPLETE HPP PROGRAM

This section presents the Vehicle Highway Performance Predictor (HPP) logic diagram and discusses the major components thereof and their interrelationships.

Figure 2 is a diagram of the logical organization of the HPP. The diagram and the discussion below show the functionally correct relationships of the major components. Note, however, that the diagram does not necessarily represent the organization of actual computation procedures. In some cases, the programmer chose to subdivide the tasks in a different way for operational convenience and economy.

The core of the HPP operations is the Computation Executive, labeled in figure 2 as V/HPP. This Executive is in charge of the sequential activation of the several peripheral modules on a given elemental length of highway, of the iteration of this sequence many times over the entire length of a highway, and of output of data as specified. Each major function is identified on one facet of the border of the Executive and is connected with the associated peripheral component. The general sequence of operations is illustrated by numbers located near each function.

(1) Vehicle speed, speed change, and curvature are derived from the two principal user input modules. The specifications of grade, speed, and curvature vs. distance are combined and then subdivided into individual road elements in the HGP (described below).

Information flow between input modules and Executive basically is one-way, into the Executive on demand.

(2) The HGP is the "navigator" for the HPP. It keeps track of where on the highway the analysis presently is located. For each road element, the HGP tells the Executive the beginning and ending speeds on the element (or, alternatively, that the vehicle is stationary at idle and for how long), the grade of the road element, the horizontal curvature, and the length of the element. Information flow between HGP and Executive (V/HPP) is bidirectional.

The VDBM is consulted by the Executive at various times as specific pieces of information are required. The first such contact is made to determine road load tractive force (as stipulated earlier in this report, "road load" is restricted in this report to mean load at constant speed on a level, straight road).

(3) Road load force is calculated as a function only of vehicle constant speed. For a given road element, the Executive calculates the linear average of starting and ending speeds to determine the average speed on the element. The Executive sends this average speed to the VDBM and requests the corresponding road load. The road load force is calculated within the VDBM and is returned to the Executive. In this way, the specific form of the road load equation is transparent to the Executive; different forms of the equation can be used by the VDBM for various vehicles without affecting the software of the Executive.

(4) The Vehicle Dynamics section of the HPP is addressed next by the Executive. The values of acceleration and road load force in effect on the element are sent to the Dynamics unit. The Executive also must obtain from the VDBM the effective inertia weight of the vehicle(s), and send this to the Dynamics unit. The Dynamics section calculates the tractive force required to produce the specified acceleration.

The Executive then sends the current road grade to the Dynamics unit, which calculates the grade and curvature (lateral acceleration) force components. The Executive obtains from the VDBM the drive wheel radius and the drive axle differential ratio and sends these data to Dynamics. All tractive force components are summed algebraically, and the driveshaft torque is computed.

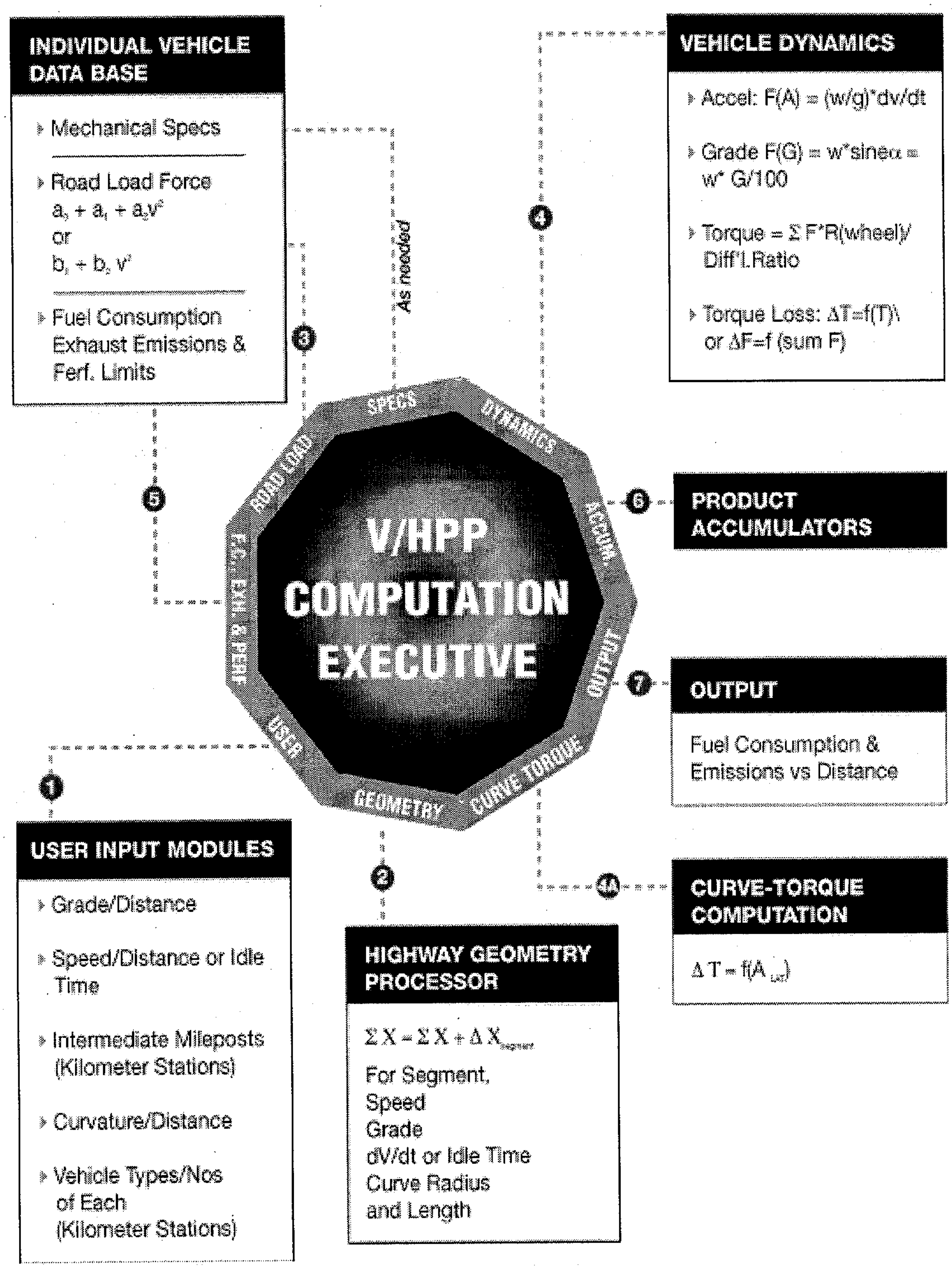


Figure 2. Vehicle/highway performance predictor software–logic diagram.

If the VDBM contains an expression for tractive force-transfer loss, this is used by the Dynamics section to calculate and add to shaft torque an increment for this effect.

The Dynamics unit finally returns to the Executive the final net driveshaft torque for the road element.

(5) The Executive sends this net torque to the VDBM and requests the rates of fuel consumption and exhaust emissions. Ancillary information such as vehicle speed also is transmitted to the VDBM. Within the VDBM, logic associated with the equations for the requested operating parameters may decide which gear in the transmission is engaged and, therefore, which of several equations should be used. The form of equation for a given parameter may vary for different vehicles; but, again, this is transparent to the Executive because the calculations are performed within the VDBM. The appropriate flow rates are returned to the Executive.

The Executive multiplies each flow rate (expressed in liters/km or grams/km) by the element length and sends the resultant quantities to the Product Accumulators.

(6) The Product Accumulators sum individually the fuel consumed and each of the three exhaust emissions of interest (H.C., CO, and $NO_x$). Whenever the Executive is required to output data on these parameters, the current totals are transferred from the accumulators to the Executive without clearing the accumulators.

(The VDBM may not always have all of the desired data; namely, fuel economy or air contaminant emissions of carbon monoxide, hydrocarbons, or nitrogen oxides. For that vehicle there would be then noted zero outputs for any input lacking. When operating the HPP program one should be cautious about whether the outputs are correct or not whether only one vehicle is involved or a "fleet" of vehicles is involved, which would mean re-runs of the model and additions for each vehicle.) At the end of operations for each road element, the Executive returns to the HGP for information on the next element, and the above process iterates to the end of the road.

(7) Data output is, of course, the ultimate objective of the exercise. The Executive prints the names of the grade and speed modules, the identification of the vehicle, cumulative totals of fuel and emissions at each intermediate milepost (see following paragraph) specified along the road and at the end of the road. If the user has specified a "long-form" output, each segment of all grade and/or speed modules is listed.

The mileposts mentioned immediately above are input by the user at the beginning of operations. They may be at any arbitrary positions within the length of the highway, and may number from zero up to a maximum of 20 for a given highway. This number does not include the final output at the end of the road, which always is printed. The Executive reads the specified mileposts and delivers them to the HGP. Mileposts may be located within segments of either or both grade and speed modules, not necessarily at boundaries. The HPP monitors the distance traveled and adjusts the length of an element if necessary to coincide precisely with a milepost. At each milepost, the HGP directs the Executive to print an output.

The above sequences are iterated along the rest of the highway in normal fashion except for omission of the aborted functions, and mileposts are ignored. All subsequent occurrences of performance overload, if any, are reported in the same manner as the first. Consequently, the designer can see, as a result of the first analysis attempted, all locations where grade, curvature, speed and/or acceleration must be modified and by approximately how much, in order to operate that vehicle successfully over that road.

The above discussion summarizes the operation of the prototype version of the HPP. For clarity, it does not include the mechanics of preparing grade, speed, curvature, and milepost modules. These are outlined briefly in Section A.2 below. The present HPP requires a user to set up and run a separate case for each vehicle type to be operated on a given highway, and outputs performance data for that vehicle only. The present version of HPP only has one of the test vehicle's results (1980 Pontiac Le Mans) of fuel consumption and air contaminant emission vehicle load performance mapping and vehicle characteristics. Comparable data can be added for other vehicles tested, as indicated in the instructions provided on the CD ROM for the HPP program.

A designer may want to analyze a highway for a representative fleet. The fleet might consist of 669 Vehicle A, 632 Vehicle B, 215 Vehicle C, 170 Vehicle D, and 114 Vehicle E (a very simplified fleet has been chosen for brevity in this example). The designer then will run five individual cases for each alternative highway geometry: one each for Vehicles A through E. The output values for each vehicle then are multiplied by the number of that vehicle type in the fleet and the results summed to obtain the totals for each road configuration. Similar calculations may be performed for any selected mileposts, or for all mileposts if desired; increments between mileposts can be calculated by difference. These intermediate milepost results can, for example, isolate the effects of a particular grade.

These calculations represent the principal effort of the designer for these highway analyses, after the initial creation of grade, curvature, and speed modules. The results give the designer a realistic estimate of the effects of the alternative highway geometries on fuel consumption. The total quantities of fuel can be multiplied by appropriate fuel costs and the number of times the fleet would travel those roads per day, per year, or over the life of the highway, to obtain comparative fuel costs or savings. Comparable calculations for air contaminant emissions are possible.

## A.2 INPUT DATA REQUIRED PRESENTLY

Data required presently by the HPP consist of two types: (a) mandatory user inputs, such as highway geometry, vehicle speed vs. distance, and station data for reporting; and (b) HPP-based inputs resident in the software, such as vehicle mechanical specifications and performance data, which may require no action from the user. Presently only results from one vehicle tested are resident in the software (1980 Pontiac Le Mans). Results of tests made on other vehicles may be added if testing and data are adequate.

These inputs are described below:

### A.2.1 HIGHWAY GRADE VS. DISTANCE (USER INPUT)

Data that describe highway grade vs. distance are organized into "Grade Modules" that consist of 1 to 40 segments per module. Each segment is entered in km, and grade in percent (meters of rise/100 meters horizontal, or feet of rise/100 feet horizontal). An example of an unusually long segment would be the Massachusetts Turnpike (I-90) through the Berkshire Mountains in the western part of the state. The road maintains a nominally constant grade of 3.5 percent for 7.7 mi (12.4 km). If one accepts the nominal grade for the entire length, this would be entered in a grade module as a single segment, "12.4,3.5"—regardless of whether speed changed anywhere along the segment.

Any number of modules can be assembled in any sequence to define a highway. Once a module is created and stored (with a name) in computer memory, it can be recalled and reused at any future time. It also can be modified and stored to replace the original module; or modified, renamed, and stored to create a new module. For example, assume a highway 10 mi (16.1 km) long and described in five modules was being analyzed for reconstruction, and a 1.7-mi (2.7-km) length in the third module was going to have the grade changed. The elevations and horizontal distances at both ends of the 1.7-mi (2.7-km) section will remain the same after reconstruction. The user will create the initial five grade modules and store them. The third module then will be recalled, the appropriate segments changed, the module given a new name, and the new module stored. For one analysis, the first five modules will be used; for the second analysis, the modified third module will be substituted for the original third module, and the run repeated.

### A.2.2 HIGHWAY CURVATURE VS. DISTANCE (USER INPUT)

The effect of cornering drag is to reduce fuel economy by about 10 percent for net lateral accelerations of 0.10-0.15 G, and the loss increases sharply with higher lateral accelerations. For modern highways, lateral accelerations above 0.1 G probably are rare in normal operation and, when found, comprise a very small percentage of road length. In such cases, the consequence of cornering drag probably can be ignored. However, older secondary/tertiary roads that exhibit high-lateral-acceleration curves (at whatever is normal speed for the road) over a significant portion of their length could be causing fuel economy penalties worth considering. If reconstruction and straightening of such roads is being contemplated, the fuel economy benefits of reducing road curvature may show a worthwhile long-term saving to the motoring public and thereby promote public support.

Calculation of this effect was added to the Vehicle Dynamics section of the algorithm. The HGP has been modified to track horizontal curvature and report this to the Executive for each road element. The Executive sends curvature and speed information to the Dynamics section along with other information that would include road load tractive force. The Dynamics section would calculate lateral acceleration and the resultant cornering-drag increment of tractive force, and include this in the summation of forces leading to net driveshaft torque.

Inclusion of horizontal curvature in the HPP required preparation of Curvature Modules to specify curvature vs. distance. The process resembled preparation of grade or speed modules. The data consists of length of curve and radius of curvature in meters. Where the segment is straight, a value of 0 is entered for the radius

### A.2.3 SPEED VS. DISTANCE/IDLE VS. TIME (USER INPUT)

Data describing vehicle speed vs. distance along the road are organized into Speed Modules similar in form to Grade Modules. Within a speed module, each of 1 to 40 segments specifies either (a) an arbitrary distance and the speed at the end of the segment, or (b) the vehicle is stationary with engine idling and the duration of idle period in seconds. The HPP software recognizes which operation is described by each type of segment; they can be intermixed at will and, during modification, one type may be changed to the other.

Similarly to grade modules, speed modules may be assembled in any sequence to define a speed vs. distance profile over a highway of arbitrary length. The distances represented by any speed module, segment thereof, or string of modules need not correspond in any way to distances defined by grade modules used in a given run, with only two exceptions: the first segments of the first grade and speed modules start at zero distance, i.e., the beginning of the road; and, the total distance represented by all speed modules must equal or exceed by any arbitrary amount the total distance of the grade modules. Any speed-module distance in excess of total grade-module distance is ignored.

When assembling a string of speed modules, a user must be cognizant of the end speed of the last segment of each module and of the first segment of the following module. Remember that the starting speed of any segment of any (speed) module implicitly is the end speed of the preceding segment. Inattention to this matter could produce unrealistic and unattainable performance demands.

### A.2.4 REPORT STATIONS FOR INTERMEDIATE OUTPUTS (USER INPUT)

HPP automatically prints the total fuel consumption (and total exhaust emissions, if data are available) at the end of each highway run. However, the user may want, in addition, to isolate and determine the effects of one or more particular portions of highway within the run. To facilitate this, the user is required to enter the filename for a file containing desired stations along the roadway for reporting; at each station, cumulative fuel consumption (and emissions) to that point will be printed. Stations can be set at the beginning and end of increments of interest; the difference in totals after and before the section comprises the subtotal for that section. The user may specify from zero to 20 mileposts at arbitrary distances from the beginning of the road, and need not include the end.

### A 2.5 VEHICLE DATA (FOR HPP)

Data on the pertinent physical characteristics and performance of a representative vehicle (1980 Pontiac) are included in software for the HPP It was intended that data for each vehicle tested in this study would be incorporated into VDBMs and that these modules could be stored in the HPP package and called up individually by name. However, this was not done. A small effort is required to extract the data and equations for each vehicle tested and create named modules. Then one or more modules could be called up by specifying the file name or names.

The experimental data base described in Section 3.8 contained information on only three cars; this did not provide much variety of vehicle type for use with the HPP. Methods have been devised by which fuel economy and air contaminant emissions data might be synthesized for other vehicles that had not been actually tested in this study. VEHSIM, a model developed by the Volpe National Transportation Systems Center, could be used for such syntheses. (See Section 2.0).

For additional vehicles tested, particularly those having notably different performance, if their data are in a format suitable for use by the HPP, these data can be added to the present vehicle data base. No changes in HPP software will be required. To create a new VDBM, a user need only follow the format of any existing VDBM and assign an appropriate file name. The HPP User's Guide contains a format specification sheet for VDBM file names. (See Sections 2.0 and A.1.5-6.)

It should be noted that, within a new VDBM, equations of virtually any form may be used to describe the data, and logic constraints can be used to select specific equations for different operating ranges. All of these functions must be contained within the VDBM. The requirement for compatibility is that the VDBM operate with no more data than is sent by the Executive (although some such data may be left unused if not needed), and that the VDBM return to the Executive the requested information in the correct units.

## A.3 OPTIONS FOR FUTURE EXPANSION

The FHWA or some other prospective user will have to determine whether technical community interest and applications of this prototype HPP software warrant further effort to increase its capabilities. Useful expansion, as seen at this time, could improve user convenience and add more vehicles to the vehicle data base.

Features recommended in future versions include the following:

- Replace or append the methods for inputting speeds, grades, and curves to enable input in the format normally found on plans (e.g., vertical information input by P.I. station, elevation, and vertical curve length).

- Revise the analysis of performance limits to analyze the data in the vehicle file format. The current program will only display a warning if a value is outside of the minimum and maximum range of any of the table values.

- Improve program performance to enable smaller increments of distance to be analyzed. The current program recalculates many values for the sake of readability for other programmers. The cumulative data can be calculated at the beginning of the analysis section and saved, thereby speeding up the plotting and listing sections.

Features not recommended for addition include road surface roughness and a traffic model. Roughness has been found to have an almost negligible direct effect up to the condition that justifies resurfacing for safety and driver comfort. A traffic model would provide an objective estimate of traffic speed, and would relieve the designer of this responsibility, but it would require a major and expensive effort, would tend to duplicate the capabilities of some existing traffic models, and its validity would be uncertain. If such a feature is desired, it is recommended that an existing model be used in its present form to generate a speed-distance profile. That profile could serve as the basis for generating speed modules in the HPP.

The hand calculations required when a user of the present HPP wants to consider a fleet composed of a mixture of different vehicles are described at the end of Section A.1.5 above. The computations are elementary in concept but require some time and effort; also, some potential for human error exists in correctly associating corresponding data items. Further, the results are not printed concisely and directly on the HPP data printout.