A New Technique for Predicting Vehicle Operating Cost

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This paper discusses the development of a new approach to the prediction of the highway user costs associated with different highway alignments. This approach is built around a digital computer program which simulates the physical operation of a sample vehicle or vehicles. Although intended to produce the same sort of information as the AASHO Road User Benefit Analysis Manual, this new technique will permit a far more detailed analysis of alternatives in highway design.

● THE basic objective underlying the development of this new approach to the vehicle operating cost problem was to provide the highway design engineer with a capability commensurate in its sophistication with the capability he already possesses for estimating construction and other such highway costs. This involved finding some easily applied technique for determining the effect of relatively minor changes in alignment and grade on operating cost. It became apparent at an early stage in the research that the only practicable way for the design engineer to do this would be for him to employ an electronic computer to analyze design alternatives.

Accordingly, an experimental program was developed for an IBM 650 EDPM which would determine the effect of design changes on the performance of a vehicle by simulating its operation over the alignments in question. This initial program was used to test the mathematical expressions which describe motor vehicle operation and to evaluate the over-all feasibility of a computer approach to the vehicle operating cost problem. As a result of this early work the decision was made to go ahead with the project, and a set of two entirely new computer programs was written to replace the original program. These new programs are more sophisticated in their simulation of vehicle operation and much more flexible insofar as their use by the highway design engineer is concerned.

The next step in the research program was to test the predictive ability of the programs by comparing the performance of actual vehicles in the field to computer simulations which assumed identical conditions of alignment and speed and identical vehicle characteristics. Although some data were available from previous field testing performed for other purposes, it was necessary to supplement these with a special series of field tests. These were carried out in September and October of 1960 in the Washington, D. C., area and are reported herein. The results of this test series indicate that with some modifications the computer programs can be expected to give satisfactory results for both the travel time and fuel consumption of any sample vehicle.

This paper is intended principally as a general discussion of the research performed to date and of the computer programs on which this research has focused. It does not treat in detail the question of precisely how the computer programs are to be operated. That is left for a Program Manual now in preparation. Similarly, the paper gives only a brief discussion (Appendix) of the mathematics of the programs. This topic is covered in detail in a somewhat more lengthy research report which is also in preparation.

Finally, the paper does not attempt a complete discussion of the way in which the results of the programs would be applied to a highway location or design problem. This phase of the research effort is not yet complete. The problems raised in this connection will therefore be touched on here only in enough detail to make clear the nature of the analyses which the computer programs will make possible.

DESCRIPTION OF THE PROGRAMS

The basic set of computer programs which has been developed consists of a Vehicle Parameter Computation Program and a Vehicle (Operation) Simulation Program (designated EA1-T1 and EA1-T2, respectively, in the DTM Program Series). A third program designed to plot the simulation output graphically is also available, but it is of no particular interest here.

Parameter Computation Program

The Parameter Computation Program converts the basic data which describe the vehicle into a set of summary parameters for use by the Vehicle Simulation Program. The engineer uses as input to the Parameter Computation Program such things as vehicle weight, frontal area, and tire size, engine bore, stroke, displacement, and number of cylinders, the full throttle torque curve, and transmission and rear axle gear ratios.

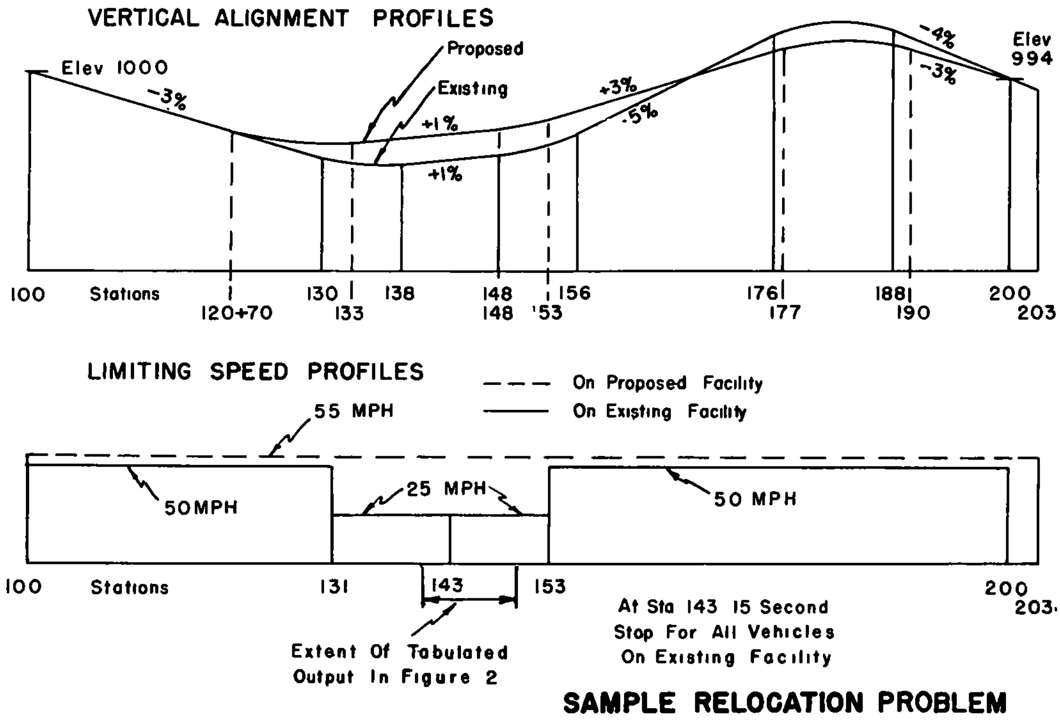


Figure 1. Vertical alignment and speed profile input to the Vehicle Simulation Program.

These are all readily available manufacturer's data. The engineer must also prepare some other information which will be supplied him in the Program Manual. This includes such things as air and rolling resistance coefficients, brake specific fuel consumption as a function of piston speed, and engine mass equivalent constants.

Using this information the program performs the following sort of operations: consolidates all the tractive resistance coefficients, computes the coefficients of the engine torque curve (by the method of least squares), prepares a table of fuel rates in terms of engine rpm and brake horsepower, and computes a table of vehicle vs engine speed parameters for each year. Using a computer for this task permits a more sophisticated analysis of the basic data than the highway design engineer would normally undertake. More importantly, it makes it possible to set up the basic programs so they can use the vehicle manufacturer's regularly published data as input to describe vehicle characteristics. This removes what would otherwise be a major problem (if not a major delay) for the engineer who wants to use the over-all analysis technique on only an occasional basis, and who does not therefore have the special knowledge required to derive summary parameters in the proper form.

The Parameter Computation Program need be used only when a new class or type of vehicle is to be simulated. This contrasts with the Simulation Program which would be run one or more times for each class of vehicle for every one of the alternatives in what might be a large number of different design problems.

Vehicle Simulation Program

The Vehicle Simulation Program itself computes travel time and fuel consumption as a function of vehicle characteristics, highway alignment, and driving speed restrictions. It does this by predicting the vehicle's motion from the basic laws of physics and calculating fuel consumption on the basis of the power thus required from the engine. As the computer follows the vehicle's motion along the alignment, it punches out the resulting information at regular increments of time as specified by the engineer.

The program as presently coded does not compute any other vehicle operating results such as oil consumption, tire wear, or maintenance costs. Too little is known about the relationships between these costs and the physics of vehicle operation to warrant their computation on anything other than a simple distance-traveled basis. Computation on that basis is done more readily by hand than with a computer. It will be a simple matter, however, to add these capabilities to the program whenever the necessary mathemetical relationships have been developed.

The program works with five sets of input information. The first of these describes the horizontal alignment of the highway—the PC, PT, radius, and superelevation of each curve. The second set describes the vertical alignment of the highway—the VPC and VPT of each vertical curve and the grades which connect these curves. The third set of input data describes the maximum speeds at which the vehicle is to be operated on different sections of the alignment under study. It also lists the stationing of any stops which the vehicle is to make and length of time it is to wait at each stop. Finally, it specifies the maximum acceleration and deceleration rates at which the vehicle is to be operated. The fourth set of input describes the mechanical and physical characteristics of the vehicle. (It is simply the output from the Parameter Computation Program previously described.) The fifth and final set of input is the control information by which the engineer tells the computer where to begin and end the simulation run, at what intervals to compute the vehicle's performance, and how often to punch out its answers.

The driving speed specifications mentioned as the third set of input data warrant further explanation. These are not intended simply to be either posted speed limits or engineering design speeds. They are intended rather to reflect the preference of the average vehicle operator. As such they must be specified by the engineer. (If he wants, an engineer can even use these restrictions to reflect a certain amount of traffic interference.) If a vehicle is physically incapable of reaching whatever speed limit the engineer has specified, the program will compute only what the vehicle can actually do.

Figure 1 shows how the speed change input might look. The case illustrated shows a slowdown first from 50 mph to 25 mph and then from 25 mph to a stop (at station 143) with a 15-sec wait. From that point the vehicle accelerates (at the specified rate if possible) up to 25 mph and continues at that speed to station 153. At Sta. 153 it begins another acceleration to 50 mph and proceeds at that speed to the final station (Sta. 200). The speed change input in this case consists of the speeds as shown and the stationing of the changes.

Given these and the other types of input data previously described, the program can compute the resulting motion profile and the fuel consumption associated with it. Figure 2 shows the tabulated output of a vehicle simulation run for the sample alignment in

Figure 1. The logic used by the program for such a run is explained subsequently. The mathematics of the computations are outlined in the Appendix.

Vehicle Simulation Logic

To simplify the mathematical relationships the Vehicle Simulation Program uses to describe vehicle dynamics, it was assumed that a vehicle would always be operating under one of the following five conditions: (1) moving at a constant speed, (2) accelerating at a constant rate, (3) decelerating at a constant rate, (4) standing with the engine idling, or (5) moving with the engine at full throttle, and thus at either maximum possi-

EA1 T2

VEHICLF SIMULATION AND OPERATING COST PROGRAM

IDENT	STA FT	VEL MPH	TIME SEC	FUEL POUNDS
318 03 200 00	140+67.097+	25.000+	70.000+	0.11755+
318 03 200 00	141+03.764+	25.000+	71.000+	0.11964+
318 03 200 00	141+40.431+	25.000+	72.000+	0.12173+
318 03 200 00	141+77.098+	25.000+	73.000+	0.12382+
318 03 200 00	142+13.765+	25.000+	74.000+	0.12591+
318 03 200 00	142+46.535+	19.685+	75.000+	0.12662+
318 03 200 00	142+71.509+	14.370+	76.000+	0.12716+
318 03 200 00	142+88.688+	9.055+	77.000+	0.12780+
318 03 200 00	142+98.072+	3.740+	78.000+	0.12828+
318 03 200 00	143+00.000+		79.000+	0.12876+
318 03 200 00	143+00.000+		94.000+	0.14542+
318 03 200 00	143+01.833+	2.500+	95.000+	0.14862+
318 03 200 00	143+07.333+	5.000+	96.000+	0.15183+
318 03 200 00	143+16.499+	7.500+	97.000+	0.15504+
318 03 200 00	143+29.332+	10.000+	98.000+	0.15826+
318 03 200 00	143+45.832+	12.500+	99.000+	0.16149+
318 03 200 00	143+65.998+	15.000+	100.000+	0.16489+
318 03 200 00	143+89.831+	17.500+	101.000+	0.16887+
318 03 200 00	144+17.331+	20.000+	102.000+	0.17349+
318 03 200 00	144+46.107+	19.772+	102.300+	0.17382+
318 03 200 00	144+76.939+	22.272+	103.300+	0.17894+
318 03 200 00	145+11.438+	24.772+	104.300+	0.18430+
318 03 200 00	145+47.937+	25.000+	105.300+	0.18667+
318 03 200 00	145+84.604+	25.000+	106.300+	0.18877+
318 03 200 00	146+21.271+	25.000+	107.300+	0.19087+
318 03 200 00	146+57.938+	25.000+	108.300+	0.19297+
318 03 200 00	146+94.605+	25.000+	109.300+	0.19507+
318 03 200 00	147+31.272+	25.000+	110.300+	0.19717+
318 03 200 00	147+67.939+	25.000+	111.300+	0.19927+
318 03 200 00	148+04.606+	25.000+	112.300+	0.20134+
318 03 200 00	148+41.273+	25.000+	113.300+	0.20348+
318 03 200 00	148+77.940+	25.000+	114.300+	0.20569+
318 03 200 00	149+14.607+	25.000+	115.300+	0.20797+
318 03 200 00	149+51.274+	25.000+	116.300+	0.21032+
318 03 200 00	149+87.941+	25.000+	117.300+	0.21274+
318 03 200 00	150+24.608+	25.000+	118.300+	0.21523+
318 03 200 00	150+61.275+	25.000+	119.300+	0.21779+
318 03 200 00	150+97.942+	25.000+	120.300+	0.22042+

Figure 2. Sample output for a portion of the Sample Relocation Problem.

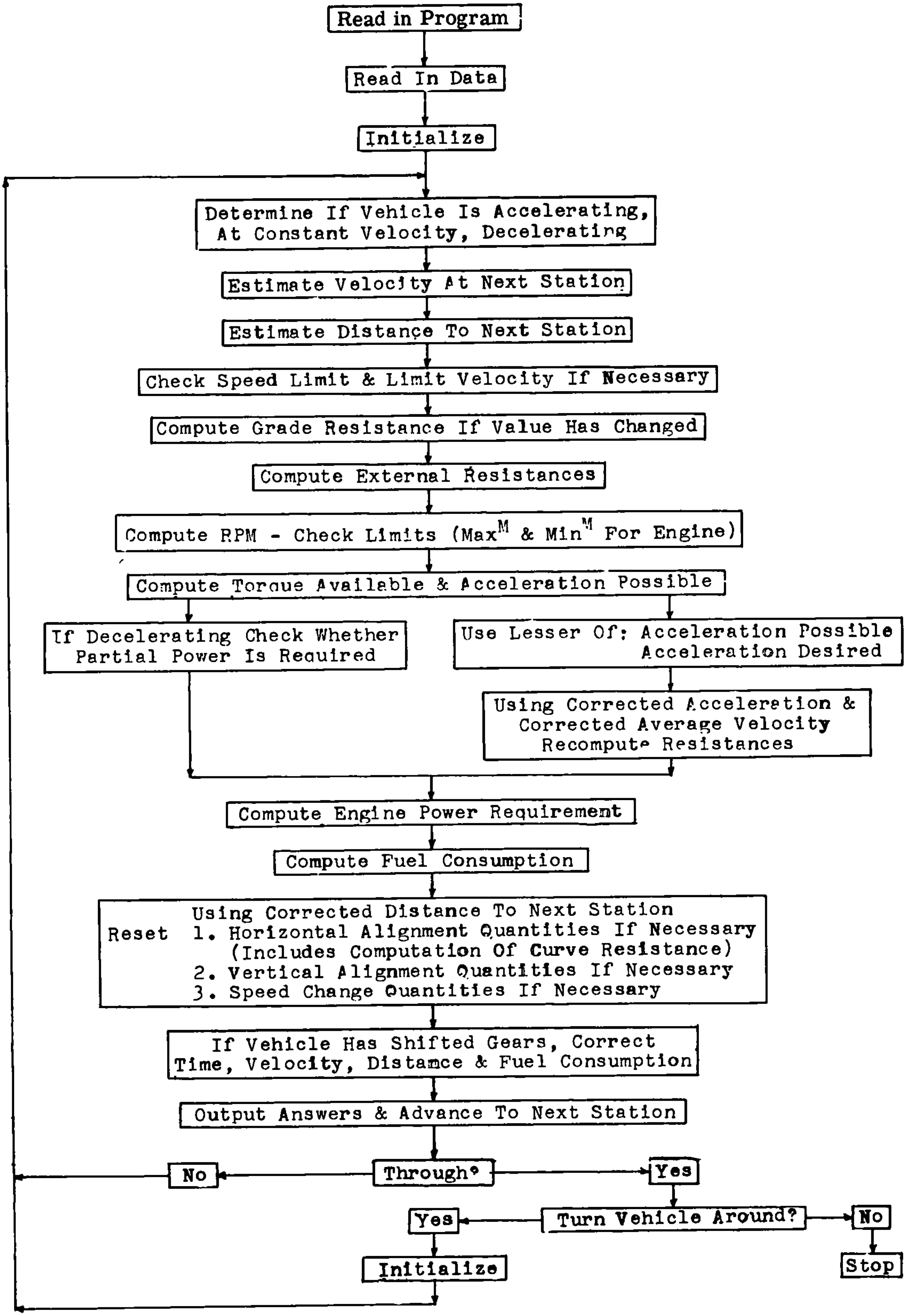


Figure 3. Explanatory flow chart showing the logical and computational steps associated with an acceleration condition.

ble acceleration or maximum sustained speed. Conditions 1 through 4 would be as specified in the input data. Condition 5 would be the result of the vehicle's performance as dictated by the alignment.

The logic of the program is best understood by looking first at the computations required when a vehicle is accelerating (which might produce either Conditions 2 or 5). Figure 3 outlines the logical steps associated with each cycle of computations for the simulation of an accelerating vehicle. The first step of such a cycle computes an estimated average vehicle speed over the next time increment as a function of the performance determined by the immediately previous computation cycle. The estimated distance traveled is computed from the estimated speed over the time increment. The estimated speed is then checked against the limiting speed at the new alignment station and is reduced to the limiting speed if it exceeds it.

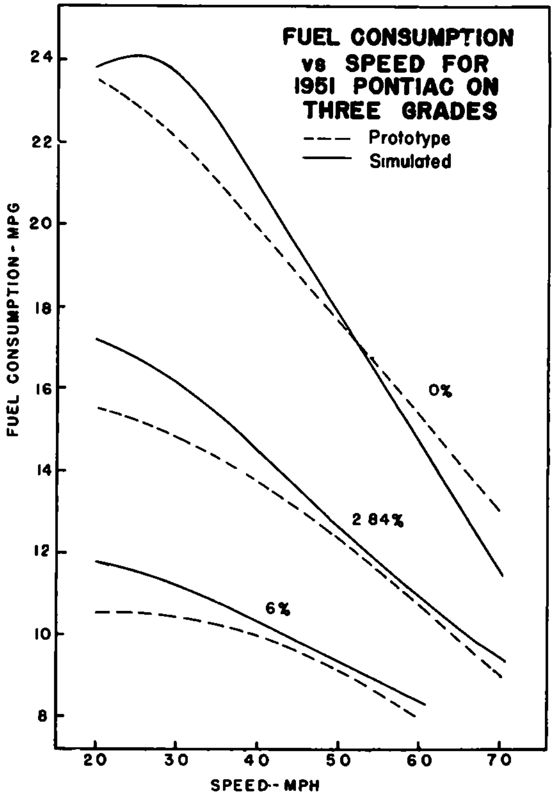


Figure 4. Comparison of simulated and prototype fuel consumptions at constant velocities for the vehicle used in HRB Bulletin 107 (1).

In the next step the program computes the external and internal resistances to vehicle motion on the basis of the average estimated speed over the time increment. Knowing these resistances as well as the maximum torque available from the engine, it computes the possible acceleration. The program then takes as the actual acceleration the lesser of either the possible acceleration or the allowable maximum acceleration. If the resulting actual acceleration is different from the acceleration rate on which the estimated speed was based, the speed, distance, and resistances are corrected. (Because the error converges rapidly on zero, this iterative procedure need be repeated only once.)

Knowing the total tractive resistance and the actual acceleration rate, it is possible to compute the total engine power requirement. The program then takes a fuel consumption rate from a table of values describing fuel consumption as a function of total power requirement and engine rpm. (This table is one of the items prepared by the Parameter Computation Program and used as input to the Vehicle Simulation Program.) The fuel consumption over the time interval is computed from this fuel consumption rate. Finally the program checks the alignment and speed profiles for any changes and resets the necessary quantities for the next computation cycle. If the vehicle exceeds the speed specified in the input as the maximum for the particular gear in which the vehicle is operating, a subroutine computes the performance profile during the gear shift before proceeding to the next computation cycle. This is shown in Figure 2 where the automatic transmission shifts at 20 mph.

In the case where a vehicle is moving at constant speed, the program will omit many of these steps. If the vehicle was moving at the limiting specified speed during the preceding cycle, for example, the program will simply check for any changes in the motion or alignment profiles and if it finds none will simply add an equal increment of distance, time, and fuel to the previous answers.

In the case where a vehicle is decelerating, the computations are also simplified. The program computes in advance the deceleration profile required to bring the vehicle down to the proper speed (which may be a complete stop) at the proper station. When the vehicle reaches a point on that profile, it merely decelerates at the prescribed rate. Fuel consumption is then taken either from the fuel table or from an idling fuel rate, depending on whether or not the engine is still furnishing power.

The program can perform all of these operations for any type and size of highway vehicle and over any type of alignment. Although the storage limitations of the computer restrict the amount of alignment data that can be read in at one time, flexible control features in the program permit getting around this problem. By specifying certain digits in an input control word the engineer can instruct the computer to read in more data when it has finished with the first batch and then to continue the motion of the vehicle where it left off. In the usual case of a road with a common alignment in both directions, the program can turn the vehicle around and run it back over the same alignment in the opposite direction.

TESTING THE PROGRAM

A basic assumption underlying this research effort is that if the Vehicle Simulation Program can demonstrate satisfactory prediction of the performance of a few representative vehicles, it can also satisfactorily predict any other vehicles whose performance would normally be of interest to the highway design engineer. An important part of the research was thus to check actual vehicle performance data against the results of computer simulations for the same vehicles and alignments. Some data collected by other researchers were available in the published literature. In general, however, these data were not sufficiently explicit with regard to either highway alignment or vehicle operating conditions to afford a thorough check on the computer program capabilities. As a result it was necessary to run additional field tests designed specifically to check the Simulation Program.

Of those data already available, the most useful were those reported on by Saal in connection with a series of fuel consumption runs made with a 1951 Pontiac sedan (1). In particular, it was possible to check computer predictions of fuel consumption for different grades and speeds against similar data collected by Saal. Figure 4 shows this comparison. In general the simulation results are quite close to the actual fuel consumption (the maximum discrepancies are approximately 7, 10 and 11 percent for the 0, 2.84 and 6 percent grades, respectively). Most of the discrepancy is probably due, moreover, to the fact that the program takes no account of the age, condition or adjustment of the engine.

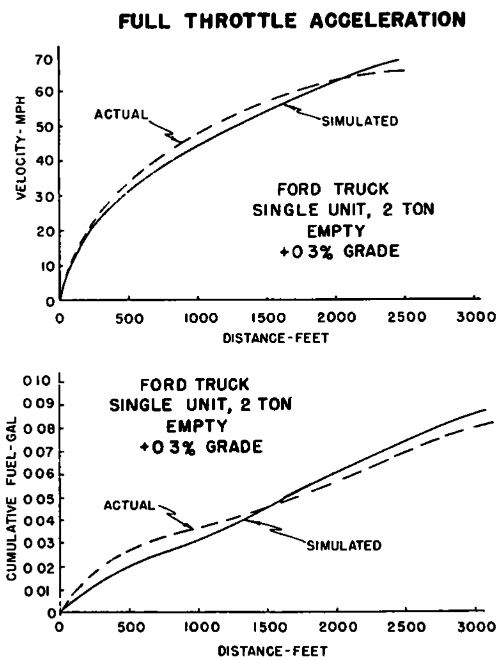
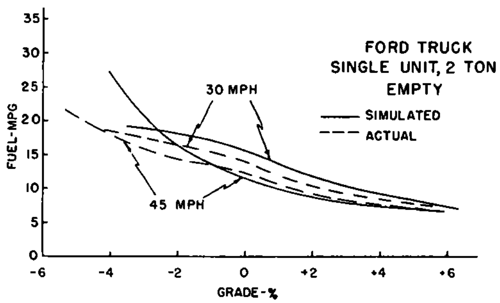


Figure 5. Performance and fuel consumption comparisons of simulated and actual runs for the single-unit test truck under full throttle conditions.

Description of Field Tests

The field tests run in connection with the present research effort were designed to supplement the very limited sort of data previously discussed. These tests were run

FUEL vs GRADE



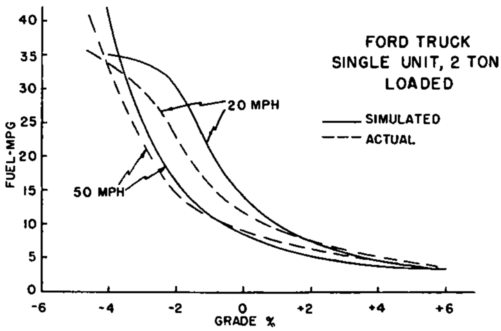


Figure 6. Fuel consumption comparisons of simulated and actual runs for the single-unit test truck empty and loaded as a function of grade.

during September and October of 1960 with the cooperation of personnel from the Division of Traffic Operations in the Office of Research of the Bureau of Public Roads. Three sites in the Washington, D.C., area were used: Dulles International Airport (where the runways, taxiways, and parking aprons had already been paved and so could be used for testing); and the Shirley Freeway in Virginia just south of Washington.

Three different vehicles were used for the tests: a light suburban-type car (not a compact model) with automatic transmission; a 2-ton single-unit truck; and a 50,000-lb GCW tractor-trailer. The two trucks were run in both an empty and a loaded condition.

The test series included four general types of runs: (a) constant speed runs in which the drivers maintained the same speed over an entire test section; (b) acceleration runs either at full throttle or at some constant rate as measured by an accelerometer; (c) deceleration runs where the vehicle was allowed either to coast to a stop or to decelerate at a constant rate; and (d) curve tests in which the vehicles were operated at constant speeds around circles of 150- and 300-ft diameter laid out on a level airport taxiway.

The measurement system employed in these tests included a number of elements. A fifth wheel mounted behind each vehicle measured speed and distance. A fanbelt-mounted tachometer provided data on engine rpm. An adjustable-precision volumetric fuel meter on loan from the Ford Motor Company measured fuel consumption. These units were connected in turn to a set of two digital recording devices provided and maintained by the Instrumentation Branch of the Division of Traffic Operations. These consisted of electronic counters and paper tape printers to output rpm, speed, distance, time, and cumulative fuel consumption (2). A series of identical constant velocity runs over 8800- and 1000-ft test sections yielded a standard deviation of only 1.5 and 3.9 percent, respectively, in the results from the fuel portion of the over-all measurement system.

Comparisons with Field Test Data

Although considerable difficulty was encountered in keeping the total measurement system operative, it was possible to gather data on a wide variety of runs with different vehicles moving over different alignments at various speeds and rates of acceleration and deceleration as previously outlined. For comparison purposes, computer runs were then made with the Simulation Program using these same vehicle, alignment, and speed conditions. Figure 5 shows the results of a comparison of actual speed profiles with those predicted for the same conditions by the computer. Figures 6 and 7 show comparisons of actual fuel consumption with that predicted by the computer. The computer results shown here are actually for the program as revised somewhat in light of the field test data. In particular, it was possible to infer from these data that the mathematical form of the chassis resistance equation, which had always been suspect, was applicable only to heavy vehicles. Changing this relation to a more generally applicable form (see Appendix) brought the simulation results much closer to the actual.

In general, the computer simulation results agree quite well with those of the field tests. Such error as does exist can be explained in part on the basis of at least three factors. The first of these is the problem of engine adjustment already mentioned. The computer programs use theoretical torque and fuel consumption performance standards which the actual engines will not generally meet, particularly in the middle speed ranges, where theoretical fuel consumption is a minimum. Adjusting the program input to account for this problem properly is difficult at best. A second problem is that in the lower speed and horsepower ranges the fuel performance map (Fig. 10) tends to be unreliable. Without a larger number of test results than were available, any comparison at low speed is thus open to some question. This unreliability is particularly noticeable in the downhill comparisons (Fig. 6). The fuel consumption rate under this condition although relatively low, is evidently somewhat erratic. A third problem stems from the uncertainty of the coefficient of air resistance which was used in simulating the performance of the test vehicles. This can produce particularly large errors in the fuel consumption at high speeds, where air resistance accounts for the bulk of the total resistances to vehicle motion.

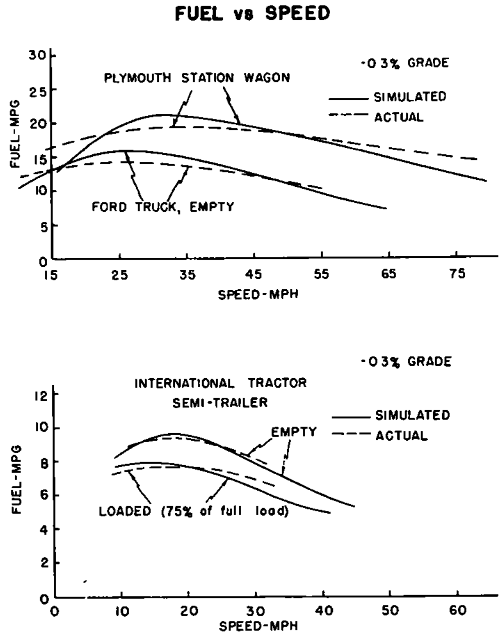


Figure 7. Fuel consumption comparisons of simulated and actual runs for all three test vehicles as a function of speed.

Such lack of agreement as remains is probably not serious. One reason is that the Simulation Program will normally be used in estimating relative rather than absolute vehicle performance and operating costs. Some inaccuracy is inevitable in the entire estimating process in any case, because of the difficulty involved in choosing the "average" vehicles which are to be taken as representative of the entire vehicle fleet using the highway under study. The conclusion is thus that the programs can provide the highway design engineer with an analysis technique of sufficient accuracy.

USING THE PROGRAMS

Possible Areas of Application

Probably the most important application of this new analysis technique will be in connection with the preliminary engineering phase of highway route location problems. In this phase the design engineer is considering alignment alternatives which could produce major differences in vehicle operating costs. A typical problem might involve determining the additional construction expense justified by the savings in vehicle operating costs which

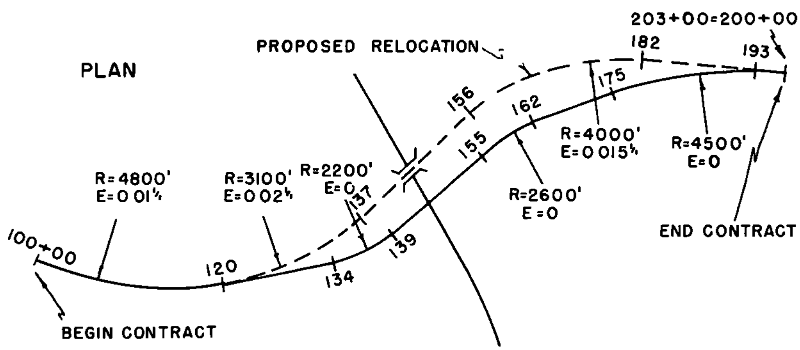


Figure 8. Plan of Sample Relocation Problem showing existing and proposed locations.

would result from a reduction in grade. Another might involve the choice between a long bridge on a direct line and a shorter and less costly bridge on a more circuitous line.

Another class of problems amenable to analysis by these computer programs is that of intersection and interchange design. The increased vehicle user costs associated with the stops required by an at-grade intersection, for instance, may in themselves justify construction of a grade separation. Further than that, the question of whether to carry a main road over or under a secondary road may even turn on the resulting difference in user costs. The decision between a directional and a cloverleaf type of interchange is still another application. Finally, the whole question of interchange spacing and location can be answered rationally only on the basis of an analysis of user costs. Because the cost per vehicle must be multiplied by thousands of vehicles, moreover, this analysis must be sufficiently detailed to detect the differences between small segments of new and old highway routes.

The computer analysis technique is able to detect just such differences in detail. The AASHO Road User Benefit Analysis Manual generally is not, based as it is on average alignment conditions only. In the few instances where more detailed analytical studies of vehicle performance on alternative alignments have been made, the results have indicated that the design engineer needs such an analysis to aid him in reaching a decision (3).

A Sample Problem

A sample highway design problem can best illustrate the use of the computer analysis technique. Figure 8 shows the plan of an existing section of highway and its proposed relocation. Figure 9 shows the vertical alignment profile and speed restrictions for the two locations. (Figure 1 showed the speed and alignment profiles for this same problem.) The proposed alignment would (a) reduce the grades and eliminate some rise and fall, (b) eliminate a stop (and 15-sec average wait) at an at-grade intersection, (c) provide better geometric design so that drivers would raise their maximum speed slightly, but (d) increase the length of the line a bit. The problem is to determine the effect of these changes on vehicle operating costs.

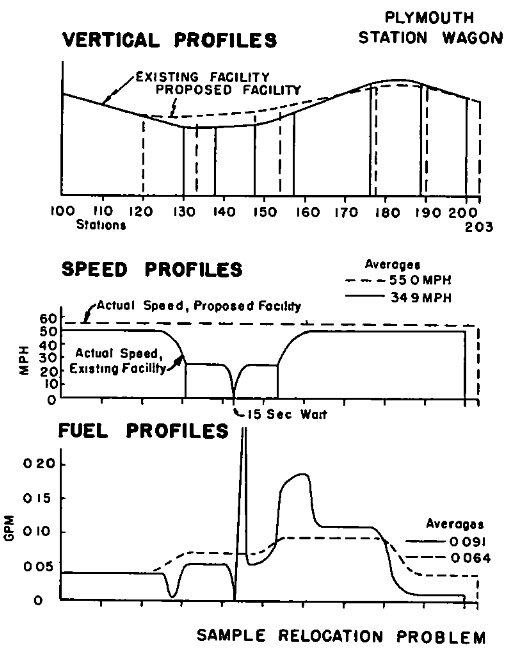


Figure 9. Speed and fuel profiles plotted from the output of the Vehicle Simulation Program (vertical profile is repeated here for reference).

Let it be further assumed that the highway in question has an ADT of 3,000 vpd, split evenly in each direction, and composed of 90 percent automobiles and 10 percent heavy trucks. For purposes of simplicity, the example considers only two classes of vehicles. In the computer simulation runs these two classes were represented, respectively, by the Plymouth station wagon and the (loaded) 50,000-lb GCW tractor-trailer used in the program of field tests previously described. Again, these vehicles were chosen for simplicity, not because they are necessarily "average" vehicles. (The determination of "average" vehicles is a problem mentioned briefly in the concluding part of this paper.) Assume also that all vehicles go straight through (that is, there are no turns on and off the intersecting road) and that traffic volumes will remain constant over the life of the facility.

Using this basic information it is possible to compute the difference in vehicle operating costs with the help of the computer programs. This requires simulation of eight trips: one for each type of vehicle in each direction (forward and return) over each alignment (existing and proposed). Table 1 gives the results of these runs. In addition, Figure 9 shows the actual speed profile and the variation in rate of fuel consumption for the station wagon when running in the "forward" direction on both the existing and proposed alignments. (These runs correspond to those entries in Table 1 marked with an asterisk.)

TABLE 1

		Average Speed (mph)			Avg. Fuel Consumption (gal/mi)		
Vehicle	Alignment	Fwd.	Ret.	Avg.	Fwd.	Ret.	Avg.
Automobile	Ex.	35.4*	35.3	35.4	0.0652*	0.0678	0.0665
	Prop.	55.0*	55.0	55.0	0.0574*	0.0592	0.0583
Heavy truck	Ex.	20.9	26.2	23.2	0.2932	0.2870	0.2901
	Prop.	45.6	48.4	47.0	0.2283	0.2242	0.2263

Note: Data on existing alignment include the stop.

Several things are interesting about these computer simulation results. First, the forward and return trips are virtually identical for the station wagon, because the alignment does not limit vehicle performance. This is not true of the heavy truck. Second, the deceleration and acceleration required for the low speed zones and the stop on the existing alignment have a serious effect on average speed, as would be expected. (The waiting time at the stop itself is relatively unimportant.) Third, the average fuel consumption rate is clearly reduced for both vehicles despite the higher speed on the proposed alignment.

Multiplying these results (expressed in average seconds and gallons per one-way trip) by the appropriate unit user costs and extending them by the estimated traffic volumes will yield the difference in total user costs between the existing and the proposed alignments. Using the cost of fuel as $0.30 per gallon and the cost of time as $2.00 per automobile hour and $3.00 per truck hour (neither unit cost is necessarily correct; the value of time must be left to the engineer's discretion) and using the traffic volumes previously suggested, the user cost savings would be as follows (no attempt has been made to include maintenance, tire wear, and oil costs, which would in any case be only slightly affected by the change in alignment suggested):

Fuel savings—auto 0.0126 gal at $0.30 =	$0.00378
Time savings—auto 65.3 sec at $2.00/3600 =	0.03628
Total savings—auto (psi 1-way trip) =	0.04006
Fuel savings—truck 0.110 gal at $0.30 =	$0.03300
Time savings—truck 145 sec at $3.00/3600 =	0.12083
Total savings—truck =	0.15383

Annual Savings

Automobiles = (3000)(0.90)(365) at $0.04006 =	$39,479
Trucks = (3000)(0.10)(365) at $0.15383 =	16,844
Total all vehicles =	$56,323

This final figure when combined with other costs and cost savings can then be used in a benefit cost, annual cost, or rate of return analysis.

OTHER CONSIDERATIONS

Discussion of Analysis Technique

One of the main objectives in setting up the computer programs was to make them simple to use. Thus, the programs are designed so that the highway design engineer can make an analysis of vehicle operating costs without any specialized knowledge of vehicle performance. In addition, all of the required vehicle parameters will either be readily available to him from the manufacturers' published data, or they will be tabulated in the Program Operating Manual. An even greater simplification can be made, however, in that it will be possible merely to furnish design offices with a deck of data cards already prepared for a set of representative vehicles by the Parameter Computation Program. This would obviate the need for an engineer to run anything but the Vehicle Simulation Program or to prepare anything other than alignment and speed restriction data as input to it.

This procedure could have the added advantage of centralizing in the hands of a more specialized group the very difficult problem of choosing precisely those vehicles which can best represent a small number of vehicle classes whose composition is almost hopelessly heterogeneous. Present thinking on this problem is that the entire fleet of vehicles using the highways should be broken into three classes: automobiles and four-wheeled light trucks, medium single-unit trucks, and heavy combination trucks. A representative vehicle would be chosen from a cross-section of the total population of each class in such a way that its performance would be average for its class. Ideally the population of vehicles sampled should, moreover, be the average population in use during the (future) life of the highway in question, a factor which makes the choice still more difficult. (Taking this problem out of the hands of the design engineer still leaves him, of course, with the job of estimating future traffic volumes by vehicle class.)

Once the necessary vehicle and alignment data are in hand, the analysis can go very fast. The computing speed of the Simulation Program is such that in the case of a detailed analysis the vehicle trip miles covered per computer hour is about three times that of the average simulated speed. As an example, three classes of vehicles moving at an average speed of 40 mph could be run in both directions over 5 mi of highway in 15 min of computer time. In a normal route location study with a good deal of constant speed running and no need to punch out intermediate answers, this time could be even further reduced.

These performance figures apply to the use of the program on the IBM 650 EDPM. The programs are presently coded for this machine and the Program Operating Manual will be written for it as well. A FORTRAN version of the programs will also be available, however, so that even better performance can be achieved on larger computers.

The brief description of the program logic and mathematics included here shows that the models used are not particularly sophisticated. The Simulation Program will not handle torque converter transmissions in quite the right way. A sacrifice was made in this respect to eliminate the need for two different simulation programs, although the discrepancy in the answers is probably not serious in any case. The program also has difficulty in predicting downhill fuel consumption. This is shown in Figure 6 by the lack of agreement between the actual and predicted fuel curves for large negative gradients. Again, this weakness may not be serious in this case because fuel consumption is low under these conditions anyway.

As pointed out, the results of the field tests indicate that notwithstanding these problems the programs can give answers which are wholly satisfactory for the highway design engineer's purposes. Certainly the answers are far better with respect to detail than anything which is otherwise available.

Future Research

The development of a satisfactory set of computer programs removes the major obstacle to the evolution of the more sophisticated technique for the analysis of highway user costs which is the ultimate objective of this research. It is clear, however, that much work remains to be done before the full benefits of this technique can be realized in highway design engineering practice. A continuing program of research contemplates work in the following areas:

1. Inquiring further into the possibilities for and desirability of increasing the ac-

curacy of the simulation model. This will involve a closer look both at the mathematics of the model as well as at some of the parameters presently being used in the equations. Part of this will be based on further analysis of the field test data and part on the experience gained by using the programs on actual test projects. As pointed out, accuracy no longer seems a problem for the bulk of the uses to which the program will be put. If minor changes can broaden the applications for which the program is suitable, however, they probably should be made.

2. Increasing the flexibility of the program. A number of things might be done in this regard. The most important is an investigation into ways of modifying the programs so that they can simulate the effect of traffic interference on vehicle performance and thus on operating costs. This is a particularly difficult problem, however, on which no early progress is in sight.

3. Applying the programs to actual location and design problems so as to study the extent to which operating costs are sensitive to design changes. This is really a three-part effort. It will, first of all, provide insight into the reasonableness of highway design criteria. Second, it will help to identify weaknesses in the analysis technique as well as the programs themselves. Finally, it will help to make more clear the ways in which the analysis techniques can be used on a practical basis.

4. Preparing summary information to relate vehicle performance and operating costs to highway alignment characteristics. The computer programs provide a very efficient way to develop this sort of data. It is envisioned, therefore, that they might be used to prepare tables and graphs similar to those in the AASHO Manual but in greater detail. These might then be used rather than the computer to analyze all but the most detailed differences between design alternatives.

5. Documentation. Although it does not properly come under the heading of further research, this phase of the work is extremely important at the present time. As mentioned at the outset of this paper, a Program Operating Manual is in the final stages of preparation. Its publication will immediately make the analysis technique available to those who want to use it. This manual will also be supplemented, however, by a detailed research report. This report will contain the detail needed as a basis for further research into and refinement of this and other techniques for the analysis of vehicle operation and costs.

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Appendix

Mathematics of Vehicle Motion Model

Referring to the description of the acceleration computation cycle, the following equations show the relationships used for estimating vehicle speed and distance over a given increment of time and subsequently correcting these in the iteration routine.

$$VE = VO + (AO)(DT) \tag{1}$$

in which
VO = speed at start of cycle,
AO = average acceleration used in previous cycle,
DT = specified time increment, and
VN = estimated speed at end of cycle (or corrected speed at end of cycle).

$$SN = SO + (VO)(DT) + (0.5)(AO)(DT)^2 \tag{2}$$

in which
SO = station at beginning of cycle, and
SN = station at end of cycle.

Grade resistance is taken as simply the tangential component of the weight of the vehicle and is computed by Eq. 3.

$$GR = (G)(W) \tag{3}$$

in which
G = grade (in feet of rise per horizontal foot),
W = weight gross vehicle weight, and
GR = approximate grade resistance in pounds of tractive effort.

According to the literature, the most accurate expression for both air and rolling resistances is an exponential equation. The expression used in the program, however, is the operationally simpler second order polynomial shown in Eq. 4.

$$RR = A + B(V) + C(V)^2 \tag{4}$$

in which
RR = sum of air and rolling resistances,
A, B, C = constants, and
V = speed in mph.

Constants A and B are derived by the Parameter Computation Program from the conventional rolling resistance parameters determined by other researchers (4). Constant C is derived from the coefficient of air resistance multiplied by the projected frontal area of the vehicle. The program does take into consideration any increase in vehicle resistance due to wind effects, but only by head or tail winds. Because none of these parameters is available from the vehicle manufacturer's data, they will be tabulated in the Program Manual. All of these parameters are based on the rolling resistance for a high-type concrete surface. Any surface of poorer quality would effect a linear increase in the rolling resistance. By increasing the value of A (again as outlined in the Program Manual), the program can account for this additional pavement resistance.

A percent efficiency is used to account for the loss in power between the engine flywheel and the drive wheels of the vehicle. This constant (actually an input parameter, EFF) is applied either to reduce the total torque available from the engine at the drive wheels as in the case of a maximum acceleration or to increase the sum of all the external resistances on the vehicle as in the case of constant velocity. Because torque is proportional to power at any given rpm, Eq. 5 can be used to account for the loss of power in the drive line. A variable factor should be used for transmissions with torque converters, but at present the program uses a constant similar to that for direct drive transmissions.

$$TQ = (TK)(EFF) \tag{5}$$

in which TK = engine torque (less accessory losses), and
TQ = torque corrected for drive train losses.

The efficiency factors used in the program vary from 90 to 95 percent for light vehicles operating in smaller gear ratios and from 85 to 90 percent for heavy vehicles with large gear reductions.

The rpm of the engine is computed by a set of rpm/V ratios for each gear as shown in in Eq. 6.

$$\frac{rpm}{V} = TF \times GRA \tag{6}$$

in which TF = tire factor (which includes a constant amount of slip), and
GRA = the total gear reduction.

Under average driving conditions a driver does not allow the curve resistance to be very large, because he either reduces his speed to that at which he can negotiate the curve comfortably, or he takes up more room in negotiating the curve so as to increase its effective radius, or both. Nevertheless, to handle certain situations where curve resistance is significant, the computations are set up to account for it. Eq. 7 and 8 illustrate this.

$$F = \frac{V^2}{15R} - E \tag{7}$$

in which F = coefficient of side friction,
V = speed in mph,
R = radius in feet, and
E = superelevation in ft/ft.

$$CR = (W)(CCR)(F)^2 \tag{8}$$

in which CCR = coefficient of curve resistance, and
CR = curve resistance

Eq. 7 uses a dimensionless parameter, F, to express unbalanced side friction force. Eq. 8 uses the second power of this parameter because of the parabolic nature of the slip angle versus cornering force relationship. Fiala (5) points out that the resistance to forward motion due to curvature is a function of the centrifugal force and the slip angle and further that the slip angle itself varies as the unbalanced centrifugal force. Thus, curve resistance can be considered as a function only of the weight of the vehicle, a coefficient to account for weight distribution, tire inflation pressure, etc., and the square of the unbalanced centrifugal force. The coefficient of curve resistance, CCR, in Eq. 8 is a function of the dimensions and weight distribution of the vehicle, the tire inflation pressure, and the friction between the tires and the pavement surface.

The rotating components of the engine, transmission, and wheel assemblies contribute an additional resistance when they are undergoing a change in angular velocity. This inertial resistance is accounted for by increasing the effective mass of the vehicle as per Eq. 9.

$$EM = M + K_1 + K_2 (GRA)^2 \tag{9}$$

in which K_1 and K_2 = mass equivalent constants (6, 7), and
EM = equivalent mass.

The program uses this equivalent mass rather than the true mass of the vehicle in computing acceleration.

The full throttle torque at any given rpm is computed by Eq. 10.

$$TK = E + F(rpm) + G(rpm)^2 \qquad (10)$$

The coefficients E, F, and G are computed by the Parameter Computation Program.

The maximum possible acceleration can then be computed by Eq. 11.

$$AO = \frac{(TQ)\,(d)\,(EFF) - TR}{EM} \qquad (11)$$

in which $d = (GRA)\,(TF)\,(d')$,
d' = dimensional constant, and
$TR = GR + RR + CR$.

As pointed out in the section on simulation logic, the program selects the lesser of either the specified maximum acceleration or the possible acceleration. It then back-figures the total tractive effort required (including the drive line resistances) and computes the power requirement by Eq. 12.

$$BHP = \frac{(AO)\,(EM) + TR}{EFF}\,\frac{V}{d''} \qquad (12)$$

in which d'' = a dimensional constant.

On steep grades it is necessary to give special consideration to the effect of gear shifting on both the speed and fuel consumption of trucks. The program makes an approximation to the real case by allowing the vehicle to coast during each gear shift for an amount of time equal to the average shift time for that type of vehicle. In the case of an automatic transmission this time interval is very small; with trucks it is the average shift time, regardless of the particular shift maneuver required. In calculating the speed lost during the shift time, resistances are computed on the basis of the initial speed for the time period involved. This produces a second order systematic error, because that speed is always larger than the average speed over the coasting interval. This error, however, helps to offset the additional amount of fuel that the driver uses in double clutching. In any case, the approximate method reduces the error which would otherwise be introduced by ignoring the gear shift.

Mathematics of Fuel Consumption Model

Fuel consumption is computed on the basis of a consolidated engine performance map (8). Performance maps for particular engines are likely to show fairly wide variations due to eccentricities in the adjustment of the engines. A consolidated map of the performance of many engines in same range of compression ratios exhibits a much more uniform behavior. Because, in the last analysis, this program deals with a large number of vehicles rather than with a single one, such a consolidation is an acceptable step. Exactly what sort of errors are introduced by using such a map is not entirely clear, but the test results suggest that they are not serious. The original experimental simulation program was used to test other much simpler approaches to the fuel consumption problem. These proved entirely inadequate from the standpoint of accuracy. The performance map approach emerged as the only feasible alternative.

Figure 10 shows a typical gasoline engine performance map. The Parameter Computation Program transforms the data on this map into specific fuel consumption values on the basis of the bore, stroke, and number of cylinders of the engine in question. The resulting values of specific fuel consumption are arranged in 20 x 20 matrix in such a way that the values in the columns are proportional to the rpm and the values in the rows are proportional to the brake horsepower. This table of values (along with the other summary vehicle parameters) is punched out on cards to be used directly as input to the Vehicle Simulation Program. It is then possible for the Simulation Program to compute the fuel consumed in any time increment by looking on the table for the fuel rate as a function of the rpm and the required horsepower and multiplying that value by the time increment itself.

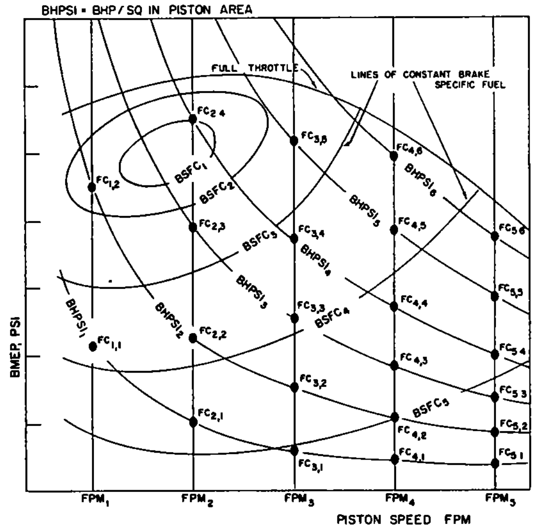

Figure 10. Typical gasoline engine performance map. Data stored in program are FPM_1, FPM_2...; $BHPSI_2$...; and $FC_{1,1}$, $FC_{1,2}$...; $FC_{2,1}$, $FC_{2,2}$....

Other input parameters are necessary to specify the rate of fuel consumption in pounds per hour for the vehicle when it is operating at closed throttle (that is, with the engine idling). One parameter specifies the rate when the vehicle is coasting; another specifies the rate when it is standing still. Carburetors are not normally designed to operate efficiently at closed throttle. A vehicle can thus have an extremely unpredictable fuel consumption curve under closed throttle conditions when the engine is turning over at high rpm. (An example of this would be coasting down a grade.) Evidently, a certain amount of additional fuel escapes past the idling jets as a result of the manifold pressure being different from the idling case. It is this additional fuel requirement that makes it necessary for the program to use one idling parameter when the vehicle is in motion and another one when it is standing still. Although the coasting rate is apt to be extremely erratic in any given vehicle, it is assumed to be consistent over a large number of vehicles.