ESTIMATION MODEL FOR THE LIFE CYCLE ENERGY CONSUMPTION FOR HIGHWAY TRANSPORT

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PREFACE

For the immediate future, highway transportation is anticipated to remain the dominant mode of passenger travel in the United States. Vast quantities of energy are consumed by vehicles traveling on the highways. In addition, energy is used for the construction and maintenance of the facilities. To reduce the total consumption of energy, particularly petroleum-based products, highway administrators need to determine how their decisions and design criteria influence the total or life cycle expenditure of energy for construction, maintenance, and use. Highway designs involve trade-offs so that the expenditures of energy to eliminate steep grades or sharp curvatures decrease the total expenditure by each vehicle traveling on the system. In an effort to optimize highway designs (including location) to minimize energy consumption, all phases of the highway system must be examined so that the total energy consumed during the life of the highway is reduced.

It is the purpose of this study to develop and formulate an energy estimating model which explores the energy expenditures for construction, major maintenance, and vehicle operations. Each of these energy-utilizing components is integrated in a PL/1 (Programming Language/One) computer program to predict the total, overall energy expenditure.

The author has attempted to give credit to all contributing sources and apologizes for any unintentional omissions. The author recognizes and appreciates the contributions of the members of his graduate committee and their directions during the course of this study: Professors

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHO	American Association of State Highway Officials, changed to the American Association of State Highway and Transportation Officials (AASHTO)
ADT	average daily traffic
AI	Asphalt Institute
BPR	Bureau of Public Roads
Btu	British thermal units
cu yd	cubic yard
f	friction factor
FHWA	Federal Highway Administration
ft	foot
gal	gallon
gpm	gallons per mile
gpmin	gallons per minute
HEC	Highway Equipment Committee
hr	hour
hp-hr	horsepower-hour
in.	inch
LCC	life cycle costing
M.Btu	1×10^6 Btu
min	minute
mpg	miles per gallon
mph	miles per hour
ODOT	Oklahoma Department of Transportation

PSI	Present Serviceability Index
sq yd	square yard
SUT	single unit truck
TRB	Transportation Research Board
veh	vehicle
vpd	vehicles per day
VPI	vertical point of intersection

CHAPTER I

INTRODUCTION

Energy Crisis and Highway Transport

The United States is rapidly exhausting its supply of petroleum reserves and is becoming increasingly dependent upon unreliable foreign sources of petroleum. This situation has vast economic, political, technological, and social ramifications. The highway transportation sector is the leading consumer of petroleum energy, expending approximately one-half of all petroleum products and one-quarter of all forms of energy (8). The historical annual energy growth rate of transportation is 3.2 per cent with 18.3 quads[1] consumed in 1970. Although efforts are underway to reduce the energy growth of transportation, the expected minimum growth rate is two percent per year, which would indicate a doubling of consumption in 35 years (6).

As witnessed during the 1973 Organization of Petroleum Exporting Countries (OPEC) oil embargo, a major disruption of the transportation industry produces significant consequences throughout the nation. The transportation sector (including highway transportation, mass transit, etc.) contributes one-fifth of the Gross National Product and employs 20 million persons. On a typical work day 50 million cars travel our

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[1] A quad is 1×10^{15} Btu and a Btu is the energy required to raise one pound of water, one degree Fahrenheit.

highways and consume 27 billion gallons of gasoline annually. Efforts to substitute less energy-intensive modes, such as mass transit, have limited near-term possibilities, primarily due to the low base (less than three percent of the commuting population uses mass transit) and ingrained reluctance of the motoring public to change to other modes (19).

To offset this growing dependence upon foreign oil, this nation should continue the policy of developing new sources of energy and expanding production capability, in conjunction with a policy of energy conservation. As part of the conservation effort, the existing transportation system should be analyzed in an attempt to increase its energy-efficiency. Efforts to improve the energy-efficiency of the automobile should be combined with an examination of the road system to determine how highway design criteria influence fuel consumption. These design criteria should be re-examined in terms of cost increases in fuel and the national objective of energy conservation of petroleum.

Life Cycle Costing and Systems Analysis

Life cycle costing (LCC) is an approach which considers the total cost, i.e., initial and operating elements, of an investment rather than merely a comparison of initial costs. By considering all costs, LCC focuses attention upon the interactive nature of elements, e.g., the trade-offs between maintenance and construction, so that the lowest overall or long-term ownership cost may be attained. For example, LCC is a particularly applicable concept for assessing the long-term effects of energy conservation in building design. This approach allows a comparison as to whether it is more economical to install a large amount of insulation and minimize subsequent heating and cooling costs or forego the thermal insulation and experience greater utilities costs.

A technique utilized in conjunction with LCC analysis is systems analysis which functions as an integrating approach, exploring the interdependencies of components or subsystems. Each component may then be designed to fit efficiently with the other components rather than merely functioning independently. Systems analysis emphasizes the factors and concepts that are common to the successful operation of relatively independent parts in an independent whole. Basically, an entire system of components acts as an unified entry rather than simply as an assembly of independent parts.

A system analysis technique is utilized in the LCC energy model because the energy expenditures of the components are interrelated. Vast amounts of energy are expended by vehicles traveling on highways and roads. Energy is also consumed in road construction for the production of raw materials, preparation of the surface mixes, shaping embankments, finishing surfaces, and maintaining the completed facility. These energy expenditures are interactive to the extent that one influences the outlays of another. For example, the allocation of energy for the construction of stronger pavements affects the quality of the riding surface. The quality of the riding surface influences vehicle fuel efficiency, and also the energy expenditures for future maintenance and overlay operations. Since the energy quantities for construction, maintenance, and vehicle usage are interdependent, a systems approach must be utilized to simulate the energy consequences of a variation in one activity to determine its effect on total energy variation. For highway officials who are considering different and competing designs (route location, geometrics, strength of the riding surface, etc.), a life cycle model would be helpful in predicting the energy cost of each of the alternatives.

Sensitivity Investigation

To determine the effect of variations of key input variables which may influence the total energy and/or total cost expenditure, a sensitivity investigation is performed upon key variables in the model. A user of this model may then be able to determine a confidence level of the output by knowing the accuracy of the input data. This investigation is performed by two methods. The first method injects a dynamic scenario into the model to determine how a variation of three key variables may influence the choice of the least energy-consuming and/or least cost-expensive road. The results of the dynamic scenario investigation are compared with the results of the traditional procedure of assuming average values throughout the analysis time-frame (i.e., static scenario). The overall performance of the model may be ascertained by comparing the total energy and total cost results with the dynamic scenario and with the static scenario being implemented.

The second method of sensitivity investigation is performed by assigning ranges of value to several input variables. It is expected that some input variables may affect the total results of the model significantly while others may have inconsequential influence upon the results. By observing the range of output results versus the input variable ranges, a user may quantify the required accuracy of his input data for a desired confidence level in his output data.

Method and Scope of Study

Until this research, an integrated life cycle energy consumption model to predict the long-term energy expeditures for highway alternatives was not developed. The bulk of the existing highway research for highway energy expenditures considered isolated components, e.g., vehicle fuel consumption under various conditions rather than the total energy expenditure over the highway's expected life.

The object of this research is to develop a systems model using LCC techniques for predicting the total energy effectiveness of various and competing highway alternatives. The research involves identification, analysis and quantification of those factors which account for the energy expenditure throughout the useful life cycle of a highway. This research provides highway officials with a new method for use in the decision-making process in highway design/construction/maintenance/usage so that the long-term energy consequences may be considered.

The scope of the investigation is limited to existing energy data and no attempt is made to ascertain energy/fuel expenditures by either laboratory or field techniques. Thus existing energy data, which are largely fragmented, are integrated into a systems approach for the life cycle energy cost. This model is structured toward a single project analysis and is not intended for macro-energy estimation of state or national systems. Therefore, the selection and source of the data base of the model do not directly include national or regional input/output data.

The model is designed and constructed to receive as input data the output of existing highway analysis and design techniques. The model does not incorporate specific subsystems such as traffic prediction or pavement design, but rather takes the results of existing methods as input data to determine the total energy expenditure. Thus, the model is readily compatible with a complete range of analysis and design methods.

The primary focus of this research is to ascertain the energy costs of highway decisions in energy units without a direct inclusion of financial costs. This approach is a new, specialized form of LCC whose objective is to determine the energy consequences in million Btu's (M.Btu) of various highway alternatives. At the time of this writing, conservation of energy is not the governing factor in highway decision analysis. The most energy-efficient solution may not be the optimum from the total decision viewpoint including safety, service, economic costs, and benefits. Therefore, the model is structured as an energy estimate or simulation, so that previously selected alternative routes may be analyzed to determine their relative energy efficiencies. If energy criteria should become the dominant factor within the decision process, then the model may be transformed into an optimization model through recursive data input.

A secondary focus of the research is the development of the capacity to ascertain the cost implication of energy/fuel prices. As the supply of fuel and energy becomes scarce, the price of fuel will rise and energy/fuel prices will become increasingly significant for the economic benefit/cost analysis. By including energy costs during the time of analysis, greater attention is placed upon conservation of energy when comparing alternatives. Only general economic factors are included and the research does not develop subsystems for cost prediction or detailed estimating procedures.

A third focus of this research is the investigation of cost and energy trade-offs between grade reduction and vehicle fuel consumption. A separate model explores the analysis and optimization of long-term energy and cost saving attainable through large earth excavation. Part of this model develops a technique for estimating earthwork quantities based upon an initial and final set of grades and a section length.

Limitations of Parameters for the Energy Model

This energy estimating model is not designed as a total transportation model, assimilating and accounting for all energy sources for highway transport. Rather, the model considers only those factors of energy consumption over which the highway official or designer has influence. These primary factors are:

1. The influence of pavement conditions upon maintenance and vehicle fuel consumption.
2. The effect of highway geometrics on vehicle fuel efficiency.
3. The effect of design and specifications upon energy expenditures for construction operations.

Other factors are excluded from the model because their energy cost is small in comparison to the total systems energy cost. For example, it is well documented (7, 37) that highway design has a significant effect on vehicle maintenance requirements, tire wear, and oil consumption. However, these data are excluded from the model because of their small energy significance. Oil consumption and tire production each represents only one percent of all highway energy, while maintenance of vehicles accounts for only two percent (21). These energy expenditures are indirectly represented because a highway improvement that produces a fuel saving generally yields a saving in these factors. For example, a dusty gravel road causes greater oil contamination and tire wear, and requires more vehicle maintenance than a smooth paved surface. The manufacture and sale of automobiles constitute nine percent of highway energy but are omitted from the model because the highway engineer has little control or influence over this aspect. The same rationale is applied in excluding the production of construction equipment. Other factors, such as parking, garaging and insurance, are not regarded as being in the realm of highway design. The energy expended for routine maintenance activities, other than pavement maintenance, e.g., mowing and litter cleanup, is eliminated from the systems energy expenditures because these activities do not directly affect vehicle performance and are largely determined by an arbitrary desired level of service. Manpower energy allowances or estimates are also excluded from consideration as a parameter in the energy model.

This model analyzes rural two- and four-lane highway driving and it is not intended to estimate energy consumption for urban street driving. The fuel consumption patterns of these two driving modes are quite dissimilar. The fuel expenditure for urban driving is largely dependent upon the amount of signalization and the extent of interference from traffic, while highway fuel performance is generally a function of geometrics and operating speed. For fuel savings in urban areas, other approaches than LCC analysis of highways may prove more effective in reducing energy expenditure. The traffic engineer may elect to concentrate his efforts on improved signalization and traffic flow for congested downtown areas, and to encourage motorists to use other modes.

Finally, the development of new techniques for pavement design, traffic volume predictions, or other planning and design functions is beyond the scope of this research. The energy model is intended to be incorporated within and serve as a supplement to existing criteria. The model does not contain stochastic parameters so that probabilistic estimates may not readily be attached to the life cycle energy cost. The data base of the model is of current data and may require periodic updating to reflect greater energy efficiencies.

CHAPTER II

REVIEW OF THE LITERATURE

The data employed in this research are compiled from a variety of sources. Since energy consideration is a recent topic of national concern, the research on this subject is fragmented and characterized generally by a specific in-depth analysis of one particular component, e.g., asphalt plant efficiency. The interrelationships and interactions are not developed between that componenet's energy characteristics and the entire highway system's energy consumption, i.e., the LCC energy cost. A specific reference was not found which deals with the life-time energy costs of highways. Thus, the data must be aggregated from a variety of sources including:

1. Economic systems analysis of highways
2. Vehicle fuel consumption studies
3. Highway construction and material energy requirements
4. Suggested energy saving techniques
5. Overlay maintenance requirements
6. General highway data.

Systems Approach to Highway Engineering

A classical systems approach to measuring highway pavement performance was the American Association of State Highway Officials' (AASHO)[1] road test. This test was a part of the Highway Cost Allocation Study (41) and analyzed the effect of repeated wheel loadings upon both flexible and rigid pavements. Differential taxes were assigned to the heavier vehicles which required stronger and more costly pavements. The lightest group of vehicles (cars and light trucks) received the smallest tax responsibility and successive increments of cost were assigned to those groups requiring the greater pavement increments. A differential benefit study was conducted to determine the extent of benefits that each group of vehicles received from highway improvements.

In a typical highway analysis a benefit was defined as the reduction of the motoring public's cost of one alternative over another. Four general classes of vehicle benefits were recognized by AASHO:

1. Reduction in operating costs, including fuel and oil.
2. Reduction in time cost, primarily by attainment of higher operating speeds.
3. Reduction in accident cost.
4. Reduction in strain and discomfort.

The AASHO "Red Book" (2) listed vehicle operating costs by gradient class, traffic interference, highway type, and operating speed, and became the basic reference for evaluating benefits resulting from highway improvements for benefit/cost analysis. Soberman and Clarke (33) developed a computer program which generated tables of operating costs so that price changes could be more readily incorporated into benefit analyses. Curry and Anderson (9) presented another systems approach for

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[1] Currently, the American Association of State Highway and Transportation Officials (AASHTO).

evaluating overall highway costs by including an economic estimate for air pollution and noise damage. In 1970, Hejal (16) developed an economic model for priority programming for rural Indiana highways.

SAMP 5 (22) and SAMP 6 (25) included computer programs to determine the systems cost of alternate flexible pavement strategies, including future overlays and a subroutine for estimating the dollar cost of bypassing traffic around the obstructed overlay area.

Vehicle Fuel Consumption

There are numerous studies on vehicle fuel consumption with different researchers producing varied results, depending on their research conditions and methods. For the same road conditions and general driving instructions, various passenger cars exhibit differences in fuel consumption. Variations of results among researchers may be attributed primarily to dissimilarity of the test vehicles, but other factors are also significant. A fully-warmed vehicle consumes less fuel than one started from a cold condition. On warmer days, vehicles are more efficient, and individual driving habits produce different performances.

Paul Claffey (7) produced the most consistent, controlled and documented study of vehicle fuel consumption patterns influenced by different road surfaces and geometric conditions. Claffey installed a very sensitive electronic fuel meter to measure minute consumption changes for a series of road conditions. Although Claffey presented conversion factors for a gasoline powered truck to a similar diesel powered truck, his data analysis lacked the influence of road conditions on large diesel powered trucks. Winfrey (37) utilized data from different sources by calculating, interpolating and extrapolating where data were not available.

In a further investigation of passenger car fuel performance, P. J. Claffey (8) measured the fuel consumption for passenger cars under different conditions. Claffey found that radial tires reduce fuel consumption by seven percent when compared to bias-ply tires. Claffey noted that a tune-up does not significantly affect fuel consumption unless there is a fault or malfunction in the car. Also, Claffey determined the best fuel consumption was obtained by drivers with even acceleration and deceleration.

Vehicle-Highway Interaction

Winfrey (37) classified highway factors that affect motor vehicle running cost and fuel consumption as follows:

1. Distance
2. Grades
3. Curvature
4. Character of roadway surface
5. Traffic volume composition, traffic controls, and speed changes
6. Legal restraint.

Other common factors included the vehicle itself (weight to horsepower ratio, type of transmission, tire size and pressure, etc.), the operator's manner of driving (rates of acceleration and deceleration, speed changes, the number and timing of gear changes, etc.), and the general environmental conditions, particularly weather and topography (air temperature, altitude, etc.). This study dwells primarily upon the influence of highway design on the fuel efficiency of the motor vehicle. The factors enumerated above are described more fully in following sections.

Distance

Distance, the travel length along a particular route between two end points, bears a direct relationship to the total fuel consumption. A realignment of the highway that decreases the total length results in a proportionate savings in fuel, provided that all other factors remain constant. A reconstruction of the road to produce a more direct route reduces both vehicle operating costs (including fuel expenditure) and operating time.

Road Gradient

Road gradient is particularly important as a determinant of motor vehicle fuel consumption. The steeper the grade, the greater is the amount of energy required to ascend the grade. For equal positive and negative gradients the additional energy required to ascend is not necessarily equivalent to the lesser amount of energy expended or energy savings during the downhill segment. For a variety of reasons, including braking on the steeper negative grades, grades have been generally regarded as undesirable for energy efficiency.

In constrast with the preceding paragraph, Claffey (7) found that the fuel consumed on grades up to 3.5 percent was slightly less than the expenditure for operating a passenger car on a level road for the same distance. Claffey stated, "It is slightly more economical at medium speeds to operate passenger cars up and down equal length grades up to about three percent than to operate continually on a level road." For grades greater than 3.5 percent there was a general increase in the rate of fuel consumption. This apparent discrepancy with earlier findings (37, 40) was verified several times. The pickup and other types of trucks did not experience this fuel savings on gently sloping grades. The gradient fuel consumption factors considered only the straight line portion of the grades and did not include the influence of vertical curves upon the vehicles' fuel performance. To analyze the influence of these curves, Claffey conducted a series of tests which found negligible difference between the results predicted by assuming continuous straight line portions and those experienced by field evaluations. It is also interesting to note that the AASHO "Red Book" (2) listed the zero to three percent grade as one gradient class, the equivalent of gently rolling hills. To illustrate the greater fuel consumption caused by an equal positive and negative grade combination as compared to an equivalent horizontal distance, Claffey found that the fuel consumption was 7 percent greater for a 5 percent grade combination, 25 percent greater for a 7 percent combination, and 49 percent greater for a 9 percent combination for a passenger car traveling at 50 mph. For single unit trucks (SUT) the difference was even greater with a rate of 2.5 times the level rate for an 8 percent hill at only 30 mph.[2]

Horizontal Curves

In vehicle operation, horizontal curves introduce a complicated set of forces which may be considered to consist of two components:

1. The normal side frictional force
2. The tangential or straight ahead force.

In order to maintain the vehicle in its curved path the tires must

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[2] For this grade of hill a SUT may maintain a speed of only 30 mph on the uphill portion.

develop friction with the road surface. The extra fuel (in percent) required on curves can be considered directly proportional and numerically equal to the frictional factor developed to maintain the vehicle through the curve (12). For example, where "f" equals 0.02, the additional fuel consumption is 2 percent; where "f" equals 0.08, the extra fuel consumption is 8 percent; and so on. This extra fuel consumed on curves provides the additional energy to propel the vehicle against the induced pavement friction. This additional frictional force, required to maintain the vehicle through the turn, may be reduced by superelevation or banking (37). For a given speed and radius of curvature there exists a degree of superelevation that balances the centrifugal force. According to Winfrey, "Probably more often than not, vehicles traveling on horizontal curves do not travel at the exact speed which balances centrifugal and gravitational forces due to several possibilities, including use of inadequate superelevation for design conditions, intersecting routes and winter icing conditions" (37). Also, additional friction is accompanied by a loss of energy as more surface area of the vehicle is exposed to an intensified air resistance.

Claffey found that the composite passenger car required a 43 percent increase in fuel consumption traveling at 50 mph on a seven degree curve compared to traveling 50 mph on a tangent. The SUT experienced a similar increase.

Road Surface

Winfrey listed four characteristics of a roadway surface which affect the running costs:

1. Flexibility of its structure, including firmness

2. Abrasiveness of the surface
3. Roughness of the surface
4. Dustiness and looseness of the surface.

Extra energy is needed on rough gravel or loose surface materials, either to force the wheels up and over the stones or to push the stones aside. Likewise, extra fuel is needed on loose sand and earth surfaces, either to force the wheels out of depressions or to push sand or soil particles aside to form ruts. Roadway surfaces may be rough and unequal in surface contour because of cracks, settlements, poorly made maintenance patches, or unbound gravel. This unevenness of the roadway surface causes bouncing of the vehicle vertically and sideways. As these vertical and horizontal movements occur, there are greater power losses and, consequently, greater fuel consumption to maintain the same speed. Also, power losses are caused when loose aggregate is used as a roadway surface, because the particles induce more slip in the power wheels on the tangent section and on both power and steering wheels in the curved sections. As the amount of slip increases, the fuel consumption becomes correspondingly larger.

Mulinazzi (12) conservatively estimated that untreated gravel lowered performance by about two miles per gallon (mpg) and unsurfaced roads reduced the efficiency by five miles per gallon. For example, at 20 mph, percent increase equals 20 percent or 4 mpg decrease. He also observed there was little difference in fuel usage for smooth paved surfaces, regardless of type. Mulinazzi stated that under unfavorable weather conditions, unsurfaced roads usually became muddy and rutted. Vehicle fuel consumption was much greater than for any other type of surface and could even be twice the rate of fuel consumption as compared to good loose surfaces. Another estimate (12) approximated the fractional increase of operating cost for gravel surfaces as the vehicle's speed in mph divided by 100, and the increased cost for unsurfaced soil roads as double the increase for gravel surfaces. Claffey found that the fuel consumption for his composite car traveling over unsurfaced roads at 40 mph increased dramatically. On well-packed gravel surfaces, there was a 58 percent increase in fuel consumption and on loose sand a 73 percent increase in consumption. For the single unit truck traveling at 40 mph on loose sand the increase was even greater, 146 percent.

Speed Changes and Traffic

The running cost of a motor vehicle is less at a specific constant or uniform speed than at a variable speed which averages the same uniform speed. The running cost and travel time during speed changes are a direct consequence of congestion under heavy traffic and the traffic control system when vehicle stops are required (37).

Lane width, together with the number of lanes and width of shoulders, affects motor vehicle running costs through its effect on vehicle speeds and road capacity. For a given traffic flow, an insufficient number of travel lanes may cause interference among vehicles, resulting in frequent speed changes. These speed changes (speed reduction followed by resumption of speed) induce extra fuel and running costs. Major highways are improved by the addition of acceleration lanes or extra lanes which aid the flow of traffic. Access points are locations where entering and/or exiting cars or trucks often require through vehicles to slow down momentarily. The change from and back to some initial speed is reflected principally in the additional fuel needed for the acceleration to regain speed. According to the Bureau of Public Roads (BPR), average vehicle speeds are reduced by ten miles per hour when interfered with by a vehicle entering or leaving the traffic stream and the average vehicle is interfered with at 0.8 percent of the rural access points (40).

Intersection-at-grade as an element of road design is responsible for a considerable share of motor vehicle fuel consumption. Extra energy is needed to accelerate vehicles back to running speed after they have been stopped or slowed. The average vehicle must stop at 30 percent of the traffic signals in rural areas and the average stopping time is 13 seconds (40).

Legal Restraint

Above the optimal fuel-conserving speed, fuel efficiency decreases as the vehicle travels faster. Strict law enforcement of speed limits may lower the average vehicle speed and thereby reduce both fuel consumption and vehicle operating costs.

Energy Requirements for Highway Construction

Highway construction is an energy-intensive activity requiring vast quantities of fuel, primarily by diesel and gasoline powered equipment and machinery. In the past the general trend was to replace manpower with larger, more productive and energy-intensive equipment. This trend may be decreasing as construction machinery approaches economical limits of size and weight, and as fuel becomes more expensive and less abundant.

For estimating construction fuel requirements the Highway Equipment Committee (HEC) of the Transportation Research Board (TRB) sought answers to questionnaires from contractor groups whose data became the basis for developing fuel usage factors for possible mandatory rationing (18). The fuel usage factors were compiled for typical work activities, such as excavation, and were expressed in terms of gallons of diesel and/or gasoline fuel per unit of in-place production. If rationing became mandatory, the contractor fuel allotment would be determined by the summation of the estimated work quantities multiplied by their fuel usage factors.

For comparing the energy requirements of different pavement systems the Asphalt Institute (AI) (3) calculated energy consumption by assuming typical pieces of equipment and reasonable production rates for each activity, and then multiplying the fuel consumption factors of 0.04 gal/hp-hr for diesel and 0.06 gal/hp-hr for gasoline powered equipment times the horsepower capacity of the assumed equipment. The fuel consumption was reduced by assuming a 45 min/hr (75 percent production time) for moving equipment and 40 min/hr (67 percent production time) for plant or stationary equipment. For example, the fuel expenditure for placing and compacting asphaltic concrete was assessed by assuming three rollers and one paver with an average production rate of 150 cu yd/hr. In general, actual fuel consumption should be higher because the AI did not include an allowance for supporting vehicles such as pickups and maintenance trucks, nor an energy inclusion for mobilization and moving of plant and equipment as the work progressed. The AI also summarized energy requirements to produce or manufacture the basic materials, e.g., cement, crushed stone, etc., from general industry sources and combined these material estimates with the equipment energy requirements for the total energy estimates per unit of in-place finished pavement. In the AI analysis, asphalt was not assigned a material energy cost, but only a prorated energy cost of production.

Highway Energy Requirements for Maintenance

As Hewes and Oglesby (17) noted, there is a close relationship between design and construction and subsequent maintenance cost. Insufficient pavement and base thickness or improper construction of these layers soon requires expensive patching and surface repairs. In contrast, a design selection that spends more in construction than can ever be recovered in reduced maintenance costs is not economically justifiable. Therefore, proper design should seek the best balance between initial pavement cost and future maintenance cost.

In addition to the initial cost and subsequent facility or maintenance cost, consideration must be given to the operating cost of vehicles using the road. This is particularly true when considering gravel surfaces as opposed to paved roadways. To illustrate, Oglesby and Altenhofen (28) suggested that the total systems cost (user, construction and maintenance) is decreased by the selection of bituminous pavement in preference to a gravel surface at a traffic flow of 100 vehicles per day (vpd). At lower traffic flows, gravel surfaces were considered more economical. Demonstrating the connection between surface selection and maintainability, Alexander (1) expressed the concept of systems cost with a maintenance constraint, a given budget which cannot be exceeded for any section of road.

Roadway Surface Maintenance

Over one-half of the highway maintenance budget is allocated to the care of road surfaces, including roadside drainage, mowing, etc.[3] For the purpose of this research the surface maintenance activities are separated into two generic categories: routine or day-to-day maintenance and major planned maintenance. Routine roadway maintenance includes both temporary and permanent patching, crack sealing and all surface coatings including fog, sand, chip, and slurry seals. Routine maintenance is generally performed by the highway department personnel and is applied as the distress becomes apparent or on a scheduled basis. Routine surface maintenance is intended to prolong the serviceability of the pavement until it deteriorates to a condition where it must be either resurfaced or reconstructed (major maintenance).

Major maintenance includes overlays which are intended to augment the structural capacity of the existing pavement and/or improve its riding surface. For the more deteriorated or obsolete sections, major maintenance may entail a reconstruction of portions of the road. Unlike routine maintenance, major maintenance is generally performed on a contract basis and its necessity is determined by a more analytical process (the evaluation survey).

Fuel Consumption and Roadway Surface

As previously noted, the condition and type of roadway surface affect the fuel consumption of vehicles. This effect is quite evident when comparing earth or gravel surfaces to a high quality pavement. However, Yoder (38) noted that for the same type of paved surface, data are

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[3] According to Oglesby the cost of highway maintenance spending nation-wide was: roadway and roadside, 61 percent; structures, 5 percent; snow removal and sanding, 14 percent; traffic services, 12 percent; and operation of toll roads and bridges, 8 percent (27).

meager as to the difference between a paved surface in poor condition and one that is in excellent condition. Claffey made the distinction between high-type concrete or asphalt and broken and poorly patched asphalt.[4] For his composite passenger car running at 50 mph the fuel consumption was 50 percent greater on the poorly patched surface. The AASHO Red Book contended that the increased operating cost for a paved surface in poor condition may be interpolated between one in good condition and a lower type surfacing, at the option of the analyst. Also, rutting which induces sidesway, and rough pavement which causes road noises, increase the fuel consumption. However, the exact quantitative relationship, or even a general expression of these factors and vehicle fuel performance, is not available in the literature. The quantitative relationships between vehicle fuel consumption and other surface distresses such as long wavelength (high amplitude and low frequency) pavement deformations caused by consolidation of deep foundation material and transverse (e.g., washboard surface) rutting have not been found in the literature.

Measurements of Surface Conditions

A commonly used measure of the riding quality of pavements is the Present Serviceability Index (PSI). The PSI is formulated from the subjective judgments of a team of raters examining a highway pavement: a value of 5 is assigned to a perfect pavement and a value of 0 is assigned for pavement in extremely bad condition. These qualitative opinions are statistically correlated with measurements of road roughness (measured by

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[4] The poorly patched pavement was described as having three patches per square yard.

a roughometer or profilometer), cracking, patching, and rutting. Generally, a PSI in the range of 2.0 to 2.5 is considered the value at which corrective measures are necessary. For example, the Interstate system is continually re-evaluated to assure that the system's PSI will not fall below 2.5 by 1984 (12).

Evaluation Survey

In addition to its use in the condition survey, the PSI serves as an integral part of the evaluation survey which determines the structural adequacy of the pavement. The evaluation survey is an all-inclusive analysis, considering such factors as pavement thickness, quality of pavement materials, traffic, etc. Figure 1 illustrates a typical performance curve for the maintenance of a section of highway. Initially, the section has a high serviceability but deteriorates to a condition where an overlay is required. The overlay returns the surface to a new high serviceability.

In addition to overlaying to increase structural capacity or to improve the smoothness of the riding surface, the highway section may be overlayed to provide a skid resistant or water impervious surface using hot sand asphalt, asphalt concrete with small maximum size particles (both of which may be constructed in layers as thin as one-half inch), or a surface seal coat. Finally, other criteria such as highway geometrics (alignment, grade, pavement width, etc.) and safety aspects (sight distances, accident history, turn lanes, etc.) need to be evaluated for overall highway adequacy.

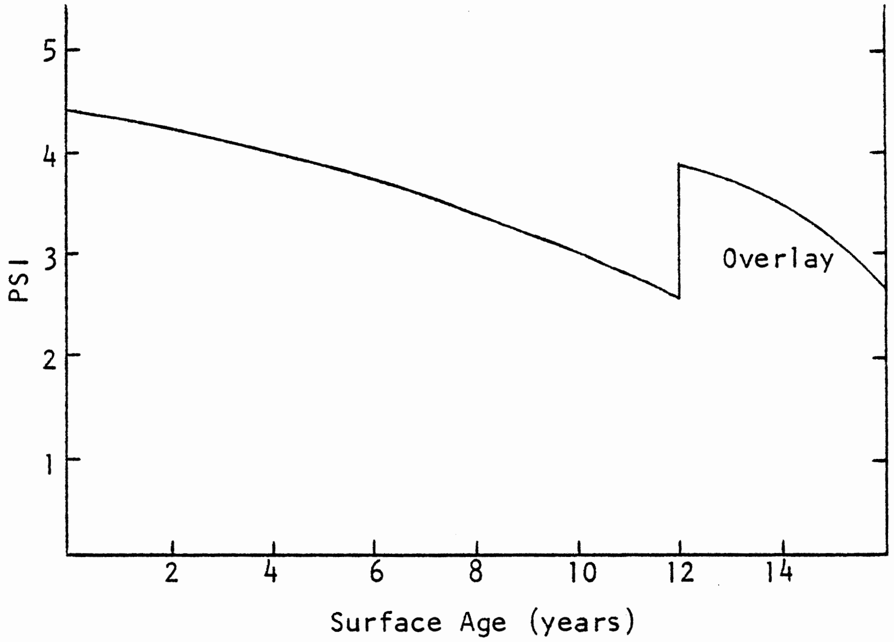

Figure 1. Typical Highway Pavement Performance Curve

Prediction of Routine Maintenance

Routine maintenance is an important factor for preserving the total life of the pavement, for extending the time period between overlays, and for maintaining the surface riding qualities. However, the quantity and frequency of routine maintenance is difficult to predict during the design stage. Even estimates or extrapolations from past maintenance data from the same geographical area may be misleading. Hejal (16) noted four objections to the reliance upon historical maintenance data:

1. Lack of exact definition;
2. Absence of a uniform accounting practice;
3. Variations in the standards of maintenance adequacy; and
4. Poor records of maintenance cost in many states.

Since routine maintenance is often performed on an as-needed basis or as the distress in the pavement becomes noticeable, projections as to the extent and quantity may be difficult to anticipate during the design stage. Yoder (38) observed, "Perhaps the most tenuous factor to be considered in economic analysis is that regarding methods for estimating routine maintenance. Methods for estimating routine maintenance developed for an area may or may not be applicable to other locations depending on many factors."

In an effort to provide better guidelines for estimating future highway maintenance requirements from the viewpoint of budgetary considerations and for projecting labor, equipment and material needs, NCHRP Report No. 42 (36) developed equations for seven different categories of routine maintenance activities and their suspected factors. This project investigated 28 sites in five states on the Interstate highway system and developed (by multiple regression techniques) the relationships between work load demands in terms of labor, equipment and material usage, and the contributing environmental, physical and traffic parameters. The maintenance requirements for pavement and shoulders (excluding resurfacing and overlays) were largely determined to be a function of two variables: surface age and freezing temperatures. Other variables such as differences in maintenance standards and work crew efficiency were concluded to be too small to influence the regression analysis. The uniformity of standards for design and construction of the Interstate system excluded variations in subgrade as a significant factor. Also, it was difficult to project the ultimate effect of age on roadway surfaces, because the oldest sections, at the time of the data acquisition, were only ten years old.

Prediction of Major Maintenance

As discussed previously, there are models that express the economic trade-off between strong initial designs and limited future maintenance or weaker initial sections at the cost of greater maintenance. SAMP 6 (25) presented a computerized systems model which is intended to optimize pavement design from the maintenance, construction, and user cost considerations, and which incorporated a subroutine for analyzing the added expense of motorists detouring around the overlay operations and another for predicting future overlays. One subroutine incorporated the NCHRP regression analysis of routine maintenance expense; another accounted for a swelling clay soil and, with some modification, frost heave. To facilitate changes or adaptations by using agencies, the model contained eight distinct subsystems or subroutines. For example, in place of the SAMP 6 flexible pavement design by the AASHO Interim Guide, a state highway department may substitute its own design methodology, e.g., the Texas Deflection Equation, without disturbing the other subsystems (maintenance cost, traffic prediction, etc.) (25). This program allowed the inclusion of estimates of salvage values for in-place materials at the end of the analysis period. Other variables may be included to simulate updating of unit prices, output of confidence levels to simulate the stochastic nature of pavement life, and the investment cost to the highway agency.

A more recent publication of the life cycle design and analysis of pavement is by Lindow (24). This is a three-volume publication including the user's manual, the program itself, and the program documentation.

Regional Energy Studies

Flachsbart (14) analyzed and discussed various policies which community officials should consider to reduce the energy consumption of local transportation. Each policy was considered by its impact upon the larger community and regional objectives. For example, land use reforms might prove counterproductive for fuel conservation unless these reforms are coordinated on a regional basis. Projections of potential fuel savings were estimated for each of the policies.

Erlbaum (10) employed home-interview sampling to analyze the impact of carpooling for upstate New York. For example, Erlbaum estimated that a 25 percent increase in carpooling for work and shopping trips would result in a 5.8 percent savings in automobile transportation energy.

CHAPTER III

DATA SOURCE OF THE MODEL

Data Acquisition

The data base of the subsystems is derived from a variety of sources based on present technology and practices. As the supply of energy diminishes and prices increase, contractors, material suppliers, highway officials, and vehicle manufacturers will seek greater energy efficiencies. The greater energy efficiencies will require future modification and updating of the data bases to reflect these new efficiencies. Under life cycle scrutiny, displacements of energy expenditures, e.g., from construction to maintenance, may become more apparent and advantageous as changes develop in the relative efficiencies of the subsystems.

Vehicle Operations Subsystem

Claffey's data are employed for the development of fuel consumption factors for various vehicle types including passenger cars (P_C), pickups (P_P), single unit trucks (P_S), and gasoline powered trucks (P_G). For data on large diesel powered trucks (P_D), which Claffey did not empirically investigate, Winfrey's data are employed. Between the two sets of vehicle-fuel consumption data there is reasonable correlation. Winfrey expressed his fuel consumption data for curvature, speed change cycle, idling, and gravel surfaces as excess gallons above the amount consumed at the same speed on smooth tangents. Claffey tabulated his data base as fuel consumption on tangents and the additional fuel for the other conditions, e.g., curvature and surface condition, as a series of condition factors which when multiplied by the grade and speed consumption factors yields the greater fuel consumption for that condition. To make the two data bases compatible for programming purposes, Winfrey's data for the large diesel powered truck are transformed into factors by adding the excess gallons to the tangent consumption and dividing by the tangent consumption:

$$\text{Condition factor} = \frac{\text{excess gallons + tangent consumption}}{\text{tangent consumption}}$$

For other data, such as fuel consumption on earth surfaces, the Claffey fuel factors for the 40 kip gasoline powered truck are used for the diesel powered truck. For the speed change cycle, Claffey listed only data for the deceleration portion, while Winfrey considered the entire cycle. Therefore, Winfrey's data are employed for this fuel loss mode.

Energy Requirements of Asphalt

In the United States, over 90 percent of the all-weather, hard surfaced roads are paved with asphaltic concrete (3). The asphaltic concrete is composed of aggregate, mineral filler, and asphalt cement. There are diverse opinions concerning what energy content should be attributed to the asphalt cement. One criterion considers that the asphalt is a by-product of petroleum distillation and should not be charged with any energy cost. Stander (12) concluded that asphalt cannot be used as a commercial fuel because of the inherent two to seven percent sulfur content which precludes commercial burning. The Asphalt

Institute (AI) assigned only a prorated cost of 587,000 Btu/ton as the asphalt's fraction of the energy required to refine and process petroleum. Other references indicated that asphalt not only has the potential for use as a fuel, but during the fuel shortage the asphalt was further refined to produce fuel. Brink (41) stated that during the 1973 oil embargo, asphalt was either burned directly as a fuel or further refined into the lighter distillates of gasoline or heating oil to an extent that partially produced the asphalt shortage during that period.

Regardless of the commercial acceptance of asphalt as a fuel, the asphalt cement must be assigned an inherent energy charge compatible with other petroleum products to account for the decreasing world supply of this resource. Also, if asphalt is not assigned this energy charge, asphaltic pavements would appear to be overwhelmingly energy-efficient and highway officials may then be tempted to overuse this increasingly scarce material. For this purpose of the research, the combined inherent and production energy content of asphalt is assumed to be the same as gasoline (125,000 Btu/gal). This is a select decision due to the disagreement concerning asphalt's energy content. It is acknowledged that this decision is a key element in comparing various pavement systems and other researchers may elect a different energy assessment for asphalt.

Energy Requirements of Raw Materials

The energy required for the production of aggregate is dependent upon the source and the amount of processing involved. Natural, river-deposited sand and gravel may be removed with little difficulty and the National Sand and Gravel Association estimated two hp-hr/ton or roughly 15,000 Btu/ton (3). Crushed stone entails drilling and blasting of rock and the loading and operation of the crusher. The energy required is 70,000 Btu/ton (3). Crushing of gravel to reduce oversize particles requires less energy than crushing of stone but more energy than natural aggregate. An average value for crushed stone is 35,000 Btu/ton (3).

The production of steel is energy intensive. The production of one ton of steel requires 21 million Btu (3). Lime may be used to stabilize road bases and, according to the National Lime Association (3), the production of one ton of lime requires six million Btu. The production of cement is also energy intensive, and requires approximately 7.5 million Btu for one ton of cement (3). Table I lists some of the common raw materials of construction and their energy requirements.

Energy Requirements for Contractor's Operations

The energy requirements for the contractor's equipment were obtained from diverse sources. The Asphalt Institute (3) based its calculation on selecting typical equipment and multiplying by the horsepower-energy conversion factors. In general, their energy values appear low, primarily because their analysis did not include allowances for supporting equipment such as maintenance vehicles. The Highway Equipment Committee's (HEC) fuel consumption factors (18) were based upon the experience of contractors, but these values appear to be inflated.

For some activities there is reasonable correlation between the two sources, e.g., the energy estimate for the placement of asphaltic concrete by the AI is 16,700 Btu/ton and by the HEC is 19,450 Btu/ton. In other instances of wide variations, judgment is exercised to modify the

TABLE I

ENERGY EXPENDITURE TO PRODUCE CONSTRUCTION MATERIALS

Material	Energy Expenditure Per Unit
Asphalt	125,000 Btu/gal[a]
Portland Cement	7,500,000 Btu/ton[b]
Steel	21,000,000 Btu/ton[b]
Lime	6,000,000 Btu/ton[b]
Aggregate	
Natural	15,000 Btu/ton[b]
Crushed Gravel	35,000 Btu/ton[b]
Crushed Stone	70,000 Btu/ton[b]

Emulsified Asphalt[c]

Anionic	Btu/gal	Cationic	Btu/gal
RS-1	91,375	CRS	94,875
RS-2	97,375	CRS-2	98,875
MS-1	91,375	CMS-2	98,875
MS-2	98,875	CMS-2h	98,875
MS-2h	98,875	CSS-1	93,375
SS-1	93,875	CSS-1h	93,375
SS-1h	93,875		

Cutback asphalt[c]

Grade	Btu/gal RC	Btu/gal MC	Btu/gal SC
-30	---	132,000	---
-70	125,000	130,000	134,000
-250	125,000	128,000	131,000
-800	125,000	128,000	129,000
-3000	125,000	127,000	128,000

[a] An assumed value due to the disagreement concerning the energy content of asphalt.

[b] Energy estimate of the Asphalt Institute (3).

[c] Energy estimate based upon an assumed 125,000 Btu/gal for the asphalt fraction.

fuel consumption estimates. Where available, data from other sources are employed to verify the AI's and the HEC's data.

For transporting materials during the construction process, the AI based its haul estimates upon general FHWA fuel consumption factors for various classes of highway vehicles. In general, these estimates appear greater than would normally be expected at a construction site. For example, the hauling of asphalt mix and concrete was presented as 4250 Btu/ton-mile. For an average 15 ton load of asphalt mix the transporting vehicle would average 2.2 mpg of diesel and a similar fuel consumption for hauling of concrete. Stillwater, Oklahoma producers of hot mix and ready mix stated their trucks average between 3.0 and 4.0 mpg for an average 15 ton load of asphalt mix and 3.0 to 3.5 mpg of diesel for a 7 cubic yard load of concrete. For a 10 to 20 mile haul of asphalt mix (average round trip of 30 miles), the HEC considered 0.49 gal/ton (4.2 mpg) of diesel and 0.58 gal/ton (3.5 mpg) of gasoline, but for delivery of concrete the HEC permitted the equivalent of a very fuel efficient 8.0 mpg truck.

The energy consumption (Table II) for construction activities is presented in a format similar to that of the HEC. The energy factors are intended to imply average conditions and, should conditions become worse (muddy roads, inclement weather) or better, upper or lower energy adjustments may be made at the discretion of the analyst. Other upward allowances may be merited by higher altitude (above 4000 feet) construction or longer (greater than 5000 feet) hauls. To convert the HEC's fuel factors to energy units, the expected fuel consumption factors are multiplied by 125,000 Btu/gal for gasoline and 139,000 Btu/gal for diesel.

TABLE II

ENERGY EXPENDITURE FOR CONSTRUCTION OPERATIONS

Construction Operation	Energy Consumption
Earth Excavation and Compaction	59,000 Btu/cu yd[a]
Rock Excavation and Compaction	74,000 Btu/cu yd[a]
Other Excavation and Compaction (more difficult than earth but not rock)	69,000 Btu/cu yd[a]
Haul of Aggregate and Other Materials to Plant	4,200 Btu/ton-mile[b]
Place and Compact Aggregate Base	17,000 Btu/ton[c]
Hot Asphalt from a Distributor Truck	450 Btu/gal[c]
Asphaltic Concrete Production	355,000 Btu/ton[b]
Haul of Hot-Mix	3,000 Btu/ton-mile[d]
Placement and Compaction of Hot-Mix	18,000 Btu/ton[b]
Concrete Production	40,000 Btu/ton[b]
Haul of Concrete	7,600 Btu/cu yd-mile[d]
Placement of Concrete	20,000 Btu/cu yd[b]
Structures	53,900 Btu/$1000 (1974)[a]
Miscellaneous	50,200 Btu/$1000 (1974)[a]

[a] Fuel consumption factors of the Highway Equipment Committee (18), multiplied by the gallons of fuel to energy conversions.

[b] Midrange energy consumption of the Asphalt Institute (3) and the Highway Equipment Committee (18).

[c] Energy consumption by the Asphalt Institute (3).

[d] Midrange values from References (3) and (18) and suggested fuel efficiencies by Stillwater, Oklahoma, producers.

Table III combines the direct energy cost for production of the raw materials and the indirect energy required by the builder to construct the facility. The total energy of the constructed facility is the summation of each of the quantities of material multiplied by their in-place energy cost and an adjustment factor, should the designer decide that an increase or decrease is warranted.

The percentage composition of stabilizing materials for soil and aggregate stabilization varies with the particular project conditions. The percentage contents in Table III are typical midrange values as described in the text by Baker (4). Other calculations for concrete and asphaltic pavements are similarly based on average compositions as presented in this text.

Energy Requirements for Asphaltic Concrete Overlays

Table IV lists the energy requirements for the in-place overlay for both the raw materials and the construction operation. The estimate for the tack coat assumes a rapid curing liquid asphalt applied at an average rate of 0.10 gal/sq yd. The energy data for the overlay is based upon Table III.

Economic Highway Cost

The economic cost for the construction of highways is dependent upon any factors which are often unique to each project. It is beyond the scope of this research to include a detailed estimating procedure for determining construction costs; however, a general parametric estimate is included to determine economically feasible trade-offs and to make

TABLE III

ENERGY ESTIMATE FOR CONSTRUCTION OPERATIONS AND MATERIAL PRODUCTION

Item	Energy
Excavation and Compaction	
Earth	0.0590 M.Btu/cu yd[b]
Rock	0.0740 M.Btu/cu yd[b]
Other	0.0690 M.Btu/cu yd[b]
Soil Stabilization (additional energy, if required)	
Lime (4.0% by weight)[a]	0.3640 M.Btu/cu yd[c]
Cement (8.5% by weight)[a]	0.8940 M.Btu/cu yd[c]
Aggregate Production and Compaction	
Gravel	0.0100 M.Btu/sq yd-in.[c]
Crushed Stone	0.0124 M.Btu/sq yd-in.[c]
Aggregate Stabilization (additional energy, if required)	
Lime (3.5% by weight)[a]	0.0109 M.Btu/sq yd-in.[c]
Cement (6.0% by weight)[a]	0.0217 M.Btu/sq yd-in.[c]
Asphalt (6.0% by weight)[a]	0.0581 M.Btu/sq yd-in.[c]
Concrete	
Unreinforced	0.0682 M.Btu/sq yd-in.[c]
CRCP	0.0914 M.Btu/sq yd-in.[c]
Distributed Steel	0.0800 M.Btu/sq yd-in.[c]
Fibrous	0.1216 M.Btu/sq yd-in.[c]
Asphalt	
Prime Coat	0.0130 M.Btu/sq yd[c]
Cold Mix (8,0% by weight)[d]	0.1120 M.Btu/sq yd-in.[c]
Hot Mix (5.0% by weight)[d]	0.1108 M.Btu/sq yd-in.[c]
Steel	
In-Place	21.8770 M.Btu/ton[c]

[a] Weight percentages are midrange values from Baker (4).

[b] Fuel consumption factors of the Highway Equipment Committee (18) multiplied by the gallon of fuel to energy conversions.

[c] Other data derived from Tables I and II

[d] Weight percentage are suggested by the Asphalt Institute (3).

TABLE IV

IN-PLACE OVERLAY ENERGY REQUIREMENTS

Material	Energy
Tack Coat	0.0125 M.Btu/sq yd[a]
Asphalt Overlay	0.1108 M.Btu/sq yd-in.[b]
Shoulders (additional material for leveling)	
Crushed Stone	0.0124 M.Btu/sq yd-in.[b]
Asphalt Stabilized Crushed Stone	0.0705 M.Btu/sq yd-in.[b]

[a] A rapid curing cutback asphalt (125,000 Btu/gal, Table III) applied at 0.10 gal/sq yd.

[b] Data from Table III.

possible the economic comparisons between additional construction and fuel costs.

The estimate in Table V is developed from data provided by members of the Planning Section of the Oklahoma Department of Transportation (ODOT). Significant variations of the excavation cost may be encountered, depending upon the nature of the terrain and conditions of the project. The grading costs presented in Table V are used as average values for the state of Oklahoma. The cost of the structures would normally be estimated with each project and an average figure would be difficult to determine. The Oklahoma Highway Needs Study (1964) by Roy Jorgenson and Associates estimated the cost of structures for rural highways as 15 percent of the total highway construction cost during the period between 1965-1985 (23). The cost of the right-of-way is based upon an ODOT suggested $500 per rural acre with a 250 foot wide right-of-way for both two- and four-lane highways. For rural highways the readjustment or relocation of existing utilities would normally be a minimal cost and is not included. The total cost includes all expenses from preliminary engineering to completion of construction.

The cost of the overlay, as suggested by members of the Planning Section of the ODOT, is $13,000 per 24 foot wide pavement per mile per inch of thickness.

Road Classification and Traffic Volumes

The decision for the road classification or the type of road, i.e., earth, gravel, or paved, is dependent upon the criteria of the design agency including technical and nontechnical factors, e.g., social, political, availability of funds, etc. For economic analysis, a small

TABLE V

PARAMETRIC COST OF RURAL OKLAHOMA HIGHWAY
(PER MILE, 1977 DOLLARS)

Number of Lanes	Surface Type	Surfacing	Right-of-Way	Grading	Structures	Total
2	Asphalt	225,000	15,000	120,000	65,000	425,000
	Concrete	250,000				450,000
4	Asphalt	450,000	15,000	200,000	135,000	800,000
	Concrete	500,000				900,000

Source: Estimates from the Oklahoma Department of Transportation and the Oklahoma Highway Needs Study (24).

projected volume of traffic may justify only a minimal expenditure of funds for road construction. Hence, very low volumes require only an unpaved earth road so that total cost (the sum of initial construction, maintenance, and operating vehicles) is kept to a minimum. On the other hand, high volumes of traffic may permit large capital expenditures for grade, alignment, and surface improvements. In order to maintain a benefit/cost ratio greater than one, large benefits must be received from the user vehicles to offset the denominator of high construction costs. To achieve these large benefits, a large traffic flow is required because the benefits per vehicle are relatively constant. Therefore, the type of road should be commensurate with the volume of traffic.

Although the decision for the classification of a road is dependent upon the design agency and the conditions surrounding the project, a general volume range may be postulated for each road type. Table VI represents four traffic ranges and corresponding classifications of road with each classification's geometric design. These ranges are intended to minimize the time of investigation by eliminating unlikely conditions, e.g., a large traffic volume using an unimproved road over a long-term period.

Energy and Cost for Road Construction

The energy and capital required to construct a road are dependent upon many factors including soil conditions, location, geometric standards, etc. In this chapter general estimates of cost and energy expenditures for initial construction and maintenance are developed based upon the following considerations. The initial alignment of each alternative route is selected to minimize longitudinal cuts and fills. A

TABLE VI

TRAFFIC VOLUME, ROAD CLASSIFICATION, AND GEOMETRICS

Range of Average Daily Traffic Volume	Corresponding Road Type Designation	Surface	Base Width (ft)	Average Vehicle Speed (mph)	No. of Lanes	Volume Input of Model (vpd)	Maximum Grade (percent)	Maximum Curvature (degrees)
0-99	IV	Earth	20	20	2	75	10	10
100-1199	III	Gravel	44	30	2	750	10	10
1200-4199	II	Paved	80	50	2	2700	10	10
4200-30000	I	Paved	180	50	4	10000	10	10

constant positive and negative gradient is maintained by following the existing gradients. The centerline of each road is assumed to be at natural grade (Figure 2) and to have a level base width which is constructed by transverse cut and fill operations. The volume of excavation is assumed equal to the volume of fill for each section. Using Figure 2, the approximate area of excavation is equal to the sum of two triangles:

$$AE = \frac{1}{2}(h_4)\left(\frac{1}{2}BW\right) + \frac{1}{2}(h_4)(x) \tag{3.1}$$

where

AE = area of excavation (cross hatch);
g,h,x = geometric dimensions;
BW = base width;

and also in Figure 2,

S = designed side slope factor; and
CS = cross slope in percent.

By geometry,

$$h_4 = \frac{CS}{100}\left(\frac{1}{2}BW\right) \tag{3.2}$$

By allowing the intersection of the side slope and BW to be the origin and using absolute values of the slopes (the mirror image of Figure 2), two equations for y are formulated:

$$y = \frac{1}{S}x \tag{3.3}$$

$$y = \frac{CS}{100}x + h_4 \tag{3.4}$$

By setting the equations equal, the x distance may be found:

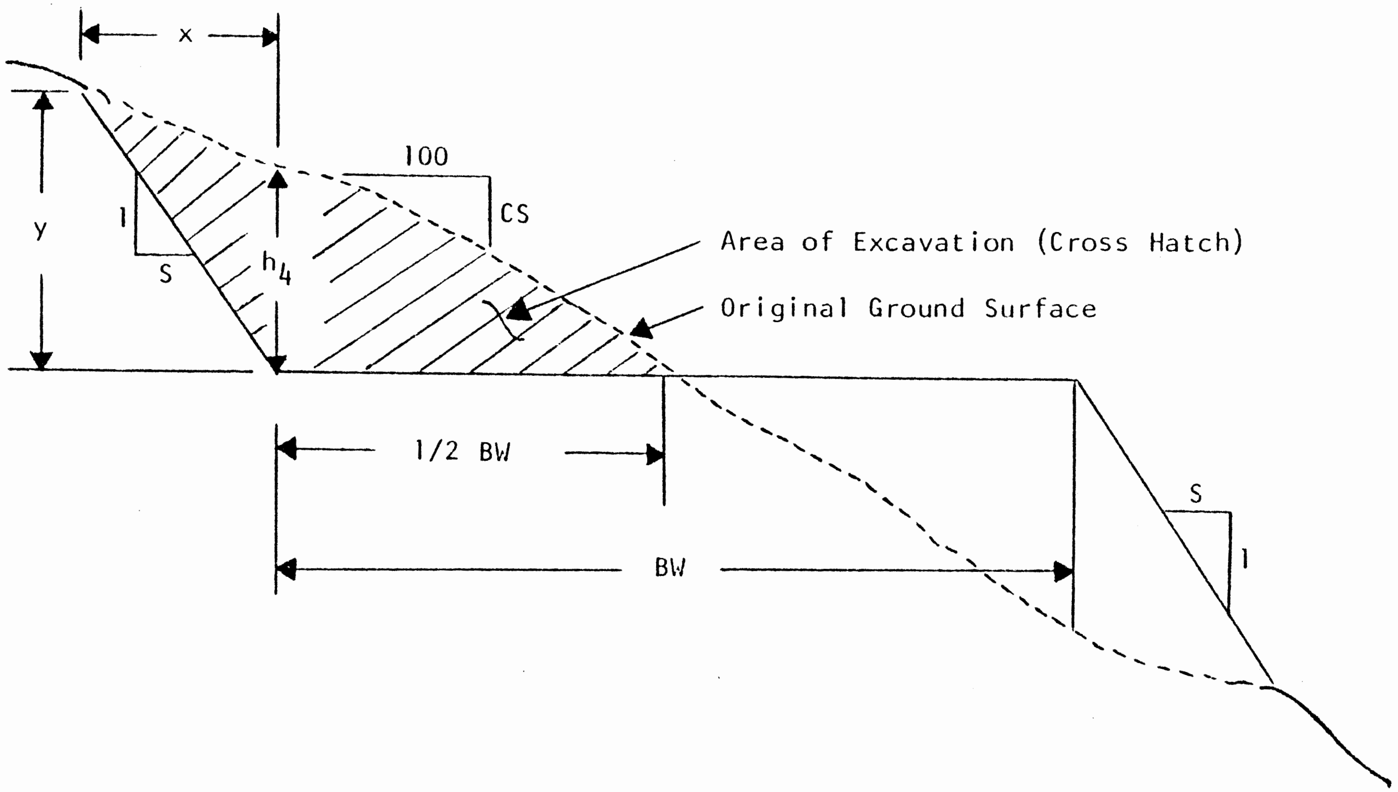

Figure 2. Transverse Excavation

$$\frac{x}{S} = \frac{CS}{100} x + h_4 \qquad (3.5)$$

Solving for x,

$$x = \frac{h_4}{(\frac{1}{S} - \frac{CS}{100})} \qquad (3.6)$$

Substituting in Equation (3.1),

$$AE = \frac{1}{8} \frac{CS}{100} (BW)^2 + \frac{1}{8} (BW)^2 (\frac{CS}{100})^2 (\frac{1}{\frac{1}{S} - \frac{CS}{100}}) \qquad (3.7)$$

For this investigation the cross slope is assumed to be nine percent (CS = 9) and the side slope factor is three horizontal to one vertical (S = 3). Equation (3.7) becomes:

$$AE = 0.015 (BW)^2 \qquad (3.8)$$

Since this area is assumed to be the average area of excavation throughout the road length, a section volume of excavation would be the product of Equation (3.8) and the section length. For a base width (BW) measured in feet and a 1000 foot section length, the approximate volume of excavation, in cubic yards, is:

$$\text{Volume/1000 ft} = 0.6 (BW)^2 \qquad (3.9)$$

Using the base width data in Table VI, the volume of excavation for each road type is calculated by the above expression and presented in Table VII. The material quantity estimates for shoulders and riding surface (gravel and pavement) are the product of the width and 1,000 foot section length and divided by nine for conversion into square yards. The depths of the shoulders are taken as one-half their corresponding pavement thicknesses and are composed of asphalt stabilized aggregate.

TABLE VII

INITIAL COST AND ENERGY REQUIREMENTS BY ROAD TYPE

Road Type	IV	III	II	I
Surfacing				
Type	Native Earth	Gravel	FDA	FDA
Depth (in.)	---	4	9	11
Width (ft)	20	22	24	48
Shoulders				
Depth (in.)	---	---	4.5	5.5
Width (ft)	---	---	16	28
Quantity/1,000 ft				
Excavation (cu yd)[a]	240	1,170	3,880	19,650
Surfacing (sq yd)	---	2,440	2,670	5,330
Shoulders (sq yd)	---	---	1,780	3,110
Energy M.Btu/1,000 ft				
Excavation	10	70	230	1,160
Surfacing	---	100	2,660	6,500
Shoulders	---	---	460	990
Total	10	170	3,350	8,650
Cost $/1,000 ft				
Excavation	480	2,340	---	---
Surfacing	---	6,240	---	---
Total	480	8,580	110,000	210,000

[a] The cost and energy expenditures for transverse fill are included in the transverse excavation.

The pavements are full depth asphalt and their thicknesses (11 and 9 in.) are taken from Baker (4) for a medium subgrade strength. All energy conversions are based upon Table III and include both energy required to produce the material and energy to construct the facility. The economic cost of the earth road is based on a nominal two dollars per cubic yard cost of excavation, which includes the excavation and placement in the fill area. The cost of the gravel road is the sum of the excavation cost (also 2 dollars per cubic yard) and gravel placed at a cost of 25 dollars per cubic yard. The costs of the two- and four-lane highways are adapted from Table V. These costs were 1977 estimates and since then highway construction costs have increased. The Federal Highway Administration composite price index increased 36 percent during the two-year period and these estimated costs are increased by 36 percent and divided by 5.28 to determine the 1,000 foot section cost (1979).

Energy and Cost of Surface Maintenance

Various road types and route lengths require different surface maintenance expenditures. The low volume of traffic associated with the earth road would entail the least maintenance expenditure. For this analysis the earth road is assumed to require only a monthly grading. To maintain the more traveled gravel surface road in a well-packed condition would entail more frequent grading. This frequency is determined generally by experience or by a given policy. According to Payne County, Oklahoma road officials, gravel roads are scheduled for grading on a weekly basis. This weekly grading is assumed for the gravel surface maintenance.

For paved highways a two-inch overlay is assumed every five years for the two-lane, and for the more traveled but thicker pavement of the four-lane a similar overlay is assumed every four years. The shoulders of the paved highway are overlayed an equal depth next to the pavements. This overlay tapers to its original shoulder surface on the outside edge. The average depth over the shoulder would then be one-half of the two-inch overlay or one inch.

For the soil and gravel roads a 250 hp grader is assumed for leveling the surface. This grader would consume 10 gallons of diesel fuel per hour (250 hp x 0.04 gal/hp-hr) or 1.39 M.Btu/hr. The total cost of the grader is assumed to be $40/hr, including operator, fuel, etc. Assuming an average working speed of five mph and four passes per section, the grader shapes 6,600 feet of road per hour (5 mph x 5280 ft/mi ÷ 4 passes). The energy requirements for grading would then be 0.21 M.Btu/1000 ft (1.39 M.Btu/hr x 1000 ÷ 6,600 ft/hr) and the cost would be $6.06/1000 ft ($40/hr x 1000 ÷ 6,600 ft/hr). The overlay depth for the two-lane is two inches over the 24 foot pavement and one inch over the 16 foot width of shoulder. The number of sq yd/in. (square yards of surface and one inch depth) per 1000 ft section of a two-lane highway is 7110 ([(1 x 16) + (2 x 24)] x 1000 ÷ 9) and the tack coat area is 4440 sq yd ([24 + 16] x 1000 ÷ 9). The four-lane divided highway has 48 foot wide pavement (4 lanes x 12 ft/lane) and 24 foot shoulders (2 outside x 8 ft/shoulder + 2 inside x 4 ft/shoulder). The quantity of overlay material for a 1000 ft section of four-lane is 13,330 sq yd/in. ([1 x 24] + [2 x 48] x 1000 ÷ 9). The energy of the overlay and a tack coat area of 8000 sq yd ([24 + 48] x 1000 ÷ 9) is obtained by multiplying the above estimate by 0.1108 M.Btu/sq yd/in. for overlay and 0.0125 M.Btu/sq yd for the tack coat (Table IV). The 1979 cost per 1000 ft overlay section is \$6,670 (\$13,000 x 2 in. depth x 1.36 ÷ 5.28) for two-lane and \$12,500 (\$6,670 x 13,300 ÷ 7110) for four-lane. The annual energy and cost of overlay maintenance is calculated by dividing each estimate by the frequency. The economic and energy requirements for surface maintenance are summarized in Table VIII.

TABLE VIII

REQUIREMENTS FOR SURFACE MAINTENANCE

Road Type	Maintenance Operation	Frequency	Requirements/Year Energy M.Btu/1,000 ft	Cost/Year Dollars/1,000 ft
IV	Grading	12/yr	3	73
III	Grading	52/yr	11	315
II	Overlay	Every 5th year	169	1,334
I	Overlay	Every 4th year	371	3,125

CHAPTER IV

STRUCTURE OF THE MODEL

Overview of the Model's Structure

In this chapter the model is developed using the data sources of the previous chapter to calculate the life cycle cost and energy consumption of a proposed route. The life cycle cost and energy consumption are the sum of the expenditures for construction and major maintenance and the fuel consumption of the operating vehicles.

The model initially enters the data base of the vehicle operations subsystem (Appendix A), followed by the traffic and route description. The selection of the road type and corresponding geometrics is determined by the input traffic volume. The length of each horizontal curve is calculated by the angle of intersection and the maximum degree of curvature. The stationing of the horizontal curve in location to the upgrade, downgrade, and horizontal sections is required for determining the vehicle fuel consumption. For example, a vehicle traveling upon a horizontal curve located on an upgrade would require more fuel to maintain the same speed than this vehicle would require on a similar curve located on a downgrade. Therefore, the model is structured to calculate the additional fuel consumption for curvature depending upon the location of the curve in reference to the start of upgrade, high point, and end of downgrade. Based upon an initial comparison between the stationing of these points and the stationing of the end points of the curve, the additional fuel consumption is calculated by one of the six expressions (designated by the address label "CURV-1" to "CURV-6" in the program of Appendix B). These six expressions are representative of a horizontal curve located on a section of:

1. horizontal only
2. horizontal-upgrade
3. upgrade only
4. upgrade-downgrade (straddles the crest)
5. downgrade only
6. downgrade-horizontal.

The program starts by entering the grade, curvature, and surface factors of the vehicle operations subsystem (Figure 3). The traffic, topographic and study parameters are introduced next and are followed by the four selected traffic volumes. The type of road and its geometrics are selected in accordance with the input traffic volume. The stations of start of upgrade and end of downgrade are calculated by the station and elevation of the high point with the design grade and the elevations of the initial and final points. Due to the existing topography, each route has short horizontal sections at the beginning and end. For each vehicle class the speed is determined for the grade, surface type, and curvature. Therefore, the vehicle speed may differ on the horizontal sections, the upgrades, and the downgrades. For the same type of vehicle the fuel consumption of each vehicle class is calculated by the attained speed for each section and the length of the section. After the number of horizontal curves and description of each curve are entered, the stations of the start and end of each curve are arrayed in the computer's memory for subsequent fuel calculations for each vehicle class and traffic volume. The

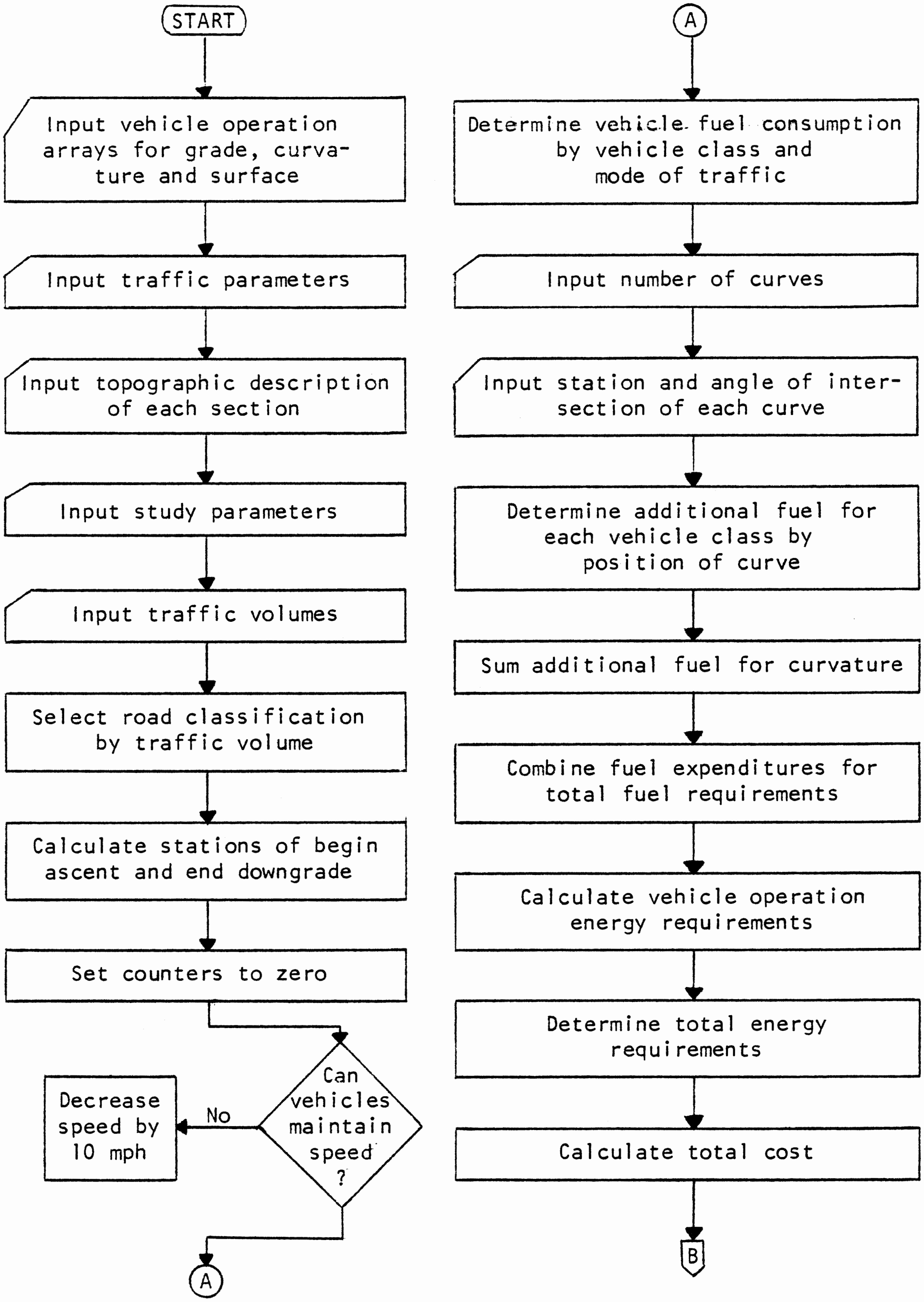

Figure 3. Summary Flowchart of Parameter Sensitivity Program

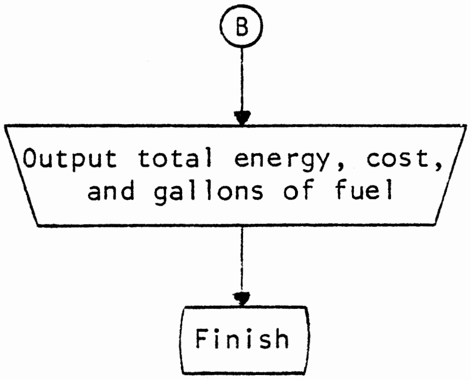

Figure 3. (Continued)

additional fuel required by vehicles for horizontal curves is summed with the fuel requirements for surface type and grade for the total fuel requirements. The energy consumed by vehicles is calculated by vehicle class with the diesel powered trucks having a higher energy content per gallon. The gallons of fuel are multiplied by the average cost of a gallon of fuel over the study period for the total cost of fuel. The total life cycle cost is the sum of the unit costs for both maintenance and construction, multiplied by the route length, and the total vehicle fuel cost. The life cycle energy requirement of each route is calculated by summing the energy expenditures of vehicles, construction, and maintenance. The output lists the total cost and energy for each route for each iteration of the four traffic volumes.

Input Parameters

The input parameters of this example investigation are entered into the program on four data cards with each data element separated by a comma. The data items are entered in the following manner with the value employed in this investigation in parentheses next to the variable description:

1. Traffic parameter card
    a. study name ('EXP')
    b. traffic mode (2 for two-way; one-way traffic would receive a 1)
    c. percentage of cars (74)
    d. percentage of pickups (10)
    e. percentage of SUT (8)
    f. percentage of gasoline powered trucks (4)

   g. percentage of diesel powered trucks (4)

2. Topographic parameter card (different values for each section)
   a. route name ('A-A' to 'F-F')
   b. number of sections
   c. design grade (assumed equal positive and negative)
   d. station of the high point (in 1,000 ft stations)
   e. elevation of the high point (in ft)
   f. initial elevation of the start point (in ft)
   g. elevation of the end point (in ft)
   h. station of the end point (in 1,000 ft stations)
3. Study parameters
   a. number of years in the study period (20)
   b. cost of gasoline ($1 per gal)
   c. numerical designation if an alternative scenario is desired (blank for static scenario, 1 for dynamic scenario)
4. Traffic volumes
   a. The traffic volumes are 75, 750, 2700, and 10,000
5. The horizontal curves description
   a. the station of the angle of intersection of each curve (in 1,000 ft stations)
   b. the degrees of the angle of intersection
   c. the designation of "R" or "L" to indicate if the curve turns to the right or left.

Fuel Savings by Grade Reduction

As described in Chapter II, steep grades are a major cause of additional fuel expenditures, particularly for heavier vehicles with low horsepower-to-weight ratios. The additional energy consumption to ascend steep grades is greater than the energy savings during the descent. Therefore, a reduction of sharp grades may result in significant energy/fuel savings, but this reduction increases the fuel required by large construction equipment. The added construction fuel expenditure may be less than the traffic energy savings over a long period, i.e., the life of the highway. In addition to possible energy savings, the lower vehicle operating costs over the life of the highway may offset the additional construction expense. There are both cost and energy trade-offs between the fuel savings by the operating vehicles and the additional construction requirements for lower initial design grades.

In selecting initial design grades, highway officials minimize the amount of earthwork by balancing cuts and fills to reduce overall construction costs. Maximum grades are limited to terrain having steep inclines or mountainous/hilly regions. For example, Oklahoma permits a maximum of five percent grade on its interstate highways and up to ten percent grade for federal-aid secondary highways with traffic flows less than 650 vehicles per day.

The amount of earthwork is generally estimated by the average end area method. This method superimposes the desired design cross sections upon the existing cross sections to compute the quantity of earth to be excavated. This portion of the research develops a computer program so that a designer knowing the initial design grades and cross sections may readily determine quantities of earthwork for reduction from initial, steeper grades to a lower set of grades. The computer program for estimating the life cycle energy and cost expenditures for construction, maintenance, and vehicle usage is combined with the program for grade reduction. An example run of this program is included in Appendix B for the 10,000 vpd of route D-D. Route D-D is selected to exemplify the potential savings through grade reduction because of its steep grades, and its relative energy and cost efficacy as compared to the other routes. The cross section data for route D-D are presented in Appendix C.

The volume calculations utilize the average end area method by averaging the cross section areas between stations and then multiplying the average by the distance between the stations. The cross section area is calculated by one or several different models depending upon a comparison between the elevation of the extended side slope and the existing topographic elevations. This comparison and the development of the area calculations are discussed in Appendix D. The summary flow chart of the volume reduction subsystem is presented in Figure 4.

In this analysis the influence of vertical curves upon volume calculations is ignored, since the curves are common to both the initial design and the trial grade combinations.[1] The base width (pavement, shoulder, ditches, etc.) of the road for the initial and trial grade combinations is assumed to be the same. Since the maximum anticipated highway grade for any highway is 10 percent, the maximum variation between horizontal and inclined distances is calculated by the Pythagorean Theorem as less than one-half of one percent. Since the difference is small, the horizontal distances are employed in both volume and fuel consumption

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[1] This assumption is conservative since the lower proposed grades would require a shorter vertical curve than the steeper existing grades. A shorter vertical curve would require less excavation and, therefore, less energy and economic expenditures.

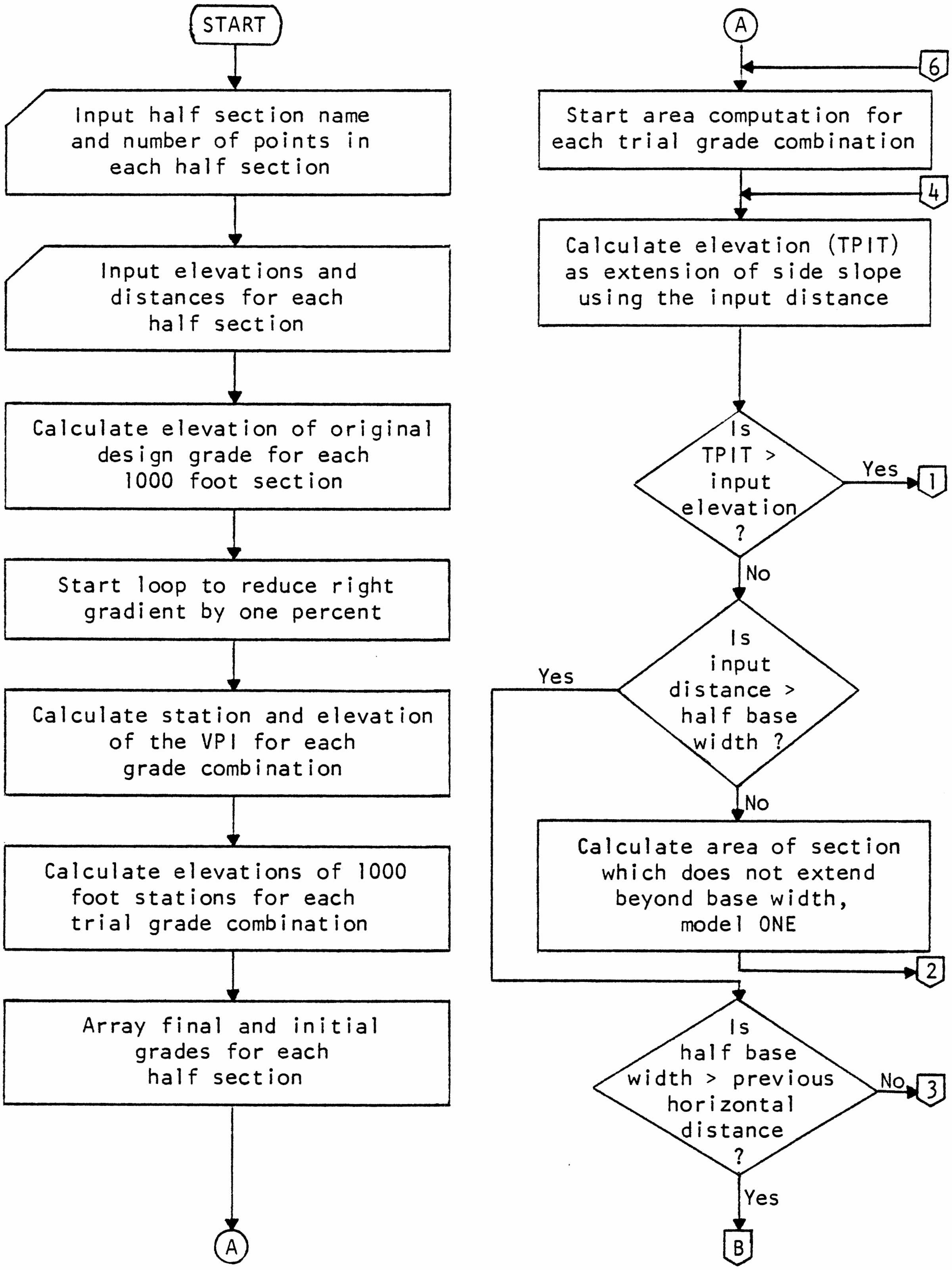

Figure 4. Summary Flowchart of Grade Reduction Subsystem

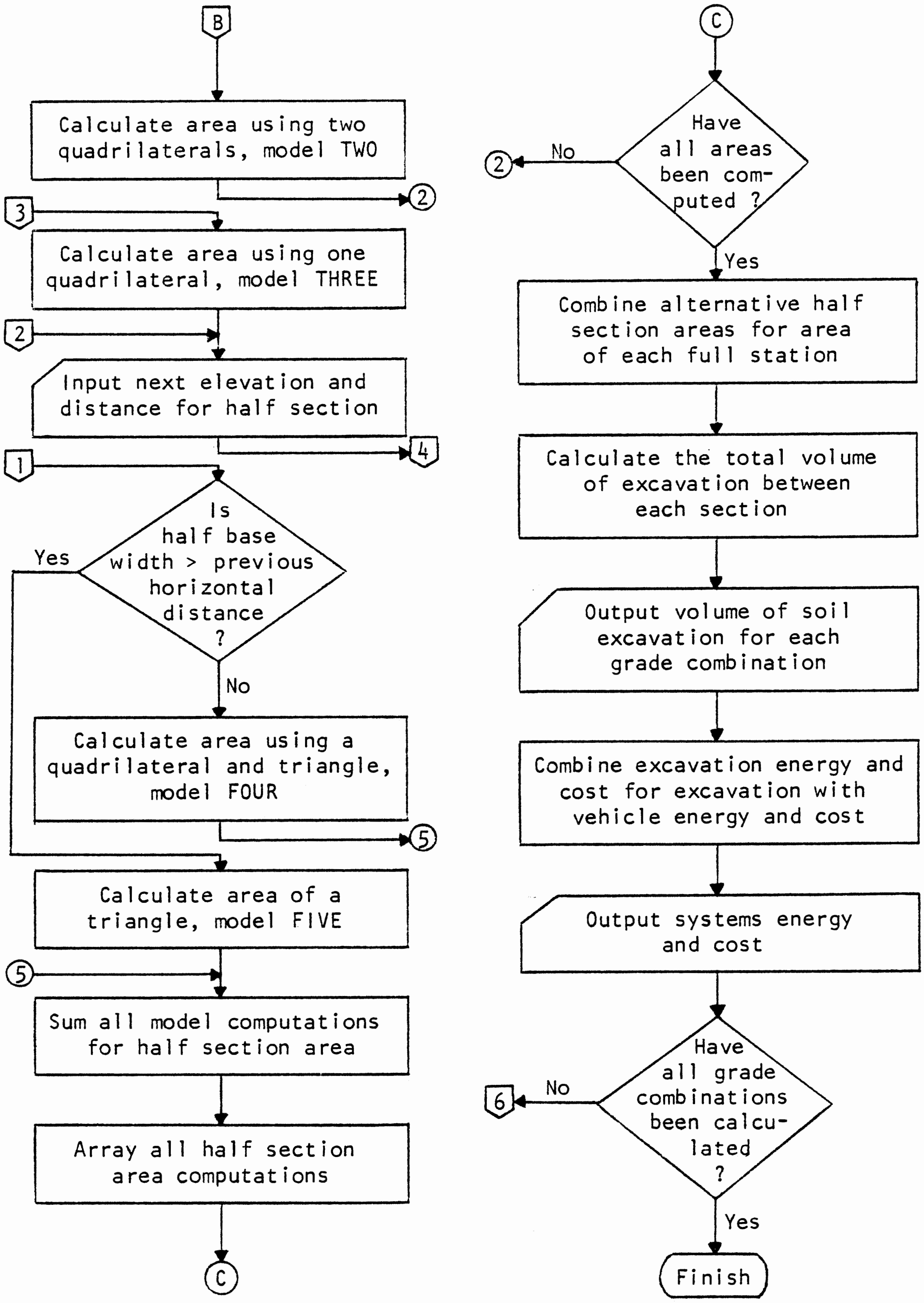

Figure 4. (Continued)

calculations. Other savings, such as reduction in pavement length, are ignored for the same reason.

The determination of optimal excavation depths (for a given set of grades and a given section) involves an iterative process for each possible set of final grades. The results of each proposed grade set are compared in terms of cost and energy requirements. A recursive process of this nature involving the vehicle operation data banks is typically suited for computer analysis. The input variables of the program are the traffic and section parameters, the economic cost per cubic yard of excavation, and the price of a gallon of vehicle fuel. The section parameters consist of the section length (in 1000 foot stations), the cross section data, the design side slope, the initial design grades, the base width of the road (in feet), and the number of years within the study period. The traffic parameters include the one-way ADT, the percentage of each of five classes of vehicles, and the scenario data if a scenario is implemented. A "1" or "2" at the end of the section parameter in the input data denotes whether the analysis is for one-way or two-way traffic. The values of the variables are the same as those of the route selection model of the earlier portion of this chapter with the addition of a nominal one dollar per cubic yard for the grade reduction excavation. The scenario is implemented throughout the analysis.

The program executes the volume computation with the initial design grades and then reduces the negative grade for each successive iteration. When the volume computation is completed for a negative grade of one percent, the program then checks to determine if the final positive grade is one percent and, if not, the positive grade is reduced by one percent. After the computation for a negative grade of one percent, the final negative grade is reset equal to the initial negative grade. If the last computed volume is for a final positive and negative grade of one percent, the program terminates.

A significant calculation of the program is the determination of the new station of the VPI based upon each iteration of a trial grade combination. The new station of the VPI is computed using the elevations and stations of the start of ascent and completion of descent with each proposed grade combination. This calculation is developed in Appendix D. From the new station and elevation of the VPI the proposed elevations are determined for each full 1000 foot station. These proposed elevations are used for the volume calculations. Also, the new stationing of the VPI is utilized for determining upgrade and downgrade lengths for vehicle fuel computations.

The initial vehicle fuel consumption is selected from Winfrey and Claffey's gradient data array (Chapter III). The individual fuel consumption rates are determined by the attained speed, the initial grades, vehicle classification, and the surface type. The fuel consumption factor (in gpm) from this array is then multiplied by the ADT, the positive or negative grade distance (in miles), the percentage of each vehicle class, the number of days in a year, and the years in the study period. This calculation is performed for negative and positive portions. The combined fuel consumption is the sum of the fuel consumptions of each of the vehicle classes. The final fuel consumption is computed similarly with the exception that final grades replace the initial grade subscripts and the initial positive and negative lengths are replaced by the final positive and negative lengths. The additional fuel for horizontal curves is included with the total vehicle cost and energy expenditures.

The energy equivalent (M.Btu) consumption is determined from the fuel consumption depending upon whether the vehicle is diesel (0.139 M.Btu/gal) or gasoline (0.125 M.Btu/gal) powered. The total energy fuel saving is the difference of vehicle energy consumption for the initial grades less the lower vehicle energy consumption for the final grades over the duration of the study period.

If the traffic mode is two-way, the total vehicle energy consumption is the sum of the vehicle energy consumption for traffic traveling in both directions. The vehicle energy saving is the difference of energy consumption between the initial and proposed grades. The energy required for excavation to each set of final grades is the product of the volume (in cubic yards) multiplied by an earthwork efficiency factor and the construction energy requirements per cubic yard.[2] The total energy saving is the difference of the vehicle energy saving less the increased energy for excavation.

The cost of excavation is the estimated cost per cubic yard multiplied by the volume of excavation. The fuel economic saving is the total vehicle fuel saving (in gallons) over the analysis period multiplied by the cost per gallon. The total economic saving is the vehicle fuel saving less the increased excavation cost.

In common highway analysis economic benefits other than fuel, e.g., safety, convenience, etc., are considered. These auxiliary benefits are not included with the program, primarily because the emphasis of this re-research is upon fuel/energy analysis and conservation. The inclusion of

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[2] For common earth the excavation energy requirement is 0.059 M.Btu/cu yd. For rock and other excavation the energy requirements are 0.074 M.Btu/cu yd and 0.069 M.Btu/cu yd, respectively. These estimates are taken from Chapter III.

these benefits would add further justification for additional grade reduction. Also, in highway analysis the economic benefits or reductions of cost are generally assumed to be price-constant over the study period and are discounted by a predetermined interest rate to a present worth value. This approach is not utilized in this analysis.

Computer Language

Appendix B contains the computer programs and Appendix C contains the sample output. The computer language, which may be unfamiliar to a FORTRAN programmer, is Programming Language/One (PL/1), and was originally intended to be an all-purpose language, utilizing the better features of both FORTRAN and COBOL and minimizing many of the limitations of either language. COBOL, which is a business-oriented language, has the ability to handle large data arrays but possesses limited scientific and mathematical capability. FORTRAN has a good scientific/mathematical abilIty, but is limited for recursive operations and efficient handling of large data banks. The PL/1 language was chosen because of its data handling and scientific capacities and its efficient input/output (I/O) abilities.

CHAPTER V

DEMONSTRATION OF THE MODEL

Introduction to the Demonstration

For the initial investigation six alternative routes are selected through an area of steep gradients. For each route and type of road the life cycle energy and cost are determined for the construction, maintenance, and fuel consumption of the input traffic volume. A comparison is made to select the most energy-efficient and economical route(s) for each type of road. For each selected route, a further analysis is performed to determine energy and/or cost savings that may be made by reducing the grades and straightening the alignment. This initial investigation determines the route(s) with the minimal life cycle energy and/or cost expenditures for each type of road during a period of constant fuel prices and vehicle energy efficiency (i.e., a static scenario).

Since the price of fuel is expected to increase and vehicles are anticipated to become more energy-efficient, the results of the initial investigation may change with variations in either of these parameters. To determine relative model sensitivity to these parameters, a dynamic scenario of these two variables and traffic growth is entered into the model. This investigation determines the least energy and/or cost consuming route(s) for each type of road for the given conditions of the dynamic scenario.

Region of Example Analysis

The most energy and cost efficient highway route, for a region of minimal obstacles and topographic variations, would be an alignment which directly connects the end points with the least length. Regions of sharp gradients and varying terrain may have one alignment which minimizes the total system's cost and/or energy expenditure depending upon the volume of traffic and standards of construction. To explore the relationship of traffic and alternative route alignments in hilly/mountainous regions, a series of contours are traced (Figure 5) from an area of Latimer County in southeastern Oklahoma (sections 25, 26, 27, 34, 35, 36, of Range 21 East, Township 7 North, and sections 1, 2, 3, of Range 21 East, Township 6 North).

Five initial routes (designated A-A, B-B, C-C, D-D, and E-E) are considered on the basis of equal magnitude positive and negative gradients from 2 to 10 percent in increments of 2 percent grade. Each route is aligned to follow the existing ground profile and thereby minimizes longitudinal excavation and fill operations. This alignment procedure produces many large angles of tangent intersection (Table IX) which are helpful in estimating system savings through route realignment, i.e., straightening of the horizontal profile. A sixth route is included as a direct connection between the trip end points. A large initial excavation and fill operation is required to construct this route at a maximum 10 percent gradient (Figure 6).

Development of the Model's Dynamic Scenario

As described in this chapter's introduction, the results of the energy investigation (the selection of the least long-term energy and/or

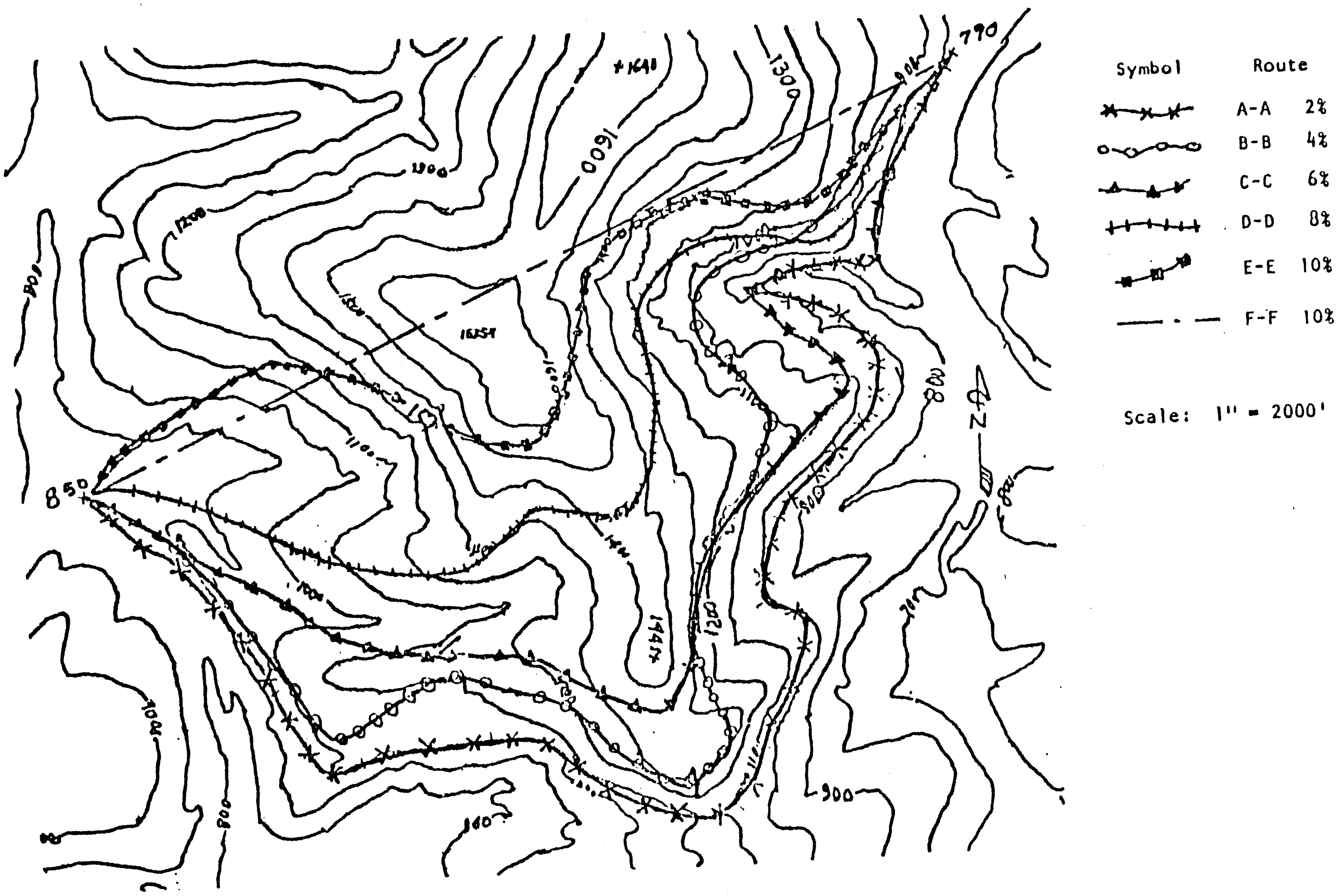

Figure 5. Alternative Proposed Routes

TABLE IX

ALIGNMENT OF PROPOSED ROUTES

Route Designation	A-A		B-B		C-C		D-D		E-E	
Maximum Grade (%)	2		4		6		8		10	
Length (ft)	27,200		24,500		21,300		18,200		16,600	
	Sta[a]	I[b]	Sta	I	Sta	I	Sta	I	Sta	I
	1	13R[c]	1	13R	5	12L	2	25R	1	19R
	5	81L	2	14R	7	27R	3	14L	3	38R
	9	51R	5	64L	9	84L	6	42L	4	18R
	12	37L	7	43R	10	28L	7	62R	5	11R
	15	80L	9	34R	14	29L	8	67L	7	72L
	16	74R	10	32L	15	91L	9	25L	10	42R
	17	31R	11	69L	17	121R	10	26L	12	34R
	19	36L	12	66L	18	29R	11	27R	13	20L
	20	56L	13	32R	19	83L	12	38R	14	39L
	21	25L	15	25R			13	24R		
	22	141R	16	25L			14	18R		
	23	40R	17	58L			15	68L		
	24	107L	18	21R						
	25	26R	19	75R						
			20	31R						
			21	34L						
			22	25L						
			24	25R						

[a] All stations (sta.) are 1,000 feet apart.

[b] The angle of intersection (I) is measured in degrees.

[c] The designation "R" and "L" indicate the curve turns right or left.

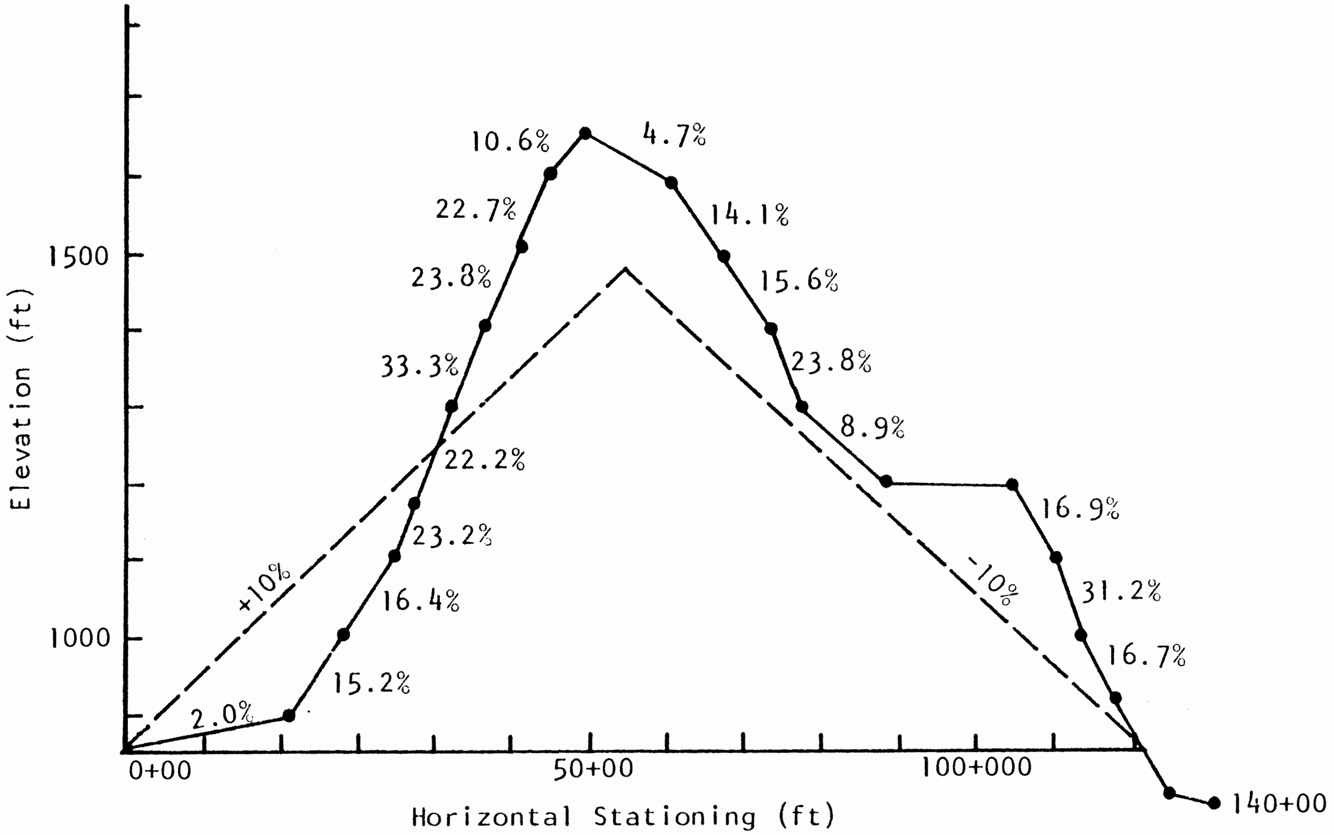

Figure 6. Profile of Direct Route F-F

cost route) is determined by assuming that the cost of vehicle fuel (in constant dollars), the passenger car fuel efficiency, and the average daily traffic remain relatively constant throughout the analysis period. Since the future magnitude of these parameters is uncertain, variations of these may alter the initial route selection. Therefore, to determine the model's sensitivity to these variables, a dynamic scenario is developed according to the following assumptions. (The base year of the study, i.e., the start of traffic on the completed facility, is 1980.)

Future Fuel Prices

The cost of vehicle fuel is primarily determined by the world's market price of a barrel of petroleum crude. The price per barrel is dependent upon the supply and demand, including the willingness and capability of the exporting nations to produce. During the period of 1950 to 1972, the production of petroleum was relatively stable and independent of political interference. The cost of gasoline fell during this period 22 percent as measured in constant dollars. From 1972 to 1975, the cost of vehicle fuel rose 29 percent in constant dollars (approximately 8 percent increase per year). Since 1975, the cost of petroleum products continued to increase at a rate greater than the inflation rate. During 1979, the price of vehicle fuel increased further with the removal of Iranian production.

In this scenario the price of vehicle fuel is assumed to increase at an annual 8 percent above the inflation rate for the first eleven years. By the twelfth year this rise is altered by the development and commercial availability of alternative sources of vehicle fuel, e.g., petroleum from oil shale, tar sand, etc. In the following period from the twelfth to the twentieth year of the investigation, larger production and technological advancements in the recovery from these sources are assumed to reduce the cost (in constant dollars) by one percent per annum (Table X).

Vehicle Fuel Efficiency

In 1974, the federal government mandated that manufacturers produce more energy-efficient vehicles (The Energy Policy and Conservation Act of 1974). According to this Act, the fleet weighted average of vehicles must have attained 18 mpg by 1978, 20 mpg by 1980, and 27.5 mpg by 1985. Large financial penalties are to be levied against manufacturers who fail to attain the stipulated fuel economy standard for each year. Beyond 1985, there are no stipulated fuel standards at present.

The increased fuel efficiency of passenger cars is anticipated to be obtained primarily by lowering the weight of the average individual vehicle. Vehicles with high weight to horsepower ratios (trucks of vehicle classes 3, 4, and 5) are not anticipated to have their weights significantly reduced without adversely affecting their performances. Therefore, these classes are expected to have only minor fuel improvements as compared to passenger vehicles (class 1).

The federal fuel economy standards pertain to vehicles produced only in each year and may not be representative of the average on-the-road vehicle fuel efficiency. There is a delay between the year of the production of vehicles and the year that these vehicles approximate the fuel efficiency of the average on-the-road vehicle.

The FHWA publishes annual data of the average vehicle age which is approximately seven years. This is based upon the average of the

TABLE X

ELEMENTS OF THE DYNAMIC SCENARIO

Year	Fuel Cost (1980 Constant Dollars)[a]	Traffic Growth (Annual Factor)[b]	Passenger Vehicle (mpg)[c]	(Fuel Factor)
1	1.00	0.719	15	0.95
2	1.08	0.726	17	0.86
3	1.17	0.734	18	0.79
4	1.26	0.741	19	0.74
5	1.36	0.748	20	0.70
6	1.47	0.756	21	0.67
7	1.59	0.763	22	0.64
8	1.71	0.771	24	0.59
9	1.85	0.779	26	0.54
10	2.00	0.786	27	0.52
11	2.16	0.894	28	0.50
12	2.13	0.810	28	0.50
13	2.11	0.834	29	0.49
14	2.09	0.859	29	0.49
15	2.07	0.885	30	0.47
16	2.05	0.912	30	0.47
17	2.03	0.939	31	0.45
18	2.01	0.967	31	0.45
19	1.99	0.996	31	0.45
20	1.97	1.026	31	0.45

[a] Based upon 8 percent growth (years 1-11) and 1 percent real deflation (years 12-20) as alternative fuels become available.

[b] Based upon a 1 percent growth (years 1-11) and 3 percent growth (years 12-20).

[c] Based upon the mileage standards of the Energy Policy and Conservation Act of 1975, and a five-year delay before these standards become the average passenger vehicle fuel mileage.

reported registration of vehicles by each state. This is not necessarily the average age of vehicles using the road, since newer vehicles tend to be driven more than older vehicles. The Environmental Protection Agency also utilizes data of vehicle age based upon actual mileage of vehicles. These data suggest that the average passenger car age is 5.1 years.

For this study the vehicle fuel efficiency standards are assumed to be delayed for five years before becoming the average vehicle fuel mileage. For example, the 1978 vehicle fuel standard of 18 mpg is anticipated to become the average passenger car fuel mileage in 1983.

By the year 1990 (year 10 of the study period) and the implementation of the 1985 standards, the weight of the passenger car is anticipated to be the lightest weight that would be commercially acceptable. Therefore, for the remaining ten years of the study period, only minor improvements in vehicle fuel efficiency, due to technological advances and redesign efforts, are assumed (approximately one percent annual improvement).

Traffic Growth

The growth of traffic over the design period for a given facility depends upon many factors (e.g., patterns of population growth and density, existence of parallel facilities, etc.) and the traffic growth for each facility would require an analysis based upon existing conditions. For this study the traffic is assumed to grow at an average annual rate of three percent. To illustrate this growth rate, the average daily traffic of 75 vpd over the study period would have a base year traffic of 53 vpd and an end year (year 20) traffic of 97 vpd (at a compounded annual growth rate of three percent). The full 97 vpd may not develop by the end year since there is an inverse relationship between vehicle fuel price increase and traffic growth. For example, economist Alan Greenspan estimates that the consumption of vehicle fuel (decline in traffic usage) decreases one and one-half to two percent for each fuel price increase of ten percent. For the model's scenario the traffic growth is assumed to increase at an annual one percent rate (i.e., the expected three percent less two percent), during the period of eight percent increases (year 1 to 11), and resume the three percent growth when the price rise approximates the average inflation rate. In Table X the traffic growth pattern is expressed as a factor of the average daily traffic. The average traffic (62 vpd or 0.82 [75 vpd]) during the study period is less than the daily traffic of the initial investigation (75 vpd) because of the decline in traffic due to the vehicle fuel price increases. This traffic growth pattern is assumed for the other three traffic volume ranges.

Implementation of the Dynamic Scenario

The fuel cost, traffic growth, and passenger vehicle fuel mileage are expressed as a series of factors. The passenger vehicle fuel mileage factors lower the fuel expenditure of only vehicle class one (passenger cars). The other vehicle classes (trucks) are assumed to have constant fuel mileage throughout the study period. The fuel cost and traffic growth factors are applied against all vehicle classes. The graphical illustration of these factors is presented in Figure 7.

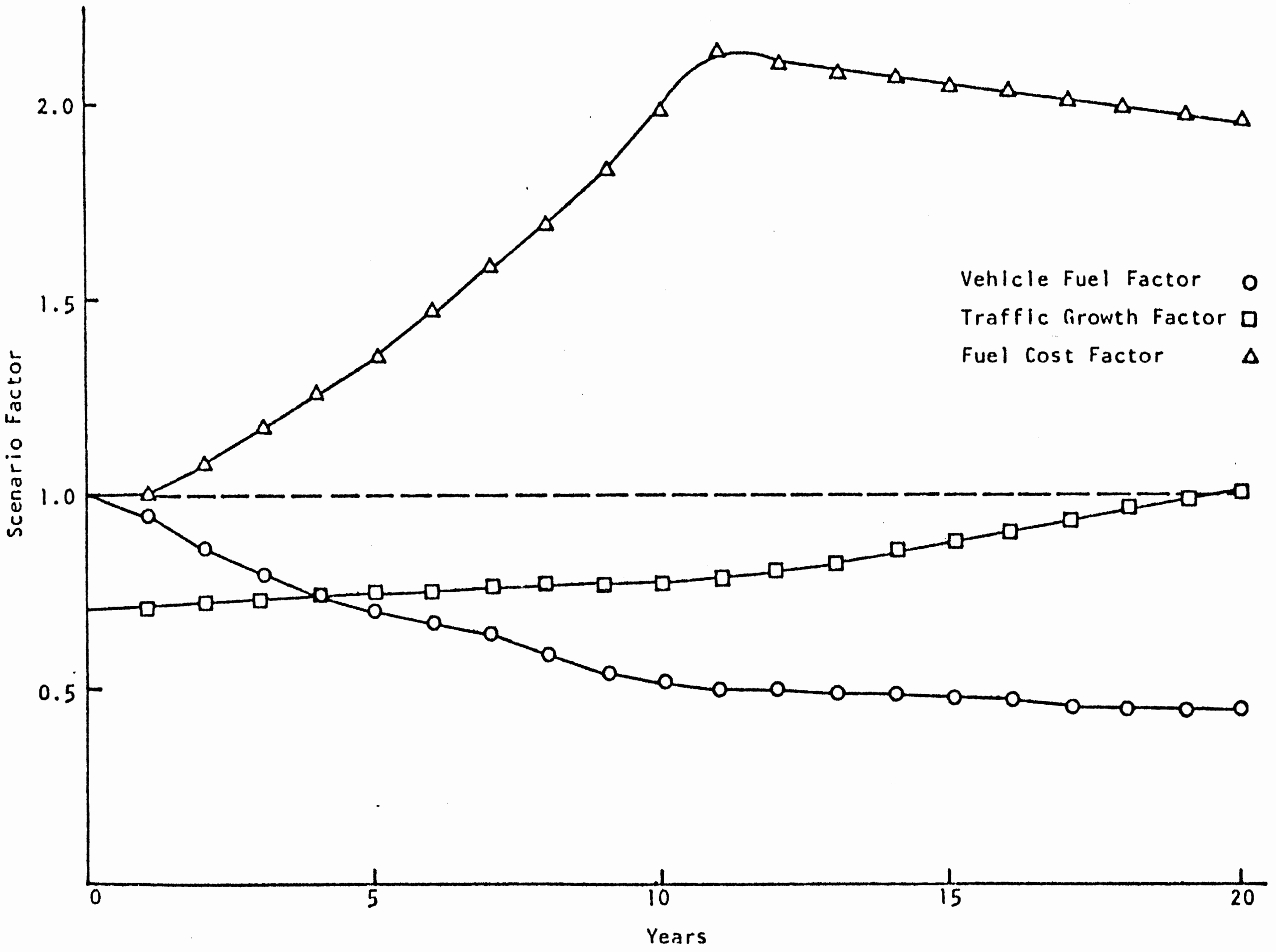

Figure 7. Dynamic Scenario Factors

Overview of the Route Selection Results

The construction of a direct route between the trip end points (route F-F) requires large energy and cost expenditures. Large excavation and fill operations are needed to bring this route selection to a minimum design standard, i.e., the maximum permissible grade of 10 percent. For example, a type IV road with a base width of 20 feet would require over 14 million cubic yards of excavation to meet the 10 percent gradient as shown in Figure 13. At a cost of $2 per cubic yard the grading operations alone would require $28 million or more than $10 million per mile for this low classification of road. The energy expenditure for grading to the design standard would be over 800,000 M.Btu or the use of over 5 million gallons of diesel fuel by earth moving equipment. Larger grading operations are required for the other types of roads for route F-F. The initial construction and the long-term maintenance cost and energy requirements are listed in Table XI for each type of road and road alternative including route F-F. Due to the huge initial grading operations for route F-F, its energy and cost requirements for construction are far greater than the other alternatives. As developed in this section, this route is noncompetitive in both long-term cost and energy because of these large, initial energy and cost expenditures to establish minimum gradient standards.

The preliminary computer program determines the life cycle energy and cost expenditures for construction, maintenance, and vehicle usage. The vehicle energy and fuel cost expenditures are computed for each of the route alternatives, the four traffic volumes, and a corresponding type of road. The total vehicle energy expenditure is computed at each route's gradients and maximum degree of curvature. The life cycle

TABLE XI

ENERGY AND COST OF MAINTENANCE AND CONSTRUCTION BY ROAD TYPE AND ROUTE

Route	Item	IV (Earth Surfaced)	III (Gravel Surfaced)	II (Two-Lane Paved)	I (Four-Lane Paved)
A-A	Energy[a]	1,904	10,608	183,056	437,104
	Cost[b]	52,768	404,736	3,717,696	7,412,000
B-B	Energy	1,778	9,906	170,942	408,178
	Cost	49,276	377,952	3,471,672	6,921,500
C-C	Energy	1,491	8,307	143,349	342,291
	Cost	41,322	316,944	2,911,284	5,804,250
D-D	Energy	1,274	7,098	122,486	292,474
	Cost	35,308	207,816	2,487,576	4,959,500
E-E	Energy	1,162	6,474	111,718	266,762
	Cost	32,204	247,008	2,268,888	4,523,500
F-F	Energy	828,600	913,060	1,122,373	1,582,634
	Cost	28,081,992	30,974,768	36,747,886	49,782,726

[a] In M.Btu.

[b] In 1980 constant dollars.

vehicle energy expenditures are determined with the static scenario (Table XII) and for the conditions of the dynamic scenario (Table XIII). Table XIV presents the results of the life cycle cost expenditures with the static scenario, and Table XV lists the results under the conditions of the dynamic scenario. The effect of the dynamic scenario upon the life cycle energy is illustrated in Figure 8. The dynamic scenario effect upon the life cycle cost is presented in Figure 9.

Analysis of the Results

Using Table XII, route A-A is the least long-term energy consuming alternative for the two-way daily traffic volume of 75, 2700, and 10,000 vpd. Route A-A has the lowest combination of grades (2 percent) but has the longest distance between the trip end points (27,200 ft). The difference of the vehicle energy expenditures for the steep grades and these lower grades is greater than the sum of the additional energy expenditure for vehicles traveling its longer route and the additional construction and maintenance energy expenditure for the added length. For road types IV, II, and I, steep grades are a major cause of vehicle energy expenditure. Therefore, the steep routes are not as energy competitive. Road type III with a traffic volume of 750 vpd has the highest life cycle energy consumption per vehicle of the four types of roads, roughly 30 percent more per average daily vehicle. The added energy consumption of this type of route is a function of the surface roughness and attained speed. For example, road type I has a rougher, more energy-dissipating surface but because of its lower average speed, the average daily energy expenditure is less per vehicle-mile. The effect of speed and surface offsets the additional energy consumption needed to overcome

TABLE XII

ENERGY RESULTS OF THE INITIAL INVESTIGATION

Route	Traffic ADT			
	75	750	2,700	10,000
A-A	27,875[a]	449,855	1,145,868	4,003,112
B-B	30,363	472,560	1,259,080	4,438,342
C-C	29,768	484,723	1,374,856	4,903,464
D-D	30,665	416,182	1,181,848	4,216,071
E-E	31,950	421,370	1,228,498	4,403,026
F-F	855,210	1,252,174	2,020,642	4,909,580

[a] In M.Btu.

TABLE XIII

ENERGY RESULTS WITH THE DYNAMIC SCENARIO

Route	Traffic ADT			
	75	750	2,700	10,000
A-A	17,868[a]	347,029	774,929	2,629,266
B-B	19,723	364,730	870,133	2,997,801
C-C	19,398	353,142	900,256	3,145,634
D-D	20,150	313,689	812,187	2,846,957
E-E	20,502	313,593	839,804	2,963,420
F-F	845,392	1,169,868	1,723,818	3,810,229

[a] In M.Btu.

TABLE XIV

COST RESULTS OF THE INITIAL INVESTIGATION

Route	Traffic ADT			
	75	750	2,700	10,000
A-A	258,253[a]	5,834,055	11,355,042	35,698,507
B-B	274,771	5,855,092	12,070,265	38,768,175
C-C	264,154	5,611,923	12,653,809	41,887,702
D-D	266,646	4,802,881	10,838,897	35,890,360
E-E	276,328	4,714,423	11,088,850	37,190,069
F-F	28,292,881	34,668,606	43,831,654	76,018,926

[a] In 1980 constant dollars.

TABLE XV

COST RESULTS WITH THE DYNAMIC SCENARIO

Route	Traffic ADT			
	75	750	2,700	10,000
A-A	271,992[a]	5,977,032	11,872,912	37,616,553
B-B	295,287	6,140,557	13,101,120	42,586,163
C-C	286,689	5,791,130	13,301,387	44,286,148
D-D	293,965	5,116,396	11,970,138	40,080,146
E-E	299,199	5,051,423	12,304,299	41,691,738
F-F	28,313,726	35,005,164	45,045,259	80,513,768

[a] In 1980 constant dollars.

the steep grades. The net result is that routes with steeper grades (D-D, E-E, F-F) have lower vehicle energy consumption between the trip end points than the longer routes.

Considering Tables X and XI, the average energy for construction and maintenance is a higher percentage (5 to 16 percent) of the total energy for the higher standard roads (types I and II) than for the lower standard roads (only 2 to 7 percent of the life cycle energy expenditure). The energy expenditure for construction and maintenance for route A-A of road type III is 10,608 M.Btu. The energy expended by vehicles traveling upon this route and road type is the difference of the life cycle energy expenditure (449,855 M.Btu) and the energy expended for construction and maintenance. This difference is 439,247 M.Btu and represents an average vehicle energy expenditure of 586 M.Btu (439,247 ÷ 750) per vehicle during the route's life cycle. For road type II of route A-A, the construction and maintenance energy expenditure is 183,056 M.Btu. The total vehicle energy expenditure for road type II of route A-A is 962,812 M.Btu (1,145,868 - 183,056). For the traffic flow of 2700 vpd, the average vehicle life cycle energy expenditure is 357 M.Btu. Therefore, upgrading route A-A from a road type III to II would permit a lower average vehicle energy expenditure. The average vehicle on a life cycle basis would consume 229 M.Btu less on a type II road than a type III road for route A-A. Upgrading the route would require an additional energy expenditure of 172,448 M.Btu. On a life cycle energy basis, the division of the additional energy expenditure for construction and maintenance by the average life cycle vehicle energy savings determines the traffic volume which would justify the selection of a type II road over a type III road. This traffic volume is 753 vpd.

Thus, the addition of three more vehicles to the traffic flow would permit the building of a two-lane paved highway rather than a gravel surfaced route. This analysis assumes that the higher geometric standards of the two-lane highway do not require additional excavation beyond the estimate of Table VII. Similar break-even traffic volume comparisons may be made for the routes and road types.

Table XIII presents the results for the life cycle energy expenditure of each route and road type with the inclusion of the dynamic scenario. The total life cycle energy expenditure for each route and road type is less under the conditions of the dynamic scenario than with the static scenario. The lower energy expenditure for the optimal route corresponding to each traffic volume optimal route is illustrated in Figure 8. There is less vehicle energy expenditure due to the increased passenger car fuel efficiency and lower total traffic volume. Route A-A is the most energy efficient selection for the traffic volumes of 75, 2,700, and 10,000 vpd. The gravel surfaced route induces higher energy losses upon the vehicle traveling on its surface. For this type of road the most energy efficient routes are those with steeper gradients and shorter lengths. The energy saving per average vehicle on a life cycle basis for route A-A is 230 M.Btu for a type II road compared to a type III road. The actual break-even traffic volume for upgrading a gravel surfaced road to a paved two-lane highway is 750 vpd under the conditions of the scenario. Since the traffic volume is only 82 percent of the projected volume, this 750 vpd would represent an estimated or planned traffic volume of 915 vpd.

Table XIV presents the economic cost results of the investigation of each route and road type with the static scenario. For the earth

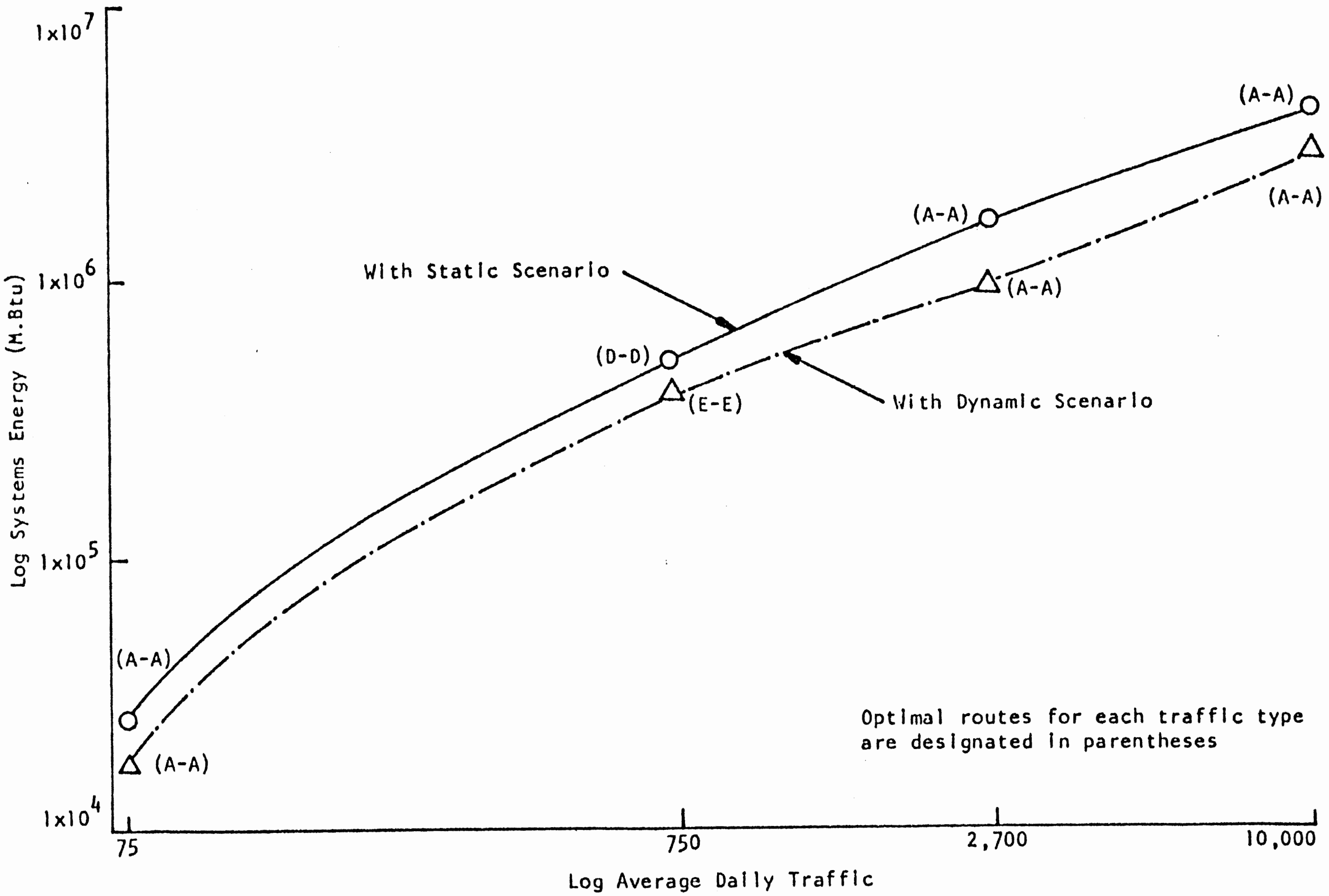

Figure 8. Scenario Implementation and Systems Energy

surfaced road and the four-lane highway, the most economical route selection is A-A. For route A-A, each of the road types requires, for maintenance and construction, about the same proportion of total life cycle cost (20.4 percent for road type IV and 20.8 percent for road type I). Road types I and IV of route A-A require a greater fraction of the total cost for construction and maintenance cost than the other types. The vehicle fuel usage is the lowest for the two road types of route A-A than for the other routes. The steeper gradient routes (D-D and E-E) are most cost efficient for the gravel surfaced road. For the two-lane highway the steeper gradient routes are also more cost efficient than the lower gradient routes B-B and C-C. For each road type route A-A has the lowest percentage of vehicle fuel usage to total cost.

With the implementation of the dynamic scenario (Table XV), the life cycle cost for each route and road type is increased because the cost of fuel increases more rapidly than the rate of inflation. Since route A-A has the smallest life cycle usage of fuel, it remains the most cost-efficient for the earth road and four-lane highway. Route A-A also has the least life cycle cost for the two-lane highway. Even under the conditions of the dynamic scenario, the higher gradient routes (D-D and E-E) remain the least cost routes for the traffic flow of 750 vpd upon the gravel surfaced road. The effect of the dynamic scenario upon the life cycle cost is presented in Figure 9.

Fuel Savings by Horizontal Curve Realignment

As described in Chapter II, vehicles traveling on sharp horizontal curves experience an increase in fuel consumption. In each of the road types and route selections of the previous investigation, the degree of

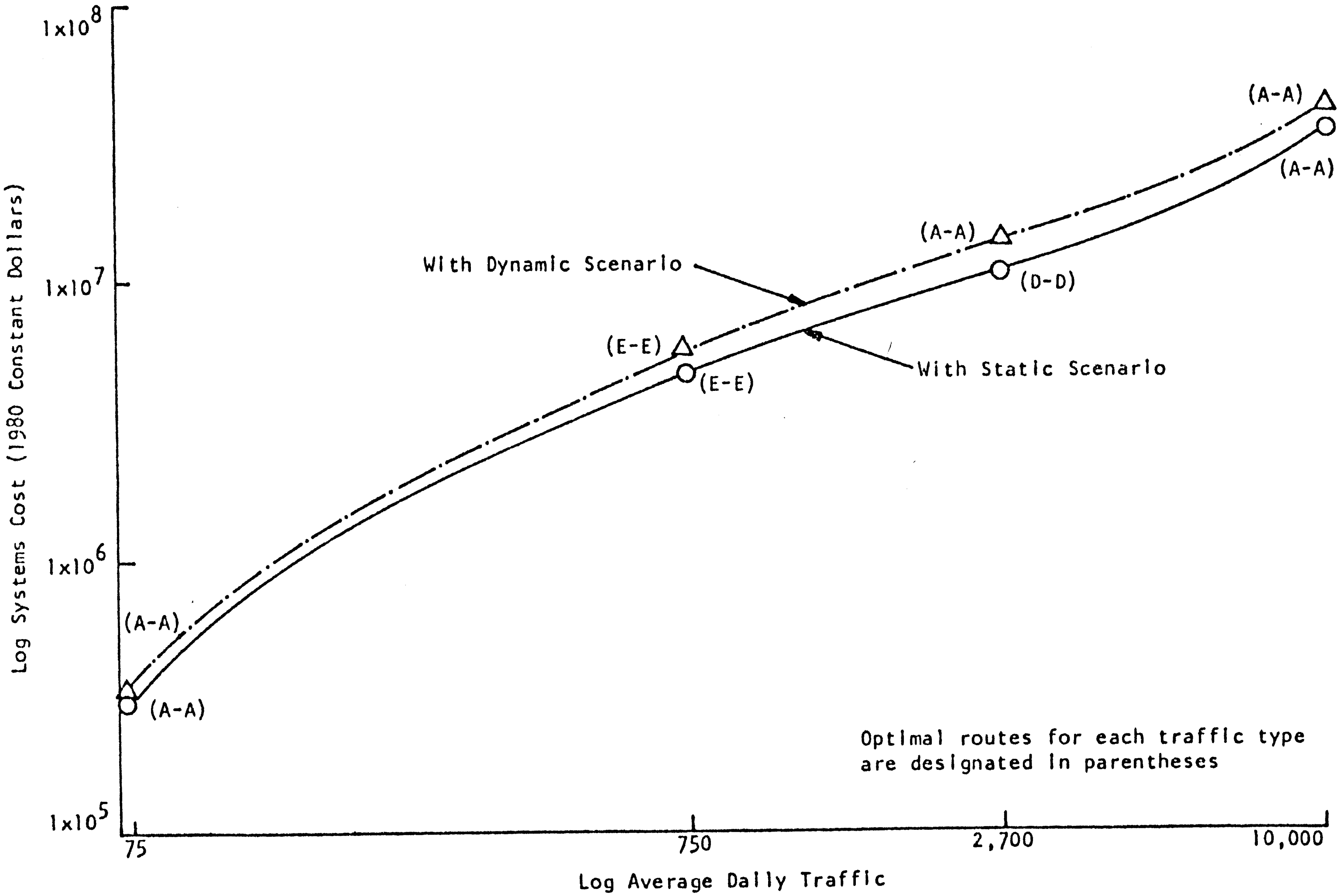

Figure 9. Scenario Implementation and Systems Cost

curvature is taken as ten degrees. By substituting a lower degree of curvature, the road is straightened and the vehicles experience a lower fuel consumption.

To investigate the influence of horizontal curves and the associated vehicle energy and cost expenditures, a do-loop is implemented in the program to reduce the design degree of curvature from ten to one. The program's output lists the total fuel consumption (in gallons) during the life cycle and the additional fuel consumed for each degree of curvature. Only routes A-A and D-D are investigated. During this analysis the stationing and angle of intersection of the tangents of each curve remain constant for each degree of curvature. The total length of each route is also held constant during the investigation.

The additional fuel consumption for maintaining each vehicle on its circular path is dependent upon several interacting variables. For example, the additional fuel consumption for curvature is an exponential function of the attained speed of each vehicle. The attained speed of each vehicle is dependent upon the type of vehicle, roughness of surface, steepness of gradient, and degree of curvature. For the same attained speed, larger vehicles expend proportionately more energy than the lighter passenger cars. Also, the length of each curve changes with the degree of curvature. Finally, the position of the curve in relation to upgrade, downgrade, crest, and horizontal tangents also affects fuel consumption.

The results of the effect of curvature on vehicle fuel consumption are presented in Table XVI in gallons. Only the additional fuel for the degrees of curvature of ten, five, three, and one are presented. Table XVII presents the potential vehicle fuel savings that could be attained

TABLE XVI

VEHICLE FUEL EXPENDITURE FOR CURVATURE

Degree of Curvature	Without Scenario	With Scenario	Without Scenario	With Scenario
	Route A-A (75 vpd)		Route D-D (750 vpd)	
10	2608[a]	1864	166,008	137,330
5	720	595	82,350	68,124
3	422	350	47,659	39,426
1	408	338	37,727	31,210
	Route A-A (2700 vpd)		Route A-A (10,000 vpd)	
10	733,234	606,568	2,715,680	2,246,544
5	383,913	317,592	1,421,899	1,176,266
3	236,155	195,359	874,648	723,552
1	191,066	158,059	707,651	585,404

[a] All fuel in gallons.

TABLE XVII

POTENTIAL SAVING THROUGH ROUTE REALIGNMENT

Item Designation	Without Scenario	With Scenario	Without Scenario	With Scenario
	Route A-A (75 vpd)		Route D-D (750 vpd)	
Savings	2,200	1,528	128,282	106,112
Total Fuel	209,505	145,510	2,178,881	1,802,479
Percent Saving	1	1	6	6
	Route A-A (2,700 vpd)		Route A-A (10,000 vpd)	
Saving	542,168	448,510	2,008,028	1,661,190
Total Fuel	7,297,711	6,037,030	27,028,554	22,359,370
Percent Saving	7	7	7	7

by reducing the maximum degree of curvature from ten degrees to one degree. For example, vehicles traveling on route A-A (75 vpd and with the static scenario being implemented) would require an additional 2608 gallons of fuel over the life cycle for a curvature of ten degrees. By reducing the degree of curvature to one degree, only an additional 408 gallons of fuel would be needed to maintain the vehicle in its circular path. This represents a potential savings of 2200 gallons. The total vehicle fuel consumption at a ten degree curvature is 209,505 gallons. As a percentage of the total vehicle fuel consumption, the 2200 gallons would represent a potential savings of approximately one percent. The potential savings are proportionately low for this road type and route because of the very low speed, i.e., maximum 20 mph. For the other road types, the average vehicle speed is greater and the potential energy saving is proportionately larger. The results for the 750 vpd of route D-D and 2,700 and 10,000 vpd of route A-A are presented in Table XVII.

In general, realignment of the route in steep sloping areas would require large cut and fill operations. The potential fuel savings from the major realignment is less than 10 percent and by itself this would not justify realignment on an energy or fuel cost basis. However, considering the other highway benefits of realignment such as safety, comfort of ride, time savings, etc., the reduction of curvature by realignment may be justified on a life cycle basis.

Areas of relatively flat topography would require less cut and fill operations and realignment may be justified more readily on an energy or fuel cost basis. Low volume roads of type III and type IV do not readily permit as much economic and energy savings as roads of higher standards because of their low speeds. Upgrading the road to a higher standard through improved surface and geometrics permits higher operating speeds of the vehicles. At higher speeds, vehicles consume exponentially more fuel for the same degree of curvature than for lower speeds. Therefore, improvements in the geometric standards which permit higher operating speeds may increase the total life cycle energy and cost.

Results of the Grade Reduction Analysis

Appendix B contains the computer analysis of the grade reduction for route D-D. The energy and cost comparisons between excavation and vehicle fuel consumption are analyzed under the dynamic scenario's conditions of decreased traffic growth, increased vehicle fuel efficiency, and increased vehicle fuel cost. The results of the cost and energy tradeoffs between increased excavation and lower vehicle fuel expenditure are tabulated after the source deck portion of the program. The results indicate that it is neither cost nor energy advantageous to reduce the grades along the entire length from the point of initial ascent to end point of descent. A reduction to seven percent positive gradient, while the negative remains at eight percent, increases the systems cost by an additional 4,859,834 dollars and increases the systems energy by an additional 263,286 M.Btu. Gradient reduction over the entire route length to any other final grade combination would increase the systems cost and energy by an even greater amount. Therefore, grade reduction over the entire route length is neither energy--nor cost--effective.

The cost and energy losses are caused by large excavation quantities which are an exponential function of the excavation length and lower vehicle fuel expenditures which are a linear function of the excavation length. However, the cost of both energy and dollars of short length grade reductions is more than offset by the reduced vehicle energy requirements. In this analysis the input data for the excavation length are entered as though it is short segment, independent of the other portions of route D-D. The elevations of initial station and final station are computed separately and entered as the points of initial ascent and final descent. Only the horizontal curves which are located on this segment are considered and their stations are changed to correspond to the stations of the segment. Since the excavation areas of the initial and final stations are zero, only the cross sections between these stations are utilized in the volume calculations.

Initially, the excavation lengths of 3000 feet (7+00 to 10+00),[1] 5000 feet (6+00 to 11+00), 7000 feet (5+00 to 12+00), and 9000 feet (4+00 to 13+00) are analyzed. The initial results of Table XVIII indicate that an optimal length for both energy and cost savings is between the 3000 foot and 5000 foot excavation lengths. The 4000 foot (6+00 to 10+00) excavation length is entered and this has the highest cost and energy saving of all the excavation lengths. This is shown graphically in Figure 10.

For the 4000 foot length, the vehicle energy expenditures at the initial eight percent positive and negative gradients is 703,524 M.Btu and the vehicle fuel cost at the initial gradients is 9,661,100 dollars. At the energy and cost optimal gradients of six percent positive and two percent negative gradient, the quantity of excavation is 1,253,734 cu yd. At an energy expenditure of 0.059 M.Btu per cu yd, the energy requirement

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[1] To be consistent with the derivations, tables, and computer analysis, all stations are presented in 1000-foot increments.

TABLE XVIII

OPTIMAL COST AND ENERGY SAVINGS THROUGH GRADE REDUCTION

Section Length	Initial Station	Final Station	Cost Saving	Gradient		Energy Saving	Gradient	
				Left	Right		Left	Right
3000[a]	7+00[b]	10+00	2,557,122[c]	2[d]	6	193,478[e]	6	3
4000	6+00	10+00	3,742,976	6	2	288,186	6	2
5000	6+00	11+00	1,976,549	7	5	177,535	6	4
7000	5+00	12+00	322,514	7	5	104,678	6	5
9000	4+00	13+00	0	8	8	0	8	8

[a] In ft.

[b] In 1000 ft station.

[c] In constant 1980 dollars.

[d] In percent.

[e] In M.Btu.

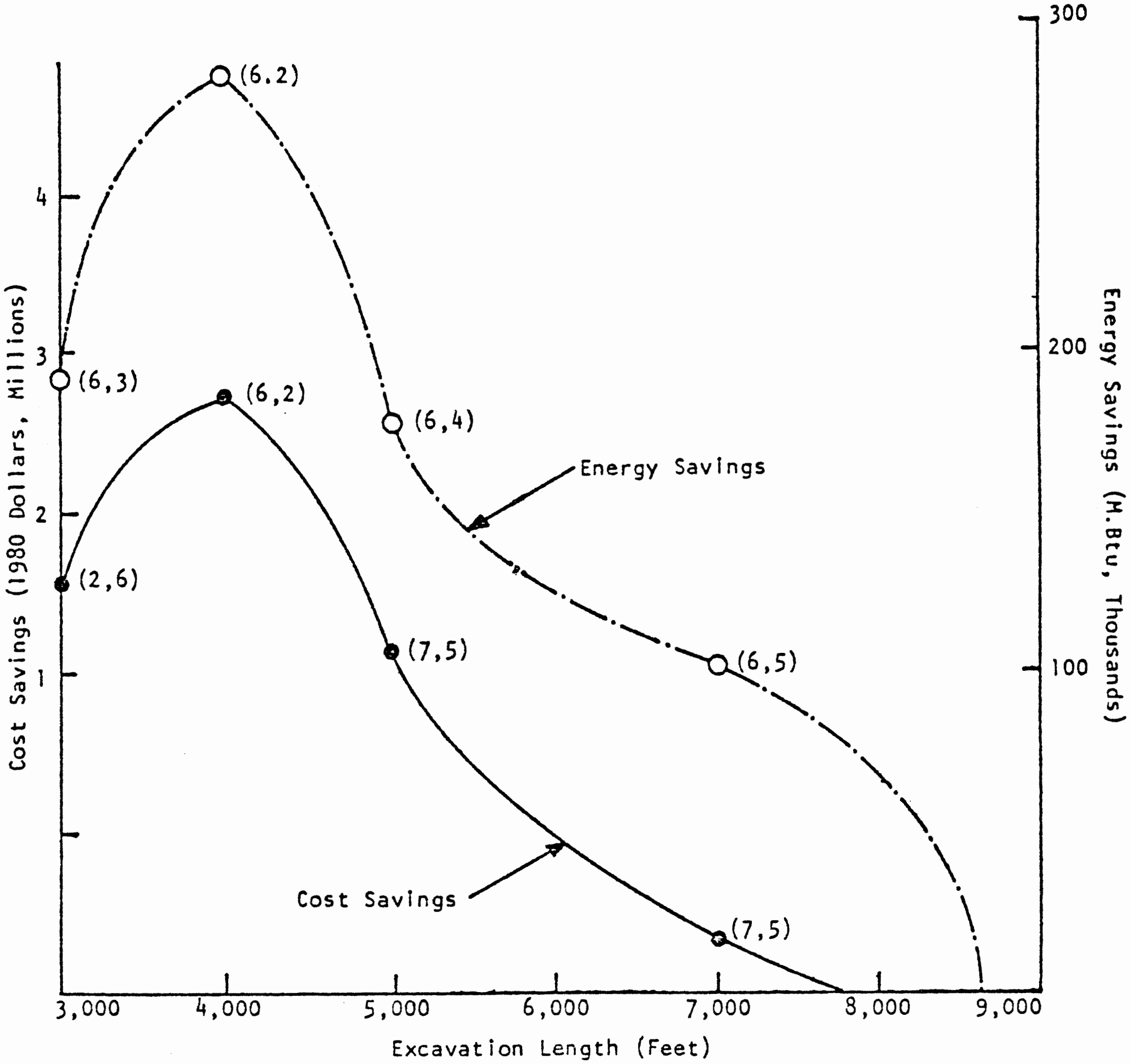
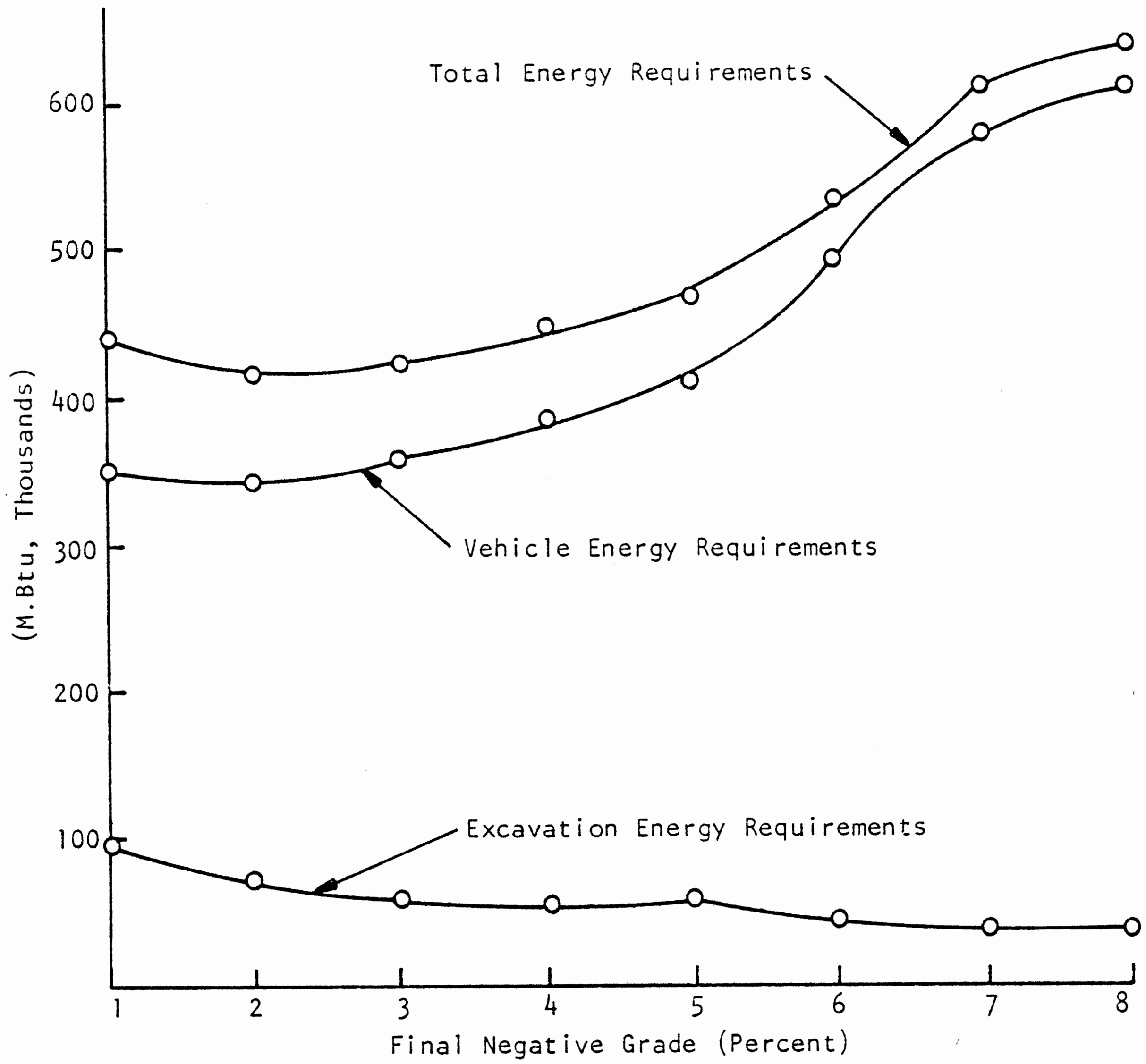


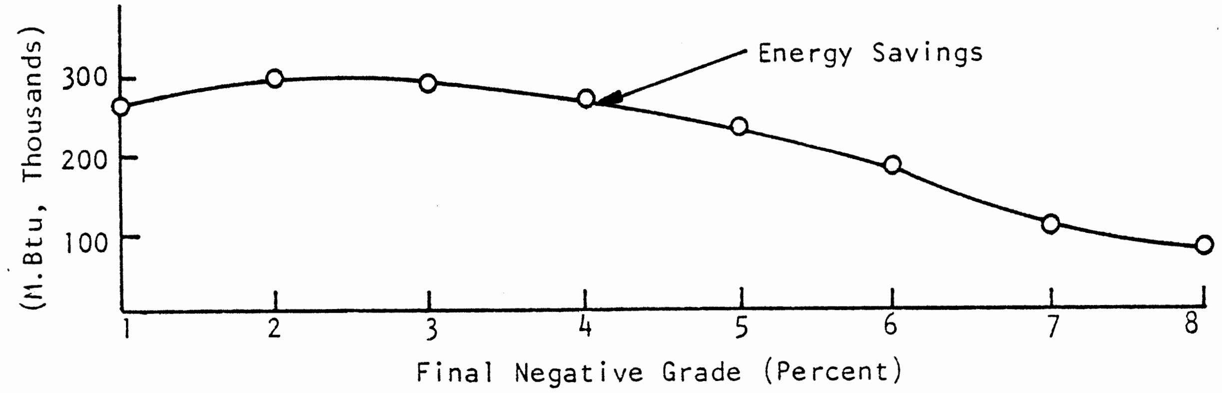
Figure 10. Energy and Cost Savings as a Function of Excavation Length for Route D-D

of excavation is 73,970 M.Btu to reduce the positive and negative eight percent gradients to the optimal combination. At the optimal combination vehicle expend 341,368 M.Btu over the life cycle. The addition of the excavation energy requirement to this vehicle energy expenditure produces a total of 415,338 M.Btu (Figure 11). The difference of this total and the initial vehicle energy expenditure is a life cycle savings of 288,162 M.Btu (lower portion of Figure 11). The excavation energy requirements to the six percent positive gradient and all possible negative grades and vehicle energy expenditures are shown in Figure 11 and the vehicle fuel savings are presented in the lower portion of Figure 11. The savings represent the difference of the excavation energy expenditure (i.e., from the initial eight percent positive and negative gradients to the lower six percent positive and negative gradients) and the resulting fuel savings of vehicles driving over these lower gradients.

At a nominal cost of one dollar per cu yd, the cost of grade reduction to the optimal combination is $1,253,374. The life cycle vehicle fuel cost at the optimal combination is $4,664,760. The total of vehicle fuel cost and excavation cost at the optimal combination is $5,918,134. The difference of initial fuel cost and the combined excavation and fuel cost at the optimal combination is $3,742,976. This is the saving for reducing only the segment from station 7+00 to station 10+00 to the optimal grade combination. The cost requirements and resulting savings for excavation to the positive 6 percent gradient are presented in Figure 12. Both the optimal grade combination and length are identical for cost and energy savings. This is a coincidence of the parameters of this investigation. Other parameters, e.g., higher excavation and fuel costs, would result in different optimal grade combination and lengths. In general,

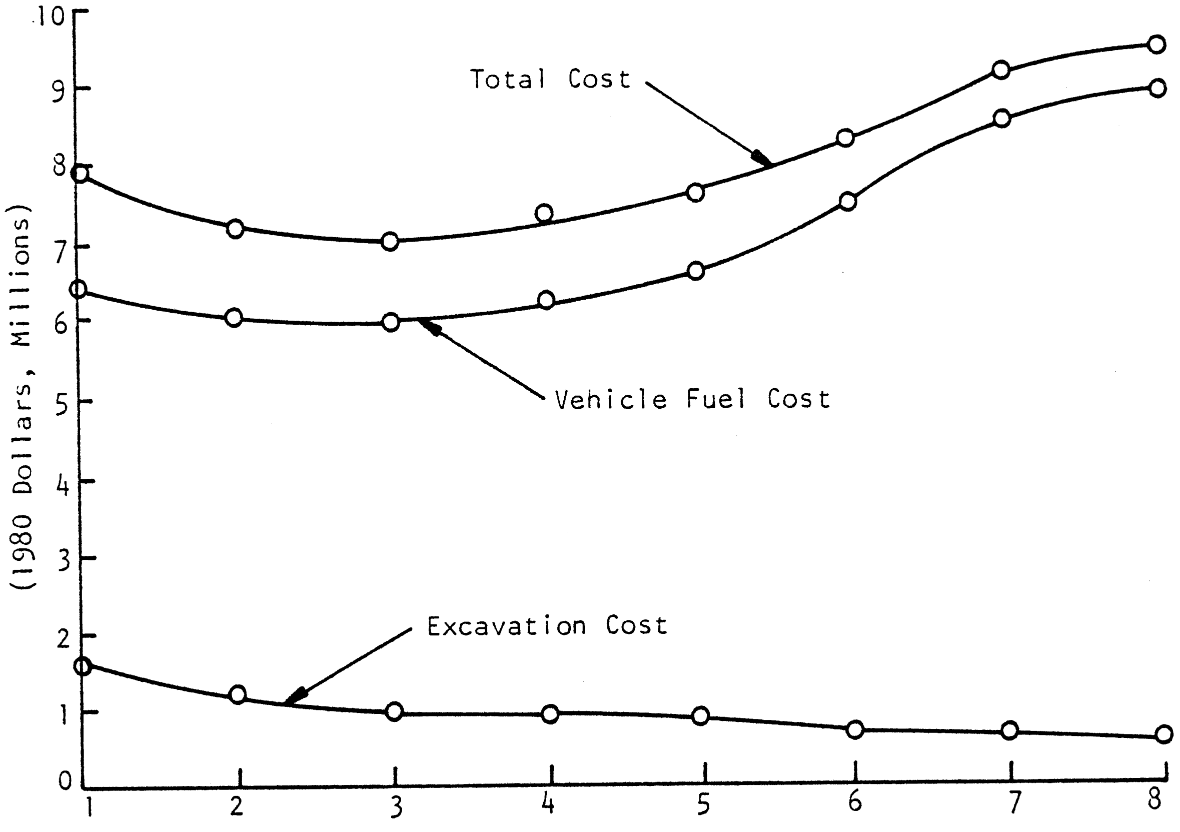


(a) Energy Requirements

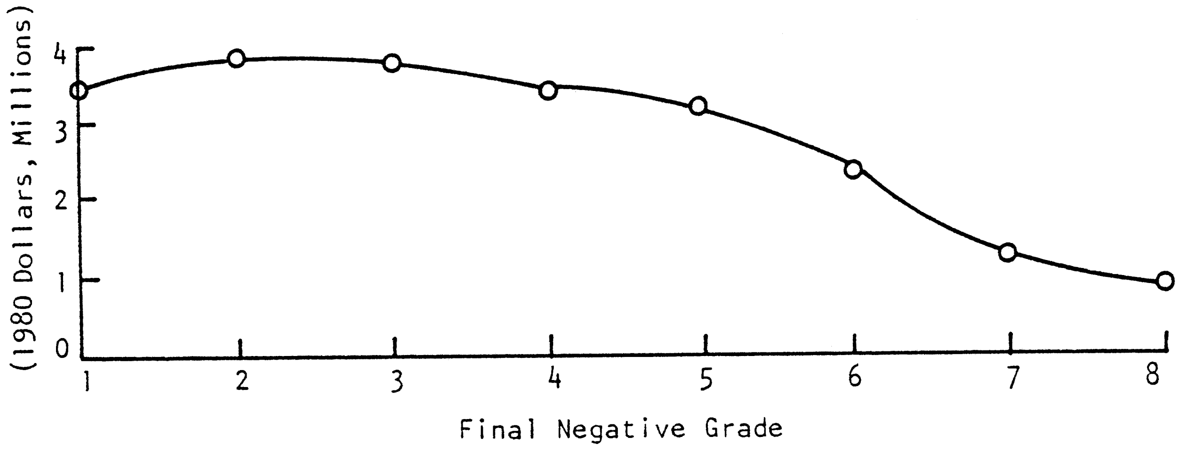


(b) Energy Savings

Figure 11. Energy Savings and Requirements for Route D-D
With 6 Percent Positive Grade



(a) Cost Requirements



(b) Cost Savings

Figure 12. Cost Savings and Requirements for Route D-D With 6 Percent Positive Grade

for a given set of traffic and excavation parameters, there is an optimal grade combination and optimal excavation length which minimized cost and energy expenditures. Shorter excavation lengths than the optimal length require flatter grades for maximum cost and/or energy savings. The optimal excavation length is a tradeoff between vehicle fuel savings, which is a linear function of the length, and the cost and energy of excavation, which are exponential functions of the length. The energy and cost requirements for long excavation lengths rapidly exceed the fuel savings. An interpretation of this analysis surmises that for long section lengths, i.e., several miles, it is both energy and cost efficient to limit the grade reduction to only a portion of the crest and not necessarily the entire section length. This limited excavation should extend only to the optimal grade combination.

Significance of Grade Reduction and Route Realignment Upon the Preliminary Selection

Under the conditions of the scenario, route A-A is deemed the most cost and energy efficient selection for a traffic flow of 10,000 vpd (divided four-lane). Using Tables VII and XV, route A-A provides a life cycle energy savings of 217,691 M.Btu (2,846,957 - 2,629,266) and a life cycle cost reduction of $2,463,593 (40,080,146 - 37,616,553) as compared with route D-D. By including the grade reduction from stations 6+00 to 10+00, the life cycle cost of route D-D is $36,337,170 (40,080,146 - 3,742,976) and the life cycle energy expenditure is 2,558,771 M.Btu (2,846,975 - 288,186). Thereby, route D-D becomes the most energy and cost efficient route under the conditions of the dynamic scenario.

The excavation end points of stations 6+00 and 10+00 (4000 ft) are general points and a further extension of the analysis may determine larger energy and cost savings with more precise excavation lengths. In addition, the soil from the excavation of the crest portion may be used to straighten the horizontal profile at a much lower energy and cost expenditure. If the degree of curvature could be reduced from ten degrees to one degree with this excess soil there would be an additional fuel cost savings of $2,846,835 and a corresponding energy savings of 208,572 M.Btu. The life cycle energy expenditure for route D-D would then be 2,350,199 M.Btu. The life cycle cost for route D-D would be $33,490,335.

Similar investigations could be conducted for the other higher gradient routes (C-C and E-E) to determine potential energy and cost saving through grade reduction and realignment under the conditions of the static and dynamic scenarios.

CHAPTER VI

SENSITIVITY OF THE MODEL'S VARIABLES

Sensitivity Investigation of the Model

As investigated in the previous chapter in the scenario analysis, the choice of a route selection to increase the overall energy conservation and/or cost effectiveness may be influenced by developments over the long-term period. Highway planners cannot precisely estimate or determine many of the long-term variables with certainty. This uncertainty concerning variance of the input variables from initial expectations may influence the amounts and/or cost of the system's energy. Even the short-term variables, such as construction requirements, may be difficult to quantify precisely.

It is the purpose of this chapter to examine, analyze, and identify those variables which influence the total energy requirements and/or the cost. A small error or variation in the input data may be magnified or minimized through the formulation of the equations and the precision of the mathematical algorithm which structure the model. The sensitivity investigation permits a highway planner, knowing that the accuracy of his input data is within a certain range, to predict the accuracy of the output data, i.e., the results. Conversely, if a highway planner desired to obtain a confidence level in his results, the planner may determine how accurate the input data must be for that confidence level. It is anticipated that the difference between the predicted and actual values of some variables, may significantly change the results, while other variables may exhibit wide variations without strongly affecting the total energy or total cost. Therefore, in order to meet the standards of the confidence level, the highway planner should determine which input variables must be precisely estimated while the less sensitive variables may require only a general estimate.

Distinction of Input Variables

The input variables are separated into two classifications. The first classification includes those variables which are under the control of the planner and are subject to relatively precise determination. Examples of this classification are the horizontal alignment and grades of the route. Once these grades and alignment are selected, their values remain constant throughout the analysis period. For example, during the planning phase, the selected grades or alignment may be changed; however, this requires a separate analysis. During the construction phase, minor variations from the selected alignment and grades may occur, but these may be limited with a minimum of quality control. During the operational phase, realignment of the route or grade reduction may be instituted, but this would also require a separate investigation. Therefore, during the life cycle of the highway, the grade and alignment are held constant and excluded from the sensitivity analysis.

The second classification of variables includes those which the highway planner may only estimate and about which some uncertainty exists. Examples of this group are the traffic volume and the construction expenditures for both energy and cost. In this chapter the sensitivity investigation is confined to the second classification.

Methodology of the Sensitivity Investigation

The sensitivity of the model is investigated by entering a range of numerical values for each variable that is being investigated. The other input variables of the model remain constant and receive the same numerical magnitude as in the model demonstration of Chapter V. Each variable that is being analyzed is given a range and the results of the model are compared for each numerical value of the range. The relative sensitivity of the model to a particular input may be noted by either graphing the results of each range or by calculating an index to identify the relative magnitude of the model's sensitivity to that variable as compared to the other input variables. The index, employed in this investigation, is the percentage change of the results from the initial results of Chapter V divided by the variable range in percentage. Larger values of this index indicate greater model sensitivity to this variable.

In this investigation, both the energy and cost results from route D-D (8 percent negative and positive grades) are analyzed. This route is selected because of its steep grades and large angles of curvature. This route is analyzed with the static scenario being implemented.

The first variable investigated is the composition of the vehicle fleet. In Chapter V the vehicle fleet consisted of 74 percent passenger cars, 10 percent pickups, 8 percent SUT, and 4 percent each for the large gasoline and diesel powered trucks. This vehicle fleet or traffic composition is designated as 74-10-8-4-4, which represents the percentage composition of each vehicle classification. Since the passenger cars are the least energy-consuming component of this traffic fleet, increases or decreases of the percentage of passenger cars should significantly affect the model's results. Two vehicle fleets are entered into the model and these are 61-15-12-6-6 and 87-5-4-2-2. The relative proportions of vehicle class II through V are the same for each traffic fleet. The second variable investigated is traffic volume. The initial traffic volume is entered as 80 percent of the traffic volume of Chapter V (-20 percent variation). Other traffic volumes are 90 percent, 110 percent, and 120 percent of the traffic volume of the model demonstration sample. The third variable is construction expenditures. This variable ranges from -50 percent (one-half of the estimate) to +100 percent (double the estimate). These three variables are investigated for both the total energy and total cost expenditures.

Results of the Sensitivity Investigation

The total life cycle energy requirements for ranges of the three variables are presented in Table XIX (traffic composition), Table XX (traffic volume), and Table XXI (construction estimate) for each of the four road types of route D-D. These data are plotted in Figure 13 for the earth surface road (Type IV) and the four-lane paved highway (Type I). Energy sensitivity indices for the three variables and four road types are presented in Table XXII.

Excluding the earth surfaced road (Type IV), the energy results of the model are most significantly changed by the traffic volume, as indicated by the sensitivity indices of Table XXII. The four-lane paved highway has the largest index of 0.93 for this variable. The value of this index is derived by dividing 3,430,330 by 4,216,071 (-18.6 percent) and dividing 4,999,264 by 4,216,071 (+18.6 percent). The absolute sum of the percentage change (37.2 percent) of the system's results is divided by the variable range of 40 percent (+20 percent to -20 percent).

TABLE XIX

ENERGY SENSITIVITY OF TRAFFIC COMPOSITION

Variation (Approx.)	Percentage of Passenger Cars	Road Type			
		IV	III	II	I
-18%	61	41,131[a]	460,873	1,353,515	4,853,962
0	74	30,665	416,182	1,181,848	4,216,071
+18%	87	21,714	364,965	1,008,367	3,575,633

[a] In M.Btu.

TABLE XX

ENERGY SENSITIVITY OF TRAFFIC VOLUME

Variation	Road Type			
	IV	III	II	I
-20%	26,550[a]	357,814	967,924	3,430,330
-10%	28,949	382,216	1,071,249	3,822,564
0	30,655	416,182	1,181,848	4,216,071
+10%	34,014	441,087	1,283,297	4,607,030
+20%	35,723	475,483	1,387,217	4,999,264

[a] In M.Btu.

TABLE XXI

ENERGY SENSITIVITY OF CONSTRUCTION ESTIMATE

Variation	Road Type			
	IV	III	II	I
-50%	30,028[a]	412,633	1,120,605	4,069,834
0	30,665	416,182	1,181,848	4,216,071
+50%	31,302	419,731	1,243,091	4,362,308
+100%	31,939	423,280	1,304,334	4,508,545

[a] In M.Btu for combined construction and maintenance.

TABLE XXII

ENERGY SENSITIVITY INDICES

Variable	Road Type				
	IV	III	II	I	Average
Traffic Composition	1.76	0.64	0.81	0.84	1.01
Traffic Volume	0.75	0.71	0.89	0.93	0.82
Construction	0.04	0.02	0.10	0.07	0.06

The indices for the other road types are obtained in the same manner. The largest indices for any road type and for the three variables is 1.76 for the variance of traffic composition using the earth surfaced road. The expenditure of energy is extremely large for truck traffic over this surface and, therefore, this road type is very sensitive to variance of the truck composition of the vehicle fleet. The total energy expenditure of the system is relatively insensitive to variations of the construction energy estimate. Each type of road does not require precise estimation of construction energy expenditures to insure the reliability of the total results. The steepness of the slopes in Figure 13 indicates the relative sensitivity of the system's energy to variations of these three input variables.

The data from the cost sensitivity investigation are presented in Table XXIII (traffic composition), Table XXIV (traffic volume), and Table XXV (construction estimate). In Table XXVI, the cost indices have results similar to the energy indices. The most sensitive variables are traffic composition and traffic volume. The total cost expenditure for the system is relatively insensitive to fluctuation in the construction cost estimate. The paved two-lane (Type II) is more sensitive to this variable because of its high ratio of construction cost to vehicle fuel expenditure. Therefore, precise estimates of construction energy or construction cost are not required to insure the overall model accuracy. The plot of these three cost variables and total system's cost (Figure 14) are similar to the energy results (Figure 13) for the earth surfaced road and four-lane paved highway.

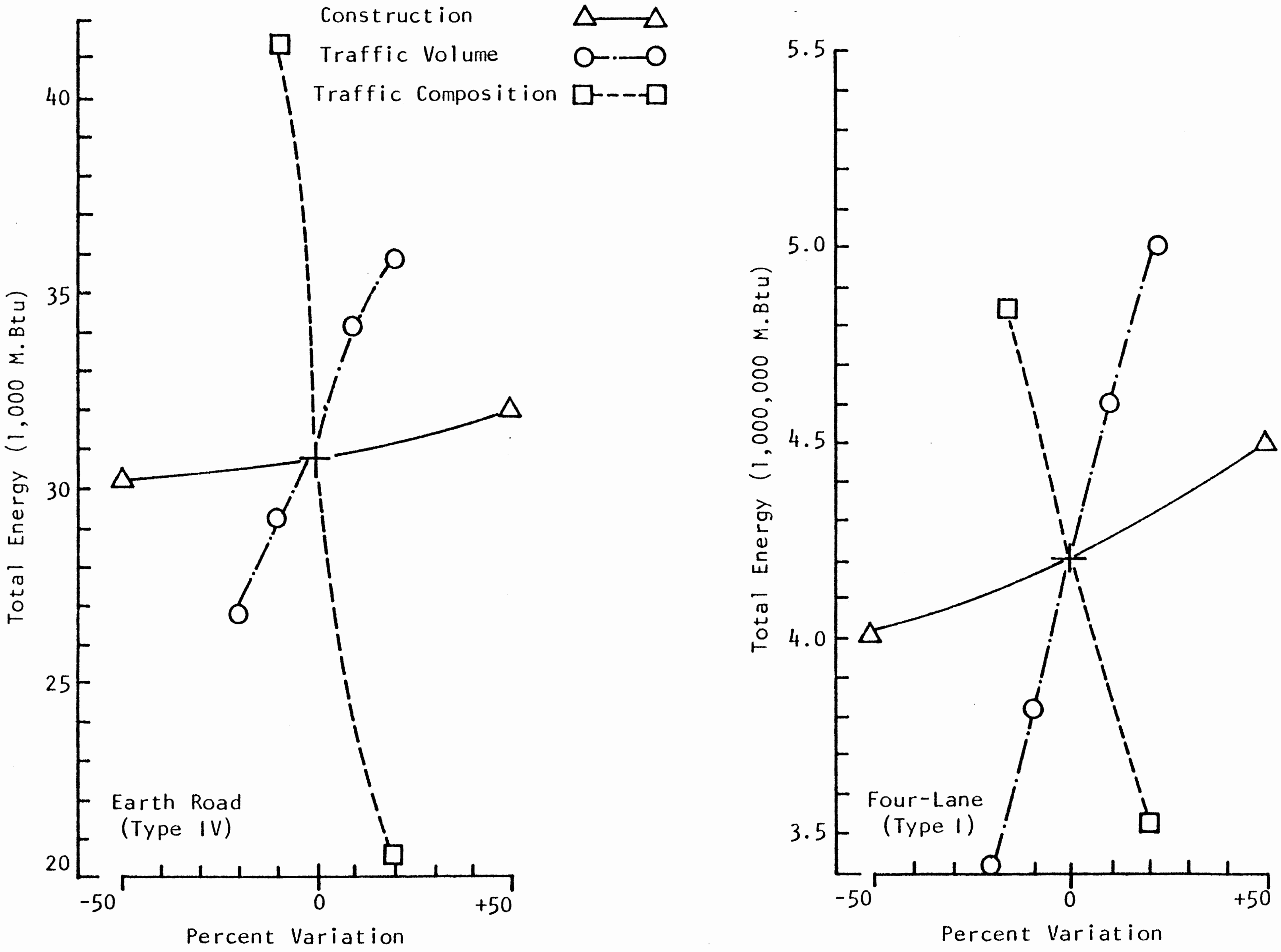


Figure 13. Total Energy Sensitivity to Input Variation

TABLE XXIII

COST SENSITIVITY OF TRAFFIC COMPOSITION

Variation (Approx.)	Percentage of Passenger Cars	Road Type			
		IV	III	II	I
-18%	61	346,527[a]	5,144,382	12,150,483	40,764,570
0%	74	266,646	4,802,881	10,838,897	35,890,360
+18%	87	198,879	4,411,464	9,512,889	30,995,870

[a] In 1980 constant dollars.

TABLE XXIV

COST SENSITIVITY OF TRAFFIC VOLUME

Variation	Road Type			
	IV	III	II	I
-20%	233,738[a]	4,342,808	7,152,706	29,696,075
-10%	252,919	4,535,750	9,967,853	32,788,147
0%	266,646	4,802,881	10,838,897	35,890,360
+10%	293,435	4,999,826	11,639,056	38,972,291
+20%	307,109	5,270,430	12,458,964	42,064,364

[a] In 1980 constant dollars.

TABLE XXV

COST SENSITIVITY OF CONSTRUCTION ESTIMATE

Variation	Road Type			
	IV	III	II	I
-50%	248,992[a]	4,698,973	9,595,109	33,410,610
0%	266,646	4,802,881	10,838,897	35,890,360
+50%	284,300	4,906,789	12,082,685	38,370,110
+100%	301,954	5,010,697	13,320,473	40,849,860

[a] In 1980 constant dollars for combined construction and maintenance.

TABLE XXVI

COST SENSITIVITY INDICES

Variation	Road Type				
	IV	III	II	I	Average
Traffic Composition	1.54	0.42	0.68	0.76	0.85
Traffic Volume	0.69	0.48	1.22	0.87	0.82
Construction	0.13	0.04	0.23	0.14	0.14

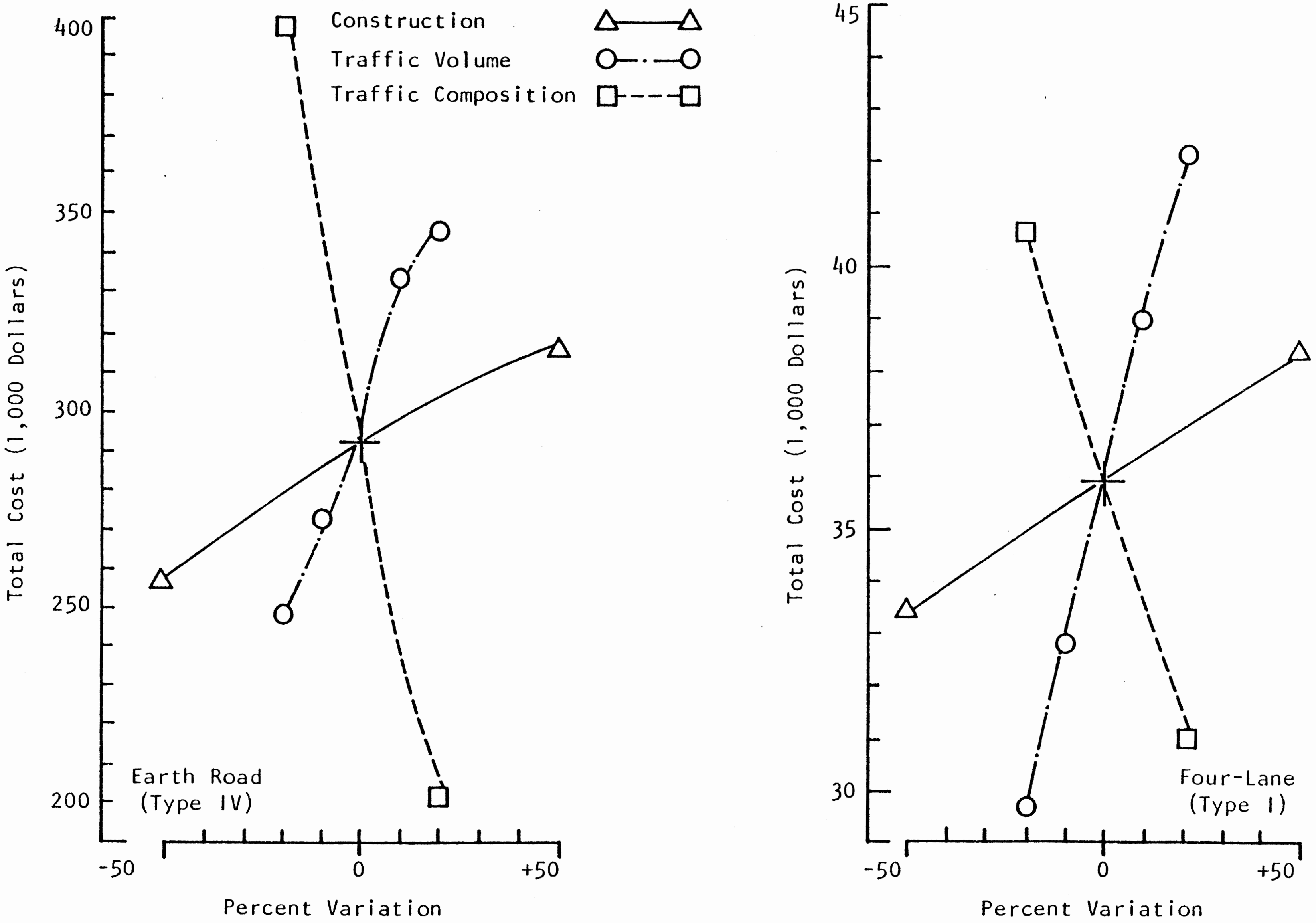


Figure 14. Total Cost Sensitivity to Input Variation

Results of Fuel Price Sensitivity

Similar to the previous investigation, the price or cost of vehicle fuel is given a lower bound of 50 percent of the price of Chapter V, i.e., 50 cents per gallon, and an upper bound of 2 dollars per gallon. The results of this analysis are presented in Table XXVII. The cost results for each of the four road types are sensitive to the fuel price with the gravel road being the most sensitive. This is directly proportional to the gravel road having the lowest maintenance and construction cost per vehicle. The average value for this index is slightly greater than the average index for the traffic composition.

TABLE XXVII

COST SENSITIVITY OF VEHICLE FUEL PRICE

Variation	Road Type			
	IV	III	II	I
-50%	150,977[a]	2,505,349	6,663,237	20,424,930
0%	266,646	4,802,881	10,838,897	35,890,360
+50%	382,315	7,100,414	15,014,558	51,355,790
+100%	497,984	9,397,946	19,190,218	66,821,220
Index Average	0.87	0.96	0.77	0.86

[a] In 1980 constant dollars.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The general trend for the United States is increased dependence upon foreign sources of petroleum energy. To reduce this dependence the nation must increase the conservation of petroleum and substitute more abundant energy resources for petroleum. The transportation sector consumes nearly one-half of all petroleum products, the bulk of which is expended in highway transport. As part of the conservation effort, the highway system and its vehicles must be closely examined to determine total energy expenditures.

The primary objective of this research is to develop a LCC energy model to assess the total or long-term energy expenditures and energy-related costs of alternative highway proposals. The underlying hypothesis of this treatise is based upon the assumption that diverse and fragmented energy data can be incorporated into a systems and life cycle framework to predict the long-term energy costs of alternative route proposals so that these proposals may be compared by their total life cycle energy and life cycle energy-related costs.

This research demonstrates the validity of the hypothesis by analyzing many of the energy consuming elements, i.e., design, operation, maintenance, etc., of the highway system to predict their energy and energy-related cost expenditures. The total energy expenditure of the highway system is the sum of the energy for operating vehicles, construction, and maintenance activities. Energy estimating techniques are developed for each of the system components by assigning to their elements or subcomponents recent energy estimates from the technical literature. The life cycle energy cost is the integration of the components' energy expenditures. A systems approach is utilized to develop and express the energy interreaction and interdependencies of the subsystems throughout the life of the highway. The expression and integration of the subsystems are accomplished through the framework of a PL/I computer program.

Conclusions

The principle conclusions of this research are:

1. The primary objective of this research is the development of a method to provide highway officials with the long-term assessment of energy expenditures. Using the method developed in this research, highway officials have the capability to ascertain the energy consequences of their decisions in order to reduce the energy expenditures by employing alternative design and construction strategies. The life cycle energy estimate is a systematic method of comparing relative energy efficiencies for competing proposals. Using this method, large initial expenditures may be justified in terms of lower subsequent vehicle and maintenance energy costs. With the current energy crisis, highway officials and planners must seek greater long-term energy efficiencies to maintain the highway transportation network which is essential to the economic welfare of this nation.

2. Design standards that increase energy consumption, such as sharp curvature, rough surfaces, and steep grades, are particularly

significant for routes with a large percentage of truck traffic. Routes with a high concentration of passenger cars are less susceptible to energy-saving improvements. Therefore, the need for energy analysis and improvement for highways having a larger composition of truck traffic is greater than for similar highways whose predominant vehicle is the lighter passenger car.

3. Through the general formulas derived in this research, the amount of excavation for reducing an initial set of design grades to a lower, more energy-saving combination of grades may be determined for steep or rolling terrain. Both the associated vehicle economic and energy savings or losses for this grade reduction may be predicted. For specific section and traffic parameters there is an optimal set of grades and optimal excavation length which minimizes cost and/or energy expenditures. It is neither cost nor energy efficient to excavate a section whose length is longer than the optimal excavation length. For these long sections, excavation should be limited to the optimal length and grades at the crest. For lengths shorter than the optimal length, a separate analysis should be conducted for minimizing cost and/or energy expenditures.

4. Under the condition of a dynamic scenario, the life cycle energy is less than it would be if key parameters are constant throughout the analysis period. The key parameters are a reduction in traffic growth and increased fuel efficiency of passenger cars. For the cost analysis, a third parameter is included in the scenario to account for an increase in the cost of vehicle fuel for a fuel price rise greater than the general inflation rate. With the three variables of the scenario implemented, the overall life cycle cost increases for each of

the four traffic volumes is relatively the same whether the scenario is implemented or not. By including grade reduction and route realignment for the higher gradient routes, the total life energy and cost is lowered. With the lowered total cost and energy expenditures, the higher gradient routes may become more long-term energy conserving selections.

5. The total life cycle energy of the model is sensitive to variations of vehicle fuel efficiency, traffic volume, and the truck composition of the traffic fleet. The total energy is relatively insensitive to variations of the combined construction and overlay energy estimated. Therefore, only general or parametric estimates of the construction and/or overlay energy are required. Other variables that are selected by the planner, such as grades and alignment, remain constant during the analysis period and are excluded from the sensitivity investigation.

6. The total life cycle cost possesses similar sensitivity to the above variables and, in addition, the total cost is sensitive to variation of the price of vehicle fuel.

Recommendations

For continuance of research in this important topic, the following recommendations are suggested:

1. The future relevance and importance of energy criteria in highway decision-making is uncertain. Therefore, the model is structured as a simulation technique to serve as an additional, and not necessarily controlling, parameter. Therefore, the model is geared towards an energy analysis of specific previously selected highway alternatives. If energy criteria become a more prominent factor in highway decision-making, the input of ranges of select design variables may prove beneficial for

determining more nearly optimal, energy-conserving designs. Since the long-term ranges of the variables are uncertain, it may be valuable to attach stochastic parameters to these variables so that probabilistic estimates may be included with the life cycle energy costs.

2. The validity of the life cycle energy model is largely dependent upon the accuracy and timeliness of its data base. As the cost of energy and energy-intensive products increases, greater energy savings will be sought. For example, the motoring public is expected to purchase cars that use less gasoline as the cost of gasoline increases. This may necessitate periodic updating of the vehicle operations subsystem's data base to reflect the shift towards vehicles that use less energy. Also, the other subsystems may require updating as contractors and material suppliers implement greater energy efficiencies.

3. It is also recommended that all future vehicle tests or evaluations by government agencies be conducted under a series of conditions that include the effects of various grades, curvatures, and surface conditions. From the data accumulated in these tests, the data base of this model can be periodically updated to include recent developments in vehicle design and performance. There is a need for further research to evaluate the effect of weather or climate conditions on the energy consumption of vehicles traveling over various pavement systems. Also, research should continue to estimate how different surface distresses, such as rutting and consolidation disturbances, influence vehicle fuel performance. It would be valuable to be able to express vehicle energy expenditure as a function of a commonly used system such as a present serviceability index. The model should also be extended to include the effects of congestion under a variety of traffic conditions and

motorists' objectives. The model should be extended to include additional maintenance activities whose magnitude would be determined by a desired level of service, e.g., mowing, snow plowing, etc. The level of service would be dependent upon the amount of highway revenue and correspondingly the extent of motor vehicle usage. Additional data would be required to express a more definite relationship between the level of service and the variables which the level of service depends upon.

4. A large, extensive computer program would be helpful in determining the cost and energy expenditures for numerous routes, on the basis of coordinates and corresponding elevations rather than cross section data. A large number of routes could be tested and compared for the least life cycle cost and/or energy expenditure. Each route may have frequent grade changes and various degrees of curvature throughout its length. By using coordinates, the total excavation and fill requirements could be estimated for any curvature or grade change.

5. The sensitivity analysis should be extended to include a large number of scenarios and input variations such that the route selection could be analyzed under many future conditions. The user should be cognizant that the more optimal route may become less advantageous depending upon the input parameters.

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APPENDIX A

VEHICLE OPERATIONS DATA BANK

The following columns are the data banks which formulate the vehicle operations subsystem. The first set of data (designated "*GRADE_P*") are the fuel consumption in gpm for driving on level tangent and positive grades to 10 percent. The data columns from left to right are 0 percent to 10 percent grade, in ascending order. The designation to the left of the data columns identifies the data card, for example:

GR 3 10 P
Positive grade data card
The speed of the vehicle in miles per hour
In this example it is 10 mph
The class of vehicle:

1. For passenger cars
2. For pickup trucks
3. For single unit trucks
4. For gasoline powered trucks
5. For diesel powered trucks

Identifies the card as a grade data card

The negative grades follow the same format with an "N" in place of a "P" to designate the negative grades. The type of pavement data card is described similarly with "PA" in place of "GR". The dimensionless pavement factors are tabulated left to right as:

Data column 1: high quality surface
Data column 2: poorly patched surface
Data column 3: gravel surface
Data column 4: earth surface.

The dimensionless curvature factors are also designated in the same manner with "CU" in place of "PA". Data columns 1 to 13 correspond to

0 degree curvature to 12 degree curvature.

The slow consumption factors are designated in gallons per speed change cycle as:

SL 1 10
Initial speed in mph
Vehicle class
Identifies the card as a slow consumption cycle data card

The data columns (from left to right) correspond to the final vehicle speed in 10 mph increments.

The stop cycle fuel consumption factors are designated in gallons as a function of the time the vehicle is halted:

SC 1 10
Initial speed in mph
Vehicle class
Identifies the card as a stop cycle data card

The data columns (from left to right) correspond to the time in one-half minute increments that the vehicle is halted and remains idling.

VEHICLE OPERATIONS SYSTEM DATA BANKS

The vehicle fuel consumption data banks are arrayed vertically in groups of seven which are interspaced by the name of the vehicle class. Each horizontal line in the group of seven represents the initial operating speed, starting at 10 mph and extending vertically to 70 mph.

Positive Grade Fuel Consumption Rates in GPM

0	1	2	3	4	5	6	7	8	9	10
Passenger Cars										
0.072	0.080	0.087	0.096	0.103	0.112	0.121	0.132	0.143	0.160	0.179
0.050	0.058	0.070	0.076	0.086	0.094	0.104	0.116	0.128	0.144	0.160
0.044	0.051	0.060	0.068	0.078	0.087	0.096	0.110	0.124	0.138	0.154
0.046	0.054	0.062	0.070	0.078	0.087	0.096	0.111	0.124	0.140	0.156
0.052	0.059	0.070	0.076	0.083	0.093	0.104	0.118	0.130	0.145	0.162
0.058	0.067	0.076	0.084	0.093	0.102	0.112	0.126	0.138	0.152	0.170
0.167	0.075	0.084	0.093	0.102	0.111	0.122	0.135	0.148	0.162	0.180
Pickup Trucks										
0.058	0.070	0.083	0.090	0.100	0.110	0.129	0.134	0.150	0.174	0.197
0.047	0.057	0.068	0.077	0.086	0.095	0.105	0.121	0.137	0.147	0.156
0.047	0.057	0.068	0.077	0.086	0.095	0.105	0.121	0.137	0.156	0.174
0.053	0.063	0.078	0.083	0.094	0.103	0.113	0.132	0.151	0.164	0.180
0.065	0.075	0.085	0.095	0.106	0.117	0.128	0.144	0.164	0.000	0.000
0.081	0.092	0.102	0.112	0.123	0.133	0.144	0.000	0.000	0.000	0.000
0.099	0.110	0.122	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

0	1	2	3	4	5	6	7	8	9	10
Single Unit Trucks										
0.074	0.094	0.120	0.143	0.175	0.195	0.225	0.255	0.289	0.324	0.357
0.059	0.080	0.112	0.140	0.167	0.190	0.214	0.254	0.295	0.344	0.394
0.067	0.094	0.121	0.150	0.181	0.206	0.232	0.268	0.305	0.000	0.000
0.082	0.112	0.141	0.173	0.210	0.228	0.000	0.000	0.000	0.000	0.000
0.101	0.130	0.159	0.194	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.122	0.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gasoline Powered Trucks										
0.365	0.405	0.475	0.540	0.615	0.735	0.858	1.027	1.195	1.340	1.490
0.208	0.289	0.364	0.462	0.555	0.685	0.813	0.000	0.000	0.000	0.000
0.164	0.253	0.342	0.474	0.618	0.800	0.000	0.000	0.000	0.000	0.000
0.163	0.275	0.390	0.560	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.195	0.344	0.485	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Diesel Powered Trucks										
0.213	0.273	0.331	0.388	0.443	0.496	0.547	0.595	0.640	0.679	0.713
0.124	0.199	0.275	0.350	0.427	0.504	0.578	0.651	0.727	0.000	0.000
0.104	0.185	0.269	0.358	0.457	0.562	0.000	0.000	0.000	0.000	0.000
0.107	0.191	0.286	0.402	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.128	0.219	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Negative Grade Fuel Consumption Rates in GPM

0	1	2	3	4	5	6	7	8	9	10
Passenger Cars										
0.072	0.060	0.045	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
0.050	0.040	0.027	0.022	0.021	0.021	0.021	0.021	0.021	0.021	0.021
0.044	0.033	0.022	0.016	0.014	0.013	0.013	0.013	0.013	0.013	0.013
0.046	0.035	0.025	0.018	0.014	0.012	0.012	0.012	0.012	0.012	0.012
0.052	0.041	0.030	0.025	0.021	0.018	0.014	0.013	0.010	0.010	0.008
0.058	0.048	0.036	0.037	0.030	0.027	0.022	0.018	0.014	0.011	0.008
0.067	0.058	0.048	0.043	0.039	0.036	0.031	0.027	0.022	0.016	0.013
Pickup Trucks										
0.058	0.049	0.040	0.036	0.032	0.032	0.032	0.032	0.032	0.032	0.032
0.047	0.036	0.027	0.022	0.020	0.019	0.018	0.018	0.018	0.018	0.018
0.047	0.036	0.028	0.024	0.020	0.017	0.015	0.013	0.012	0.012	0.012
0.053	0.046	0.039	0.033	0.028	0.024	0.020	0.015	0.010	0.010	0.010
0.065	0.060	0.054	0.047	0.041	0.035	0.030	0.024	0.018	0.014	0.010
0.081	0.077	0.074	0.067	0.059	0.053	0.047	0.037	0.027	0.019	0.011
0.099	0.098	0.098	0.089	0.081	0.073	0.065	0.053	0.041	0.028	0.015
Single Unit Trucks										
0.074	0.064	0.055	0.053	0.051	0.051	0.051	0.051	0.051	0.051	0.051
0.059	0.049	0.039	0.034	0.030	0.030	0.030	0.030	0.030	0.030	0.030
0.067	0.054	0.041	0.034	0.027	0.026	0.025	0.025	0.024	0.024	0.024
0.082	0.071	0.051	0.041	0.032	0.029	0.025	0.023	0.021	0.020	0.020
0.101	0.090	0.072	0.058	0.045	0.038	0.031	0.025	0.020	0.020	0.020
0.122	0.110	0.090	0.075	0.062	0.052	0.043	0.035	0.025	0.020	0.020
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

0	1	2	3	4	5	6	7	8	9	10
Gasoline Powered Trucks										
0.355	0.247	0.145	0.132	0.120	0.120	0.120	0.120	0.120	0.120	0.120
0.208	0.140	0.069	0.062	0.055	0.055	0.055	0.055	0.055	0.055	0.055
0.164	0.115	0.066	0.053	0.040	0.040	0.040	0.040	0.040	0.040	0.040
0.163	0.128	0.091	0.065	0.040	0.040	0.040	0.040	0.040	0.040	0.040
0.195	0.164	0.131	0.095	0.040	0.040	0.040	0.040	0.040	0.040	0.040
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Diesel Powered Trucks										
0.213	0.162	0.137	0.112	0.116	0.132	0.144	0.156	0.164	0.164	0.164
0.124	0.072	0.044	0.026	0.030	0.039	0.050	0.065	0.000	0.000	0.000
0.104	0.051	0.022	0.013	0.013	0.016	0.000	0.000	0.000	0.000	0.000
0.107	0.056	0.026	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.128	0.074	0.046	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.165	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Pavement Factors by the Quality of the Surface

	High Quality	Poorly Patched	Gravel	Earth
Passenger Cars	1.00	1.01	1.09	1.23
	1.00	1.05	1.13	1.28
	1.00	1.20	1.26	1.40
	1.00	1.34	1.56	1.73
	1.00	1.50	1.70	2.00
	1.00	0.00	0.00	0.00
	1.00	0.00	0.00	0.00
Pickup Trucks	1.00	1.00	1.07	1.33
	1.00	1.00	1.09	1.49
	1.00	1.01	1.16	1.67
	1.00	1.06	1.27	2.02
	1.00	1.16	1.34	0.00
	1.00	1.40	0.00	0.00
	1.00	0.00	0.00	0.00
Single Unit Trucks	1.00	1.03	1.24	1.46
	1.00	1.06	1.28	1.62
	1.00	1.07	1.45	2.16
	1.00	1.08	1.58	2.46
	1.00	1.20	1.69	0.00
	1.00	0.00	0.00	0.00
	1.00	0.00	0.00	0.00
Gasoline Powered Trucks	1.00	1.01	1.07	1.06
	1.00	1.10	1.27	1.80
	1.00	1.20	1.59	0.00
	1.00	1.35	1.75	0.00
	1.00	0.00	0.00	0.00
	1.00	0.00	0.00	0.00
	1.00	0.00	0.00	0.00

	High Quality	Poorly Patched	Gravel	Earth
Diesel Powered Trucks	1.00	1.01	1.07	1.06
	1.00	1.10	1.27	1.80
	1.00	1.20	1.59	0.00
	1.00	1.35	1.75	0.00
	1.00	0.00	0.00	0.00
	1.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00

Curvature Factors by the Degree of Curvature

0	1	2	3	4	5	6	7	8	9	10	11	12
Passenger Cars												
1.000	1.000	1.001	1.002	1.002	1.003	1.004	1.005	1.005	1.006	1.008	1.010	1.020
1.000	1.001	1.002	1.003	1.004	1.005	1.006	1.007	1.008	1.010	1.030	1.070	1.110
1.000	1.005	1.010	1.016	1.022	1.028	1.034	1.040	1.080	1.140	1.200	1.280	1.360
1.000	1.015	1.031	1.048	1.065	1.082	1.120	1.170	1.230	1.340	1.480	1.620	1.800
1.000	1.025	1.054	1.090	1.120	1.180	1.250	1.430	1.610	1.820	2.070	2.200	2.500
1.000	1.040	1.080	1.132	1.200	1.300	1.400	1.900	0.000	0.000	0.000	0.000	0.000
1.000	1.060	1.120	1.182	1.300	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pickup Trucks												
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.000	1.000	1.000	1.001	1.001	1.002	1.005	1.010	1.020	1.040	1.080	1.100	1.130
1.000	1.000	1.001	1.002	1.003	1.008	1.020	1.040	1.080	1.120	1.160	1.210	1.260
1.000	1.000	1.003	1.004	1.007	1.026	1.050	1.100	1.160	1.220	1.260	1.320	1.380
1.000	1.001	1.004	1.005	1.010	1.050	1.100	1.170	1.240	1.330	1.360	1.430	1.500
1.000	1.002	1.005	1.010	1.020	1.080	1.140	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.005	1.010	1.020	1.050	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Single Unit Trucks												
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.000	1.000	1.001	1.002	1.005	1.020	1.030	1.040	1.050	1.060	1.080	1.090	1.100
1.000	1.001	1.004	1.005	1.010	1.030	1.050	1.090	1.130	1.170	1.210	1.250	1.300
1.000	1.002	1.006	1.009	1.040	1.090	1.140	1.200	1.260	1.320	1.430	1.550	1.690
1.000	1.010	1.020	1.060	1.130	1.230	1.330	1.430	1.530	0.000	0.000	0.000	0.000
1.000	1.020	1.050	1.100	1.150	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.050	1.100	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Gasoline Powered Trucks

1.000	1.000	1.000	1.002	1.004	1.006	1.008	1.010	1.020	1.030	1.040	1.040	1.040
1.000	1.002	1.006	1.008	1.010	1.020	1.040	1.070	1.100	1.120	1.130	0.000	0.000
1.000	1.004	1.008	1.010	1.020	1.040	1.080	1.150	1.220	1.280	1.340	0.000	0.000
1.000	1.006	1.010	1.020	1.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.008	1.012	1.022	1.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Diesel Powered Trucks

1.000	1.000	1.000	1.002	1.004	1.006	1.008	1.010	1.020	1.030	1.040	1.040	1.040
1.000	1.002	1.006	1.008	1.010	1.020	1.040	1.070	1.100	1.120	1.130	0.000	0.000
1.000	1.004	1.008	1.010	1.020	1.040	1.080	1.150	1.220	1.280	1.340	0.000	0.000
1.000	1.006	1.010	1.020	1.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.008	1.012	1.022	1.024	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Slow Cycle Consumption Rates in Gallons

0	10	20	30	40	50	60	70
Passenger Cars							
0.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0044	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0080	0.0057	0.0031	0.0000	0.0000	0.0000	0.0000	0.0000
0.0118	0.0099	0.0076	0.0048	0.0000	0.0000	0.0000	0.0000
0.0165	0.0151	0.0130	0.0106	0.0061	0.0000	0.0000	0.0000
0.0232	0.0219	0.0240	0.0174	0.0138	0.0086	0.0000	0.0000
0.0338	0.0320	0.0300	0.0274	0.0239	0.0193	0.0128	0.0000

0	10	20	30	40	50	60	70
Pickup Trucks							
0.0012	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0037	0.0020	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0070	0.0048	0.0026	0.0000	0.0000	0.0000	0.0000	0.0000
0.0109	0.0083	0.0056	0.0029	0.0000	0.0000	0.0000	0.0000
0.0151	0.0121	0.0090	0.0060	0.0029	0.0000	0.0000	0.0000
0.0195	0.0160	0.0124	0.0089	0.0056	0.0026	0.0000	0.0000
0.0240	0.0197	0.0156	0.0117	0.0081	0.0049	0.0021	0.0000
Single Unit Trucks							
0.0033	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0118	0.0055	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0203	0.0139	0.0075	0.0000	0.0000	0.0000	0.0000	0.0000
0.0287	0.0222	0.0159	0.0089	0.0000	0.0000	0.0000	0.0000
0.0372	0.0305	0.0239	0.0170	0.0095	0.0000	0.0000	0.0000
0.0456	0.0388	0.0319	0.0248	0.0173	0.0095	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gasoline Powered Trucks							
0.0110	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0348	0.0256	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0708	0.0589	0.0382	0.0000	0.0000	0.0000	0.0000	0.0000
0.1160	0.1032	0.0817	0.0476	0.0000	0.0000	0.0000	0.0000
0.1667	0.1535	0.1307	0.0978	0.0537	0.0000	0.0000	0.0000
0.2198	0.2074	0.1850	0.1506	0.1053	0.0541	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

0	10	20	30	40	50	60	70
Diesel Powered Trucks							
0.0057	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0265	0.0156	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0485	0.0393	0.0250	0.0000	0.0000	0.0000	0.0000	0.0000
0.0725	0.0624	0.0502	0.0332	0.0000	0.0000	0.0000	0.0000
0.0993	0.0870	0.0739	0.0591	0.0394	0.0000	0.0000	0.0000
0.1294	0.1141	0.0977	0.0816	0.0643	0.0429	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Stop Cycle Consumption Rates in Gallons/Minute

0	1	2	3	4	5	6
Passenger Cars						
0.0016	0.0021	0.0026	0.0031	0.0035	0.0040	0.0045
0.0066	0.0071	0.0076	0.0081	0.0085	0.0090	0.0095
0.0097	0.0102	0.0107	0.0112	0.0116	0.0121	0.0126
0.0128	0.0133	0.0138	0.0143	0.0147	0.0152	0.0157
0.0168	0.0173	0.0178	0.0183	0.0187	0.0192	0.0197
0.0208	0.0213	0.0218	0.0223	0.0228	0.0238	0.0238
0.0243	0.0248	0.0253	0.0258	0.0263	0.0268	0.0273
Pickup Trucks						
0.0016	0.0054	0.0092	0.0130	0.0168	0.0206	0.0244
0.0048	0.0086	0.0124	0.0182	0.0200	0.0238	0.0276
0.0081	0.0119	0.0157	0.0195	0.0233	0.0271	0.0309
0.0108	0.0144	0.0182	0.0220	0.0258	0.0296	0.0334
0.0132	0.0170	0.0208	0.0246	0.0285	0.0322	0.0360
0.0157	0.0195	0.0233	0.0271	0.0309	0.0347	0.0385
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

0	1	2	3	4	5	6
Single Unit Trucks						
0.0036	0.0090	0.0144	0.0198	0.0252	0.0306	0.0360
0.0097	0.0151	0.0205	0.0259	0.0313	0.0367	0.0421
0.0173	0.0227	0.0281	0.0335	0.0389	0.0443	0.0497
0.0242	0.0296	0.0350	0.0404	0.0458	0.0512	0.0566
0.0270	0.0326	0.0380	0.0434	0.0488	0.0542	0.0596
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gasoline Powered Trucks						
0.0150	0.0220	0.0290	0.0360	0.0430	0.0500	0.0570
0.0470	0.0540	0.0610	0.0680	0.0750	0.0820	0.0890
0.0850	0.0920	0.0990	0.1060	0.1130	0.1200	0.1270
0.1330	0.1400	0.1470	0.1540	0.1610	0.1680	0.1750
0.2050	0.2120	0.2190	0.2260	0.2330	0.2400	0.2470
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel Powered Trucks						
0.0150	0.0220	0.0290	0.0360	0.0430	0.0500	0.0570
0.0470	0.0540	0.0610	0.0680	0.0750	0.0820	0.0890
0.0850	0.0920	0.0990	0.1060	0.1130	0.1200	0.1270
0.1330	0.1400	0.1470	0.1540	0.1610	0.1680	0.1750
0.2050	0.2120	0.2190	0.2260	0.2330	0.2400	0.2470
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

APPENDIX B

COMPUTER PROGRAM AND OUTPUT OF PARAMETER SENSITIVITY AND SCENARIO MODEL

```
@DATA,LI TPFS.
DATA 9R1 SL74T9 12/05/80 09:21:15 (->0)
         RUNID CAROL  FILE PU"COOCAROL  PART NO 000 DATE 120480 UNIT PU3
         /*PASSWORD MASS
         // EXEC PLC,REGION.GO=500K
         //GO.SYSIN DD *
         *PL/C TIME=(3,0)
          MAIN: PROC OPTIONS (MAIN);
          /*
             THIS SECTION OF THE HIGHWAY TRANSPORT ENERGY STUDY CONTAINS TWO
          SEPARATELY DEVELOPED PROGRAMS WHICH ARE LINKED TOGETHER BY TWO
          BEGIN BLOCKS. THE FIRST BLOCK IS AN ESTIMATION OF THE QUANTITY OF
          EXCAVATION IN CUBIC YARDS TO REDUCE AN INPUT SET OF GRADES WITH A
          GIVEN SECTION DESCRIPTION TO A LOWER SET OF DESIGN GRADES. EACH OF THE
          INITIAL GRADES ARE REDUCED BY ONE IN A DOUBLE DO-LOOP SO THAT ALL
          POSSIBLE TRIAL GRADES ARE CALCULATED. THE CUBIC YARDS OF EACH TRIAL
          GRADE COMBINATION ARE CONVERTED INTO APPROPPRIATE COST AND ENERGY
          UNITS. THE RESULTS FROM THE FIRST BLOCKS ARE USED IN THE SECOND BLOCK.
          THE NEXT BLOCK ESTIMATES THE VEHICLE FUEL CONSUMPTION FOR THE INPUT
          GRADES. IN A SIMILAR FORMAT AS THE FIRST BLOCK, THE VEHICLE FUEL
          CONSUMPTION ARE ESTIMATED FOR EACH TRIAL GRADE COMBINATION. BY REDUCING
          THE GRADES TO A LOWER SET, VEHICLES REQUIRE LESS FUEL. THE DIFFERENCE
          FROM THE FUEL CONSUMPTION OF THE INITIAL COMBINATION IS THE VEHICLE
          FUEL SAVINGS. THE RESULTS FROM THIS BLOCK ARE COMPARED WITH THE FIRST
          BLOCK TO DETERMINE POSSIBLE ENERGY AND COST SAVINGS BY A REDUCTION OF
          GRADES THROUGH EXCAVATION.
             FOR A FURTHER DESCRIPTION REFER TO CHAPTER V OF THE  PH.D.
          DISSERTATION "" ESTIMATION MODEL FOR THE LIFE CYCLE ENERGY CONSUMPTION
          FOR HIGHWAY TRANSPORT"".
                                                                               */


          DECLARE (BW,SSF,N\S) FIXED DEC (3,0);
          DECLARE (S\HP,SHP) FIXED DEC (6,3);
          DECLARE (S\BA,S\XY,E\BA,E\EA,S\AHP,S\YHP,E\AHP,E\YHP) FIXED DEC (8,3);
          DECLARE (CTOT,ETOT,VOLU(8,8),CO\E,CO\C) FIXED DEC (15,0);
          DECLARE (EX\C(8,8),EX\E(8,8)) FIXED DEC (15,0);
          DECLARE (COST(8,8),FUEL(8,8),ENERGY(8,8)) FIXED DEC (15,2);
          DECLARE (C\Y,C\F,E\F) FIXED DEC (3,2);
          B1: BEGIN;

          DECLARE (S(30),E(30),D(30)) FIXED DEC (8,3);
          DECLARE (SS(60),EE(60),DD(60)) FIXED DEC (8,3);
          DECLARE VOL(0:30) FIXED DEC (15,4);
          DECLARE ARR(60) FIXED DEC (15,4);
          DECLARE ARRT(0:30) FIXED DEC (15,4);

          DECLARE (G1,G2,GRD,CG) FIXED DEC (2,0);
          DECLARE (AB,XY,AHP,YHP,AAB,YYX,EP,VPI) FIXED DEC (3,0);
          DECLARE VOT FIXED DEC (12,0);
          DECLARE MASS FIXED DEC (15,4);
          DECLARE (DIS,BEF,TPI,BPD) FIXED DEC (12,3);
          DECLARE (E\SS,X\SS,DI,TPIT,ELE,MINE) FIXED DEC (12,3);
          DECLARE (BP,TP) FIXED DEC (8,3);
          DECLARE M FIXED DEC (7,4);
          DECLARE (E\AB,FFS,E\XY,EFS,E\VPI,E\VAB,E\VYHP) FIXED DEC (8,3);
           DECLARE (E\HP,E\BP,E\EP,S\EP,S\AB,S\EA,EED,S\VPI) FIXED DEC(8,3);
```

```
DECLARE (NP,PN) FIXED DEC (2,0);
DECLARE AREA FIXED DEC (15,4);
DECLARE ARE FIXED DEC (15,4);



 SHP = S\HP;
GET LIST (C\Y,C\F,E\F);
GET LIST (BW,SSF);

E\EA = E\EP;
E\BA = E\BP;


/*           CALCULATE THE STATION FOR END OF DESCENT                 */

   S\EA = S\HP + (( E\HP - E\EP) / (10 * GRD));
         IF S\EA > S\EP THEN S\EA = S\EP;

/*           CALCULATE THE STATION FOR START OF ASCENT                */

VFC: S\BA = S\HP- ((E\HP- E\BP) / (10 * GRD));
       IF S\BA < 0 THEN S\BA = 0;
EFS = 0;
FFS = 0;
IF S\BA > 0 THEN FFS = 1- S\BA;
IF S\BA > 1 THEN FFS = 2- S\BA;
IF S\BA > 2 THEN FFS = 3- S\BA;
IF S\BA > 3 THEN FFS = 4- S\BA;
IF S\BA > 4 THEN PUT SKIP (2) LIST ('REROUTE THE ROAD');
EED = S\EP - S\EA;
IF EED > 0 THEN EFS = 1 -EED;
IF EED > 1 THEN EFS = 2 -EED;
IF EED > 2 THEN EFS = 3 -EED;
IF EED > 3 THEN EFS = 4 -EED;
IF EED > 4 THEN PUT LIST ('** REROUTE THE ROAD***') ;


AB = S\BA + 1;
XY = S\EA;
S\AB = AB;
S\XY = XY;
E\AB = E\EA + (FFS * 10 *GRD);
E\XY = E\EA + (EFS * 10 *GRD);

AHP = S\HP;
YHP = S\HP + 1;
S\AHP = AHP;
S\YHP = YHP;

/*         CALCULATE THE ELEVATION OF THE FIRST FULL STATION        */

E\AHP = E\HP - ((S\HP -S\AHP) *GRD * 10);

/*         CALCULATE THE ELEVATION OF THE LAST FULL STATION        */

E\YHP = E\HP - ((S\YHP -S\HP) *GRD * 10);
```

```
/*   SET THE ELEVATIONS ON THE HORIZONTAL TANGENT TO THE END OF ROAD */

DO I = 1 TO AB;
IF I < AB THEN S(I) = E\BP;
IF I = AB THEN S(I) = E\AB;
END;

/*     CALCULATE THE ELEVATION OF EACH FULL STATION OF THE ASCENT    */

DO I = AB +1 TO AHP;
         S(I) = E\AB +(10 * GRD *(I - AB));
END;

/*     CALCULATE THE ELEVATION OF EACH FULL STATION OF THE DESCENT   */

DO I = YHP TO XY;
S(I) = E\YHP -(10 * GRD *(I- YHP));
END;


/*     SET THE ELEVATION OF THE HORIZONTAL TANGENT PORTIONS          */

  EP = S\EP;
DO I = XY + 1 TO EP + 1;
S(I) = E\EP;
END;


/*    START THE DOUBLE DO-LOOP FOR REDUCING THE RIGHT AND LEFT
                GRADIENTS, RESPECTIVELY                              */

G1 = GRD;
G2 = GRD;
DO L = 0 TO G1 - 1;

/*              CALCULATE THE STATION OF THE VPI                     */

MAT: DO K = 0 TO G2 - 1;
S\VPI =(((E\EA - E\BA)+((G2-K)*(S\EA - S\BA)*10))/((G1-L)+(G2-K)))/10;
S\VPI = S\VPI + S\BA;
VPI = S\VPI;
E\VPI = E\BA + ((G1-L) * 10 * (S\VPI - S\BA));
E\VAB = E\BA +( (G1 -L)* 10 * FFS);
E\VYHP = E\VPI - (((VPI + 1) -S\VPI) * (G2-K) * 10);



/*    SET THE ELEVATIONS ALONG EACH TRIAL GRADE COMBINATION          */
DO I = 1 TO AB - 1;
IF I < AB THEN E(I) = E\BP;
IF I = AB THEN E(I) = E\AB;
END;

DO I = AB TO VPI;
E(I) = E\VAB +((G1-L) * 10 * (I - AB));
```

```
END;

DO I = VPI + 1 TO XY;
E(I) = E\VYHP -((G2-K) * 10 * ( I - (VPI + 1)));
END;

DO I = 1  + XY TO EP +1;
E(I) = S(I);
END;


/*      ARRAY THE INITIAL AND TRIAL ELEVATIONS FOR THE HALF SECTION */

DO I = 1 TO N\S;
END;

DO I = 1 TO N\S;
EE(2*I-1) = E(I);
EE(2*I) = E(I);
SS(2*I-1) = S(I);
SS(2*I) = S(I);
END;


DO I = 1 TO NS;

VOL(0) = 0;
VOT = 0;
B = 0.5 * BW;
NP = 0;
DI = 0;
BP = EE(I);
TP = SS(I);
   ARE = 0;
IF EE(I) = SS(I) THEN GO TO FIN;

DO J = 1 TO N\P(I);
IF NP = 10 THEN GO TO MOT;
IF DI < B THEN TPIT = BP + (DIST(I,J) - B) / SSF;
IF DI = B THEN TPIT = BP + (DIST(I,J) - B) / SSF;
IF DI > B THEN TPIT = BP + (DIST(I,J) - DI) / SSF;
IF TPIT > ELEV(I,J) THEN GO TO FOUR;
IF DIST(I,J) > B THEN GO TO TWO;

 /*   START HALF SECTION AREA MODELS                            */

ONE: TPI = ELEV(I,J);
    BPD = EE(I);
    DIS = DIST(I,J) - DI;
AREA = 0.5 * (TPI + TP - BP - BPD) * DIS;
    DI = DIST(I,J);
TP = ELEV(I,J);
    BP = BPD;
ARE = AREA + ARE;
GO TO MOT;
```

```
TWO: IF B < DI THEN GO TO THREE;
      DIS = B -DI;
      PERMA = (ELEV(I,J) - TP) * (DIS/(DIST(I,J)-DI));
      TPI = TP + PERMA;
BPD= BP + (DIST(I,J) - B) / SSF;
AREA = 0.5 *(TPI + TP -(2*BP)) *DIS + 0.5 *(TPI + ELEV(I,J) -BP - BPD)*
(DIST(I,J) - B);
ARE = AREA + ARE;
     DI = DIST(I,J);
TP = ELEV(I,J);
     BP = BPD;
GO TO MOT;

THREE: TPI = ELEV(I,J);
BPD= BP + (DIST(I,J) - DI) / SSF;
     DIS = DIST(I,J) - DI;
AREA = 0.5 * (TPI + TP - BP - BPD) * DIS;
     DI = DIST(I,J);
     TP = TPI;
     BP = BPD;
ARE = AREA + ARE;
GO TO MOT;


FOUR: IF DI > B THEN GO TO FIVE;
TPI = TP + ((ELEV(I,J) - TP) * ((B - DI) / DIST(I,J) - DI));
IF TPI < BP THEN ARE = 0;
IF TPI < BP THEN GO TO FIN;
   M = (ELEV(I,J) - TPI) / (DIST(I,J) - B);
X\SS = (TPI - BP);
X\SS =      X\SS  / (0.3333 - M);

/* AREA FOR A TRIANGLE AND QUADRILATERAL  FROM BASE TO SLOPE STAKE */

AREA =0.5 * (B-DI) * (TPI + TP - (BP * 2)) + 0.5 * (X\SS * (TPI - BP));
ARE = AREA + ARE;
NP = 10;
GO TO MOT;

FIVE:    M = (ELEV(I,J) - TP) / (DIST(I,J) - DI);
X\SS = (TP - BP)  / (0.3333 - M);
AREA =0.5 * (X\SS * (TP - BP));
ARE = AREA + ARE;
NP = 10;
MOT: END;


FIN: ARR(I) = ARE;
END;
DO I = 1 TO N\S;
ARRT(I) = ARR(2*I) + ARR(2*I-1);
END;
IF ARRT(I) < 0 THEN ARRT(I) = 0;
DO I = 1 TO N\S + 1;
ARRT(N\S+1) = 0;
ARRT(0) = 0;
/*         START THE VOLUME CALCULATIONS                              */
```

```

       VOL(I) = ((ARRT(I-1) + ARRT(I)) / 2) * 1000 / 27;
       VOT = VOT + VOL(I);
       END;


       /*   CALCULATE THE ENERGY AND COST FOR GRADE REDUCTION FOR EACH TRIAL
                       GRADE COMBINATION                                      */

       EX\E(G1-L,G2-K) = 0.059 * E\F * VOT;
       EX\C(G1-L,G2-K)  = C\Y * C\F * VOT;
        EX\E(GRD,GRD) = 0;
        EX\C(GRD,GRD) = 0;
       FAP: END;
       END;
       END;



       B2: BEGIN;
       DECLARE EPZ FIXED DEC (13,4);
       DECLARE (RESUL,TWGR) FIXED DEC (9,6);
       DECLARE (S\EP,S\EA) FIXED DEC (8,3);
       DECLARE (GR\P(5,7,11),GR\N(5,7,11),PAVE(5,7,4))FIXED DEC (4,3);
       DECLARE CURV(5,7,14) FIXED DEC (4,3);
        DECLARE (C\F(5), CC\F(5)) FIXED DEC (15,6);
        DECLARE (RESULT(5),TWO\R(5),BE(5)) FIXED DEC (15,2);
       DECLARE (PT\C(0:20),PC\C(20),LEN\C(20)) FIXED DEC (7,3);
        DECLARE (CG\F(20),TG\F(20),PV\F(20),PVF(20)) FIXED DEC (6,3);
       DECLARE ADT(5) FIXED DEC (5,0);
        DECLARE NUM(5) FIXED DEC (5,0);
       DECLARE (STA(20),AI(20)) FIXED DEC (8,3);
       DECLARE (F\COST,F\COS) FIXED  DEC (15,2);
       DECLARE (SPL,SPP,SPN,TRAF,OEN) FIXED DEC (1,0);
        DECLARE (DC,N\C) FIXED DEC (2,0);
       DECLARE (SP,GR,PA,CU,SCEN) FIXED DEC (2,0);
        DECLARE LEN FIXED DEC (5,2);
       DECLARE CCF FIXED DEC (15,6);
       DECLARE (P\C,P\P,P\S,P\G,P\D) FIXED DEC (4,2);
        DECLARE (PRICE,E\C,M\C,M\E,P\F,F\C,F\E) FIXED DEC (15,2);
        DECLARE (S\TOT,TOTAL) FIXED DEC (15,2);
       DCL YR FIXED DEC (2,0);
       DCL CG FIXED DEC (4,2);
       DECLARE (G1,G2,R) FIXED DEC (2,0);


       DECLARE R\N CHARACTER (6);
        DECLARE N CHARACTER (09);
       DECLARE B CHARACTER (1);
       DECLARE S CHARACTER (1);



       /* INPUT THE VEHICLE OPERATIONS DATA ARRAY FOR GRADE, PAVE AND CURVE */

       DECLARE FUEL\F FIXED (9,6);
        N='*GRADE\P*';
```

```
 DO I = 1 TO 5;
 DO J = 1 TO 7;
 GET EDIT (N) (COLUMN(1),A(09));
 DO K = 1 TO 11;
 GET EDIT (GR\P(I,J,K)) (F(4,3));
END;
END;
END;
 N=´*GRADE\N*´;
 DO I = 1 TO 5;
 DO J = 1 TO 7;
 GET EDIT (N) (COLUMN(1),A(09));
 DO K = 1 TO 11;
 GET EDIT (GR\N(I,J,K)) (F(4,3));
END;
END;
END;
 N=´*PAVE*´;
 DO I = 1 TO 5;
DO J = 1 TO 7;
 GET EDIT (N) (COLUMN(1),A(09));
 DO K = 1 TO 4;
 GET EDIT (PAVE(I,J,K)) (F(4,2));
END;
END;
END;
 N=´*CURV*´;
 DO I = 1 TO 5;
 DO J = 1 TO 7;
 GET EDIT (N) (COLUMN(1),A(09));
 DO K = 1 TO 14;
 GET EDIT (CURV(I,J,K))(F(4,3));
END;
END;
END;


/*          INPUT THE TRAFFIC AND GEOMETRIC DESCRIPTION             */
  GET LIST (R\N,TRAF,P\C,P\P,P\S,P\G,P\D);
  GET LIST (R\N,N\S,GRD,S\HP,E\HP,E\BP,E\EP,S\EP);

/* INPUT THE YEARS OF THE STUDY PERIOD, THE COST PER GALLON OF FUEL
AND ´1´ IF THE SCENAPIO IS IMPLEMENTED                              */

GET LIST (YR,CG,SCEN);


IF SCEN = 1 THEN GO TO SCENO;

/*         DIMENSION ALL FACTORS TO ONE IF THERE IS NO SCENARIO     */

  DO I = 1 TO YR;
PV\F(I) = 1;
TG\F(I) = 1;
CG\F(I) = 1;
END;
GO TO FUN;
```

```

  /*                    INPUT AND ARRAY THE SCENARIO FACTORS         */

SCENO: GET SKIP EDIT ((CG\F(I) DO I = 1 TO YR)) (F(3,2));
GET SKIP EDIT ((TG\F(I) DO I = 1 TO YR)) (F(4,3));
GET SKIP EDIT ((PV\F(I) DO I = 1 TO YR)) (F(2,2));

FUN: OEN = 0;
  GR = GRD + 1;
  LEN = S\EP;

  /*      INPUT THE SAMPLE TRAFFIC VOLUMES                           */

GET LIST (ADT(1));
K = 1;


 /*            SELECT THE ROAD CLASSIFICATION BY TRAFFIC VOLUME      */

   IF ADT(K) < 99    THEN GO TO R\IV;
   IF ADT(K) < 1199  THEN GO TO R\III;
   IF ADT(K) < 4199  THEN GO TO R\II;
   IF ADT(K) < 30000 THEN GO TO R\I;
  IF ADT(K) > 30000 THEN PUT LIST ('* TRAFFIC GREATER THAN 30,000 *');

  R\IV:  PRICE = LEN * 0.48;
         E\C = LEN *0.01;
         SP = 2;
         PA = 4;
         DC = 10;
         BW = 20;
         M\C = LEN * 0.003 * YR;
         M\E = LEN * 0.073 * YR;
         GO TO VFC;
  R\III: PRICE = LEN * 8.58;
         E\C = LEN *0.17;
         SP = 3;
         PA = 3;
         BW = 44;
         M\C = LEN * 0.011 * YR;
         M\E = LEN * 0.315 * YR;
  R\II : PRICE = LEN * 110;
         E\C = LEN * 3.35;
         SP = 5;
         PA = 1;
        DC = 10;
         BW = 80;
         M\C = LEN * 0.169 * YR;
         M\E = LEN * 1.334 * YR;
         GO TO VFC;
  R\I  : PRICE = LEN * 210;
         E\C = LEN *8.65;
         SP = 5;
         PA = 1;
         DC = 10;
         BW = 180;
         M\C = LEN * 0.371 * YR;
```

```
         M\E = LEN * 3.125 * YR;

IF OEN = 1 THEN GO TO OPT;
VFC: S\BA = S\HP- ((E\HP- E\BP) / (10 * GRD));
   S\EA = S\HP + (( E\HP - E\EP) / (10 * GRD));
         IF S\EA > S\EP THEN S\EA = S\EP;
       IF S\BA < 0 THEN S\BA = 0;

/*            DIVIDE THE ADT IN HALF FOR TWO WAY TRAFFIC              */

OPT: IF TRAF = 2 THEN ADT(K) = 0.5 * ADT(K);

/*             INPUT THE ROUTE NAME AND THE NUMBER OF CURVES          */

     IF OEN = 0 THEN GET LIST (R\N,N\C);

DO L = 1 TO GRD;
DO R = 1 TO GRD;
G1 = (GRD + 1) -L;
G2 = (GRD + 1) -R;
S\VPI =(((E\EP - E\BP)+((G2)*(S\EA - S\BA)*10))/((G1)+(G2)))/10;
S\HP = S\VPI + S\BA;
G1 = G1 + 1;
G2 = G2 + 1;

DO J = 1 TO N\C;

IF OEN = 1 THEN GO TO CAL;

/*        INPUT THE STATIONING, THE ANGLE OF INTERSECTION AND THE
                             DIRECTION OF TURN                        */

                 GET LIST (STA(J),AI(J),B);

CAL: LEN\C(J) = AI(J) / (DC * 10);
PC\C(J) = STA(J) - (LEN\C(J) / 2);
PT\C(J) = STA(J) + (LEN\C(J) / 2);
PT\C(0) = 0;
IF PT\C(J-1) > PC\C(J) THEN PC\C(J) = PT\C(J-1);
IF PT\C(J-1) > PC\C(J) THEN PT\C(J-1) = (PT\C(J-1) + PC\C(J)) / 2;
LEN\C(J) = PT\C(J) - PC\C(J);
IF PC\C(1) < 0 THEN PC\C(1) = 0;
END;
 CEN = 1;

   /*             CALCULATE VEHICLE FUEL            */

 CALC:   PT\C(0) = 0;
   CU = DC + 1;

 /*     CALCULATE THE NUMBER OF EACH TYPE OF VEHICLE                  */

  NUM(1) = ADT(K) * P\C / 100;
  NUM(2) = ADT(K) * F\P / 100;
  NUM(3) = ADT(K) * P\S / 100;
  NUM(4) = ADT(K) * P\G / 100;
  NUM(5) = ADT(K) * P\D / 100;
```

```

   T\RE = 0;
   S\RE = 0;
CCF = 0;
    S\TOT= 0;
F\COS = C;
F\COST = 0;


 DO I = 1 TO 5;


  IF SP = 7 &I > 2 THEN SP = 6;

   SPL = SP;
  AGAIN6: DO WHILE (PAVE(I,SPL,PA) = 0.0);
    SPL = SPL - 1;
GO TO AGAIN6;
END;
  AGAIN7: DO WHILE (CURV(I,SPL,CU) = 0.0);
    SPL = SPL - 1;
GO TO AGAIN7;
END;
    SPN = SPL;
  AGAIN1N: DO WHILE (GR\N(I,SPN,G2) = 0.0);
SPN = SPN - 1;
         GO TO AGAIN1N;
         END;
   SPP = SPL;
  AGAIN1P: DO WHILE (GR\P(I,SPP,G1) = 0.0);
       SPP = SPP - 1;
GC TO AGAIN1P;
         END;


DC M = 1 TO YR;
IF I = 1 THEN PVF(M) =PV\F(M);
IF I > 1 THEN PVF(M) = 1;
 RESUL     = (GR\P(I,SPL,1) * PAVE(I,SPL,PA) *(S\BA - 0) / 5.28
            + GR\P(I,SPP,G1) * PAVE(I,SPP,PA) * (S\HP - S\BA) / 5.28
            + GR\N(I,SPN,G2) * PAVE(I,SPN,PA) * (S\EA - S\HP) / 5.28
            + GR\P(I,SPL,1) * PAVE(I,SPL,PA) * (S\EP - S\EA) / 5.28);
 EPZ      = NUM(I) * 365 * RESUL * PVF(M);
RESULT(I) =    TG\F(M) * EPZ;
 IF TRAF = 1 THEN GO TO FEL;
  AGAIN2N: DO WHILE (GR\N(I,SPN,G1) = 0.0);
SPN = SPN - 1;
         GO TO AGAIN2N;
         END;
   SPP = SPL;
  AGAIN2P: DO WHILE (GR\P(I,SPP,G2) = 0.0);
       SPP = SPP - 1;
GC TO AGAIN2P;
         END;
  TWOR     = (GR\P(I,SPL,1) * FAVE(I,SPL,PA) *(S\BA - 0) / 5.28
            + GR\N(I,SPN,G1) * PAVE(I,SPN,PA) * (S\HP - S\BA) / 5.28
            + GR\P(I,SPP,G2) * PAVE(I,SPP,PA) * (S\EA - S\HP) / 5.28
```

```
            + GR\P(I,SPL,1) * PAVE(I,SPL,PA) * (S\EP - S\EA) / 5.28);
RESULT(I) = (RESUL   + TWOR) * NUM(I) ;
RESULT(I) = (RESULT(I))              * 365 *PVF(M) * TG\F(M);
 FEL: S\TOT = S\TOT + RESULT(I);
RCTO:    IF I < 5 THEN BE(I) = 0.125*RESULT(I);
   IF I = 5 THEN BE(I) = 0.139*RESULT(I);
 S\RE = S\RE + BE(I);
 F\COS = F\COS + RESULT(I) * CG\F(M) * CG;


      DO J =1 TO N\C;
     IF PT\C(N\C) > S\EP THEN PT\C(N\C) = S\EP;

/*   CHOOSE THE MODEL FOR CALCULATING THE EXTRA FUEL FOR CURVATURE
  DEPENDING UPON THE CURVE'S POSITION TO THE HORIZONTAL TANGENTS,
 THE ASCENT, THE CREST, AND THE DESCENT                                    */

   IF PC\C(J) < S\BA & PT\C(J) < S\BA THEN GO TO CUR\1;
    IF PC\C(J) < S\BA & PT\C(J) > S\BA THEN GO TO CUR\2;
    IF PC\C(J) > S\BA & PT\C(J) < S\HP THEN GO TO CUR\3;
    IF PC\C(J) < S\HP & PT\C(J)  > S\HP THEN GO TO CUR\4;
   IF PC\C(J) > S\HP & PT\C(J) < S\EA THEN GO TO CUR\5;
    IF PC\C(J) < S\EA & PT\C(J) > S\EA THEN GO TO CUR\6;
    IF PC\C(J) > S\EA THEN GO TO CUR\1;

CUR\1:C\F(I) =GR\P(I,SPL,1)*PAVE(I,SPL,PA)*(CURV(I,SPL,CU)-1)*LEN\C(J);
 CC\F(I) = C\F(I) * NUM(I) * 365 ;
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;
GO TO FIN;
CUR\2: C\F(I) = GR\P(I,SPL,1)*PAVE(I,SPL,PA)*(CURV(I,SPL,CU)-1)
                *(S\BA - PC\C(J)) +
                GR\P(I,SPP,G1)*PAVE(I,SPP,PA)*(CURV(I,SPP,CU)-1)
                * (PT\C(J) - S\BA);
 CC\F(I) = C\F(I) * NUM(I) * 365 ;
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;
GO TO FIN;

CUR\3:C\F(I)=GR\P(I,SPP,G1)*PAVE(I,SPP,PA)*(CURV(I,SPP,CU)-1)*LEN\C(J);
 CC\F(I) = C\F(I) * NUM(I) * 365 ;
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;
GO TO FIN;

CUR\4: C\F(I) = GR\P(I,SPP,G1)*PAVE(I,SPP,PA)*(CURV(I,SPP,CU)-1)
                * (S\HP -PC\C(J))
              + GR\N(I,SPN,G2)*PAVE(I,SPN,PA)*(CURV(I,SPN,CU)-1)
* (PT\C(J) - S\HP);

 CC\F(I) = C\F(I) * NUM(I) * 365;
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;
GO TO FIN;

CUR\5:C\F(I)=GR\N(I,SPN,G2)*PAVE(I,SPN,PA)*(CURV(I,SPN,CU)-1)*LEN\C(J);
 CC\F(I) = C\F(I) * NUM(I) * 365 ;
```

```
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;
GO TO FIN;

CUR\6: C\F(I) = GR\N(I,SPN,G2)*PAVE(I,SPN,PA)*(CURV(I,SPN,CU)-1)
                * (S\BA - PC\C(J)) +
                GR\P(I,SPL,1)*PAVE(I,SPL,PA)*(CURV(I,SPL,CU)-1)
                * (PT\C(J) - S\BA);
 CC\F(I) = C\F(I) * NUM(I) * 365 ;
 CC\F(I) =           CC\F(I)     * PVF(M) ;
 CC\F(I) =           CC\F(I)               * TG\F(M) / 5.28;


 FIN: IF TRAF = 2 THEN CC\F(I) = 2 * CC\F(I);
      CCF =CC\F(I) + CCF;
S\COST = CC\F(I) * CG\F(M);
F\COST =        S\COST     * CG + F\COST;

/*                SUM ENERGY REQUIREMENTS BY VEHICLE CLASS           */

         IF I < 5 THEN BE(I) = 0.125*CC\F(I);
         IF I = 5 THEN BE(I) = 0.139*CC\F(I);

/*    CALCULATE ENERGY REQUIREMENTS                                  */

 T\RE = T\RE + BE(I);
IT: END;
OEN =1;
END;
END;
IF G1-1 = 8 & G2-1 = 8 THEN CCOT = F\COS + F\COST;
IF G1-1 = 8 & G2-1 = 8 THEN ENER = S\RE + T\RE;
ENERGY(G1-1,G2-1) = -(S\RE + T\RE) + ENER;
COST(G1-1,G2-1) = -(F\COS + F\COST) + CCOT;
FUEL(G1-1,G2-1) = CCF + S\TOT;

 END;
END;
END;


CO\E = 0;
CO\C = 0;
PUT PAGE;
PUT SKIP(2) EDIT ( 'FINAL  GRADE','VOLUME OF','ENERGY OF','$ COST OF',
'ENERGY','$ FUEL','TOTAL $','TOTAL E') (COLUMN(1),A,X(5),A,X(6),A,X(6),
A,X(9),A,X(9),A,X(9),A,X(8),A);
PUT SKIP EDIT ('LEFT','RIGHT','EXCAVATION','EXCAVATION','EXCAVATION',
 'SAVINGS','SAVINGS','SAVINGS','SAVINGS') (COLUMN(1),A,X(3),
A,X(5),A,X(5),A,X(5),A,X(8),A,X(8),A,X(8),A,X(6),A);
DO I = 1 TO 8;
DO J = 1 TO 8;
CTOT = - EX\C(I,J) + COST(I,J);
ETOT = - EX\E(I,J) + ENERGY(I,J);
VOLU = EX\C(I,J) / (C\Y * C\F);
IF CO\E < ETOT THEN CO\E = ETOT;
 IF CO\E = ETOT THEN L = J;
```

```
  IF CO\E = ETOT THEN K = I;
 IF CO\C < CTOT THEN CO\C = CTOT;
 IF CO\C = CTOT THEN M = I;
 IF CO\C = CTOT THEN N = J;
 PUT SKIP EDIT (I,J,VOLU(I,J),EX\E(I,J),EX\C(I,J),ENERGY(I,J),COST(I,J),
 CTOT,ETOT) (F(4,2),X(4),F(4,2),X(1),F(14,0),X(1),F(14,0),X(1),F(14,0),
 X(1),F(14,0),X(1),F(14,0),X(1),F(14,0),X(1),F(14,0));
 END;
 END;
 PUT PAGE;
 PUT SKIP(2) LIST ('THE OPTIMAL ENERGY SAVING',CO\E);
 PUT SKIP(2) LIST ('THE OPTIMAL COST SAVING ',CO\C);
 PUT SKIP(2) LIST (' AT LEFT GRADIENT        ',K);
 PUT SKIP(2) LIST (' AT RIGHT GRADIENT       ',L);
 FINI: END MAIN;
*DATA
1,1,1
180,3
GR110P   00720080008700960103011201210132014301600179
GR120P   00500058007000760086009401040116012801440160
GR130P   00440051006300680078008700960110012401360154
GR140P   00460054006200700078008700960111012401400156
GR150P   00520059007000760083009301040118013001450162
GR160P   00580067007600840093010201120126013801520170
GR170P   00670075008400930102011101220135014801620180
GR210P   00580070008300900100011001290134015001740197
GR220P   00470057006800770086009501050121013701470156
GR230P   00470057006800770086009501050121013701560174
GR240P   00530063007300830094010301130132015101640180
GR250P   006500750085009501060117012801440164
GR260P   0081009201020112012301330144
GR270P   009901100122
GR310P   00740094012001430175019502250255028903240357
GR320P   00590080011201400167019002140254029503440394
GR330P   006700940121015001810206023202680305
GR340P   008201120141017302100228
GR350P   0101013001590194
G.360P   01220150
GR370P
GR410P   03550405047505400615073508581027119513401490
GR420P   0208028903640462055506850813
GR430P   016402530342047406180800
GR440P   0163027503900560
GR450P   019503440485
GR460P
GP470P
GR510P   02130273033103880443049605470595064006790713
GR520P   01240199027503500427050405780651072700000000
GR530P   010401850269035804570562
GP540P   0107019102860402
GR550P   01280219
GP560P   0165
GR570P
GP110N   00720060004500400040004000400040004000400040
GR120N   00500040002700220021002100210021002100210021
GR130N   00440033002200160014001300130013001300130013
GR140N   00460035002500180014001200120012001200120012
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740.      GR150N    00520041003000250021001800140013001000100008
741.      GR160N    00580048003600370030002700220018001400110008
742.      GR170N    00670058004800430039003600310027002200160013
743.      GR210N    00580049004000360032003200320032003200320032
744.      GR220N    00470036002700220020001900180018001800180018
745.      GR230N    00470036002800240020001700150013001200120012
746.      GR240N    00530046003900330028002400200015001000100010
747.      GR250N    00650060005400470041003500300024001800140010
748.      GR260N    00810077007400670059005300470037002700190011
749.      GR270N    00990098009800890081007300650053004100280015
750.      GR310N    00740064005500530051005100510051005100510051
751.      GR320N    00590049003900340030003000300030003000300030
752.      GR330N    00670054004100340027002600250025002400240024
753.      GR340N    00820071005100410032002900250023002100200020
754.      GR350N    01010090007200580045003800310025002000200020
755.      GR360N    01220110009000750062005200430035002500200020
756.      GR370N
757.      GR410N    03550247014501320120012001200120012001200120
758.      GR420N    02080140006900620055005500550055005500550055
759.      GR430N    01640115006600530040004000400040004000400040
760.      GR440N    01630128009100650040004000400040004000400040
761.      GR450N    01950164013100950040004000400040004000400040
762.      GR460N
763.      GR470N
764.      GR510N    02130162013701120116013201440156016401640164
765.      GR520N    01240072004400260030003900500065
766.      GR530N    010400510022001300130016
767.      GR540N    0107005600260011
768.      GR550N    012800740046
769.      GR560N    0165
770.      GR570N
771.      PA110     0100010101090123
772.      PA120     0100010501130128
773.      PA130     0100012001260140
774.      PA140     0100013401560173
775.      PA150     0100015001700200
776.      PA160     01000
777.      PA170     01000
778.      PA210     0100010001070133
779.      PA220     0100010001090149
780.      PA230     0100010101160167
781.      PA240     0100010601270202
782.      PA250     010001160134
783.      PA260     010001400
784.      PA270     01000
785.      PA310     0100010301240146
786.      PA320     0100010601280162
787.      PA330     0100010701450216
788.      PA340     0100010801580246
789.      PA350     010001200169
790.      PA360     01000
791.      PA370     01000
792.      PA410     01000101010701060
793.      PA420     0100011001270180
794.      PA430     010001200159
795.      PA440     010001350175
796.      PA450     01000
```

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797.     PA460    01000
798.     PA470    01000
799.     PA510    01000101010701060
800.     PA520    01000110012700180
801.     PA530    01000120 0159
802.     PA540    010001350175
803.     PA550    01000
804.     PA560    01000
805.     PA570
806.     CU110    1000100010011002100210031004100510051006100810101020     1130
807.     CU120    1000100110021003100410051006100710081010103010701110     2000
808.     CU130    1000100510101016102210281034104010801140120012801360
809.     CU140    1000101510311048106510821120117012301340148016201800
810.     CU150    1000102510541090112011601250143016101820207022002500
811.     CU160    10001040108011321200130014001900
812.     CU170    10001060112011821300
813.     CU210    1000100010001000100010001000100010001000100010001000
814.     CU220    1000100010001001100110021005101010201040108011001130
815.     CU230    1000100010011002100310081020104010801120116012101260
816.     CU240    1000100010031004100710261050110011601220126013201380
817.     CU250    1000100110041005101010501100117012401330136014301500
818.     CU260    1000100210051010102010601140
819.     CU270    10001005101010201050
820.     CU310    100010001000100010001000100010001000100010001000100010001000
821.     CU320    10001000100110021005102010301040105010601080109011001180
822.     CU330    10001001100410051010103010501090113011701210125013002000
823.     CU340    1000100210061009104010901140120012601320143015501690
824.     CU350    100010101020106011301230133014301530
825.     CU360    10001020105011001150
826.     CU370    100010501100
827.     CU410    10001000100010021004100610081010102010301040104010401050
828.     CU420    1000100210061008101010201040107011
829.     CU430    10001004100810101020104010601150122012601340
830.     CU440    10001006101010201022
831.     CU450    10001008101210221024
832.     CU460
833.     CU470
834.     CU510    10001000100010021004100610081010102010301040104010401050
835.     CU520    10001002100610081010102010401070110011201130
836.     CU530    10001004100810101020104010801150122012601340
837.     CU540    10001006101010201022
838.     CU550    10001008101210221024
839.     CU560
840.     CU570
841.     'D-D',2,74,10,8,4,4
842.     'D-D',19,8,8.37,1440,850,790,18.2
843.     20,1,1
844.     100108117126136147159171185200216213211209207205203201199197
845.     07190726073407410748075607630771077907860794081008340859088509120939096709961026
846.     9586797470676459545250504949474745454545
847.     10000
848.     'D-D',12
849.     2,25,'R',3,14,'L',6,42,'L',7,62,'R',8,67,'L',9,25,'L',10,26,'L',11,27,
850.     'R',12,38,'R',13,24,'R',14,18,'R',15,68,'L'
851.     //
852.     //
853.     //
```

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  854.
  855.
END DATA. EPRORS: NONE. TIME:  2.351 SEC. IMAGE COUNT: 855

@FIN
```

FINAL LEFT	GRADE RIGHT	VOLUME OF EXCAVATION	ENERGY OF EXCAVATION	$ COST OF EXCAVATION	ENERGY SAVINGS	$ FUEL SAVINGS	TOTAL $ SAVINGS	TOTAL E SAVINGS
1.00	1.00	247140000	14581843	247145996	1157182	15856192	-231293704	-13424660
1.00	2.00	208820000	12320743	208826153	1111546	15235303	-193590850	-11209197
1.00	3.00	193300000	11405260	193309509	1068031	14636140	-178673368	-10337228
1.00	4.00	185450000	10942049	185456458	1028539	14094197	-171364261	-9913510
1.00	5.00	181240000	10693673	181248703	1002154	13731745	-167516958	-9691519
1.00	6.00	179140000	10569502	179144104	1080410	14861126	-164282977	-9489092
1.00	7.00	177490000	10472484	177455737	951804	13024207	-164475529	-9520680
1.00	8.00	176780000	10430227	176782513	885862	12155384	-164628129	-9544354
2.00	1.00	244930000	14451305	244937386	1140567	15630002	-229307383	-13310738
2.00	2.00	190380000	11232507	190361475	1093224	14986967	-175394508	-10139283
2.00	3.00	159240000	9395710	159249337	1004591	13770321	-145479016	-8391118
2.00	4.00	142550000	8411027	142555787	946440	12972615	-129587171	-7464587
2.00	5.00	132100000	7794162	132104453	888274	12174929	-119929524	-6905888
2.00	6.00	125420000	7399944	125422796	986701	13586385	-111836411	-6413242
2.00	7.00	122120000	7205436	122126036	828409	11344992	-110781044	-6377027
2.00	8.00	120740000	7123935	120744663	755588	10380324	-110364339	-6368347
3.00	1.00	244240000	14410443	244244012	1121082	15351264	-228883547	-13289360
3.00	2.00	183590000	10832125	183595342	1081272	14818819	-168776522	-9750852
3.00	3.00	142170000	8388277	142174188	964516	13214686	-128959502	-7423751
3.00	4.00	115430000	6810626	115434342	858044	11754256	-103680086	-5952582
3.00	5.00	99170000	5851616	99179946	781327	10701239	-88478706	-5070289
3.00	6.00	88610000	5228404	88617022	895560	12338993	-76278029	-4332843
3.00	7.00	81430000	4804481	81431957	724346	9924649	-71507248	-4080135
3.00	8.00	79000000	4661319	79005410	641452	8818266	-70187143	-4019856
4.00	1.00	243950000	14393051	243950024	1111049	15222819	-228727205	-13282002
4.00	2.00	181000000	10679271	181004606	1053208	14432601	-166572005	-9626063
4.00	3.00	133270000	7863256	133275540	932512	12772563	-120502976	-6930743
4.00	4.00	100010000	5900756	100012828	787289	10780202	-89232676	-5113466
4.00	5.00	77950000	4599369	77955423	672303	9202158	-68753265	-3927065
4.00	6.00	63470000	3745167	63477410	806369	11125528	-52351882	-2938797
4.00	7.00	53390000	3150134	53392113	616935	8462655	-44929457	-2533199
4.00	8.00	49260000	2906677	49265727	520661	7172116	-42093610	-2386015
5.00	1.00	243830000	14386463	243839366	1095334	15007063	-228831303	-13291129
5.00	2.00	179750000	10605821	179755692	1015487	13914948	-165844744	-9590333
5.00	3.00	129090000	7616312	129090046	886835	12144835	-116945211	-6729476
5.00	4.00	91350000	5389857	91353517	725282	9927917	-81425600	-4664575
5.00	5.00	64880000	3828002	64881403	570206	7800059	-57081343	-3257796
5.00	6.00	46320000	2733431	46329342	712306	9841882	-36487459	-2021124
5.00	7.00	34210000	2018891	34218502	495603	6856679	-27361822	-1519288
5.00	8.00	28180000	1663030	28186962	373682	5161742	-23025220	-1289348
6.00	1.00	243780000	14383406	243786545	1168915	16046891	-227739654	-13214590
6.00	2.00	179100000	10561397	179106742	1182924	16280321	-162726420	-9378473
6.00	3.00	127060000	7496550	127060185	1145246	15782124	-111278061	-6351304
6.00	4.00	86650000	5112855	86658576	1067456	14737927	-71920648	-4045398
6.00	5.00	56930000	3359166	56935021	963175	13328411	-43606610	-2395990
6.00	6.00	35820000	2113550	35822897	633596	8753859	-27069027	-1479953
6.00	7.00	21270000	1255450	21278919	403548	5523579	-15755240	-851902
6.00	8.00	14560000	859570	14569334	258915	3570674	-10998659	-600674
7.00	1.00	243660000	14376321	243666466	1157207	15898736	-227777729	-13219113
7.00	2.00	178750000	10546741	178758332	1157186	15930747	-162827584	-9389554
7.00	3.00	125690000	7416152	125697499	1107217	15266120	-110431378	-6308934
7.00	4.00	84050000	4959147	84053345	1021249	14111445	-69941899	-3937897
7.00	5.00	52180000	3090756	52185709	914380	12667433	-39718275	-2176376
7.00	6.00	30100000	1776095	30103319	647615	9037235	-21066084	-1128479
7.00	7.00	14320000	844912	14320551	268168	3662199	-10658351	-576744
7.00	8.00	6600000	389664	6604487	126377	1744653	-4859834	-263286

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8.00    1.00    243720000    14375856    243726374    1111662    15289989    -228436384    -13268193
8.00    2.00    178560000    10535307    178564528    1095311    15111937    -163452590     -9439995
8.00    3.00    125460000     7402373    125463959    1038408    14352708    -111111251     -6363964
8.00    4.00     83300000     4514784     83301426     961951    13328101     -69973325     -3952833
8.00    5.00     51020000     3010326     51022476     837452    11646095     -39376380     -2172874
8.00    6.00     27910000     1646887     27913348     540173     7579503     -20313845     -1106713
8.00    7.00     11330000      668903     11337340     155460     2189773      -9147566      -509422
8.00    8.00            0           0            0          0           0             0            0



THE OPTIMAL ENERGY SAVING                                  0

THE OPTIMAL COST SAVING                                    0

 AT LEFT GRADIENT                                     8

 AT RIGHT GRADIENT                                    8


IN STMT  558  PROGRAM RETURNS FROM MAIN PROCEDURE.
```

APPENDIX C

CROSS SECTION DATA

```
THE CROSS SECTIONAL DATA FOR ROUTE D-D APPEARS BELOW.
THE SECTION IS DESIGNATED AS A NUMBER AND LETTER.
THE NUMBER DENOTES THE 1000 FOOT STATION AND THE
LETTER SIGNIFIES RIGHT OR LEFT OF CENTERLINE.
THE ELEVATION AND DISTANCE ARE IN FEET.


                   ELEVATION                 DISTANCE

1R                   850.000                  510.000
1R                   900.000                  970.000
1R                  1000.000                 1910.000
1L                   900.000                  970.000
1L                  1000.000                 1590.000
2R                   860.000                  630.000
2R                  1000.000                 1510.000
2L                   630.000                 1070.000
2L                   900.000                 1920.000
3R                   890.000                 1020.000
3R                  1000.000                 1820.000
3L                   890.000                  310.000
3L                   900.000                  780.000
3L                   900.000                 2130.000
4R                  1040.000                  280.000
4R                   950.000                 1450.000
4L                   930.000                  400.000
4L                  1000.000                  990.000
4L                   900.000                 1590.000
5R                  1230.000                  480.000
5R                  1150.000                  970.000
5R                  1200.000                 2070.000
5L                  1030.000                  570.000
5L                  1130.000                 1210.000
5L                  1000.000                 2460.000
6R                  1300.000                  360.000
6R                  1200.000                 1490.000
6R                  1200.000                 2120.000
6L                  1100.000                  620.000
6L                  1230.000                 1360.000
6L                  1170.000                 2310.000
7R                  1400.000                  580.000
7R                  1500.000                  880.000
7R                  1500.000                 1360.000
7R                  1620.000                 2040.000
7L                  1180.000                 1040.000
7L                  1290.000                 2110.000
8R                  1500.000                 1040.000
8R                  1400.000                 1970.000
8R                  1300.000                 2410.000
8L                  1300.000                  950.000
8L                  1350.000                 2240.000
9R                  1500.000                  780.000
9R                  1600.000                 1690.000
9R                  1670.000                 2390.000
```

9L	1350.000	220.000
9L	1300.000	660.000
9L	1200.000	1180.000
9L	1100.000	1520.000
10R	1500.000	670.000
10R	1580.000	1950.000
10R	1590.000	2690.000
10L	1200.000	570.000
10L	1100.000	1720.000
10L	1000.000	2790.000
11R	1300.000	290.000
11R	1400.000	710.000
11R	1500.000	1010.000
11R	1600.000	1430.000
11L	1100.000	690.000
11L	1000.000	1480.000
11L	1020.000	1850.000
12R	1200.000	370.000
12R	1300.000	620.000
12R	1400.000	900.000
12R	1500.000	1290.000
12R	1590.000	1750.000
12L	1000.000	650.000
12L	1000.000	1920.000
13R	1200.000	650.000
13R	1600.000	2260.000
13L	1000.000	250.000
13L	900.000	750.000
13L	1000.000	1600.000
14R	1100.000	480.000
14R	1200.000	850.000
14R	1330.000	1880.000
14L	900.000	310.000
14L	850.000	550.000
14L	900.000	780.000
14L	1000.000	2430.000
15R	1000.000	410.000
15R	1100.000	690.000
15R	1200.000	1410.000
15L	500.000	480.000
15L	980.000	1990.000
16R	1000.000	400.000
16R	1100.000	700.000
16R	1300.000	1490.000
16L	750.000	820.000
16L	800.000	1920.000
17R	900.000	410.000
17R	1000.000	720.000
17R	1100.000	1310.000
17R	1300.000	2520.000
17L	770.000	400.000
17L	800.000	950.000
17L	900.000	2410.000

18R	900.000	400.000
18R	1000.000	1140.000
18R	1100.000	2450.000
18L	800.000	490.000
18L	900.000	960.000
18L	1000.000	1510.000

APPENDIX D

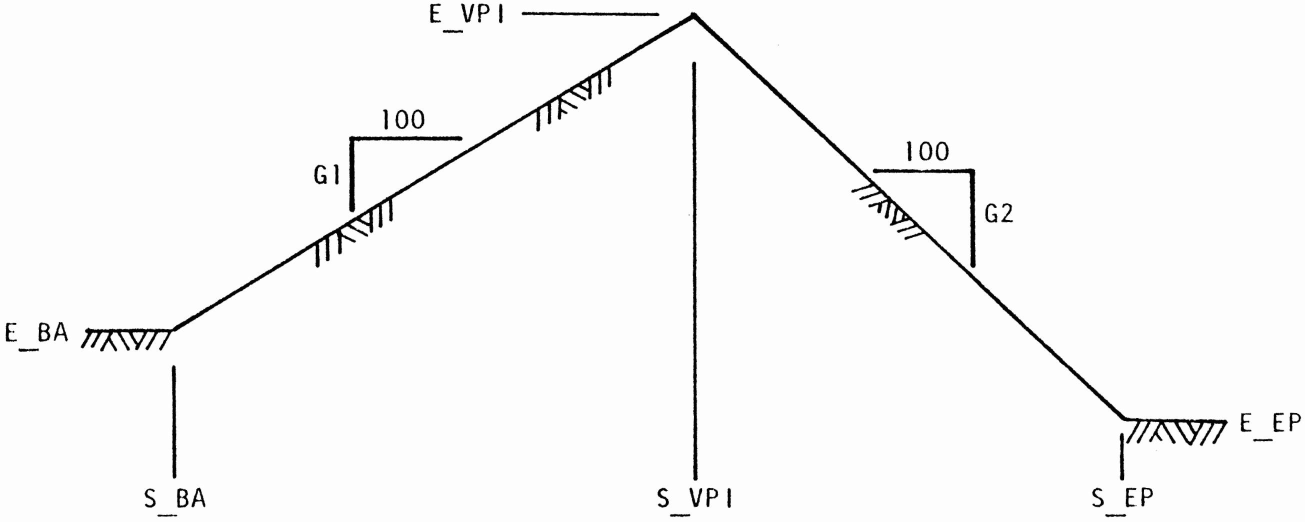
DERIVATION OF CROSS SECTION EXCAVATION EQUATIONS

Derivation of the Station of the VPI With Grade Changes

An important calculation during the excavation subsystem is the position of vertical point of intersection of the grades (VPI) due to a change in proposed grades. Position changes of the VPI determine the length of the positive and negative gradients (G1 and G2, respectively) which is a factor for calculating the quantity of vehicle fuel as well as the quantities of excavation.

Considering equal initial grades (G1 = G2), the horizontal station of the VPI would be mid-distant of the length if the end points are at the same elevation. If the far end point is at a lower elevation than the initial elevation, the VPI would shift closer to the initial point. As the gradient from the initial point is lowered (the slope of the initial grade), the VPI approaches the end point. The resultant position of the VPI for any design or proposed grades would be dependent upon the initial elevations and the relative magnitude of the proposed or trial grades.

Once the station of the VPI is determined for a design grade combination, the elevation or the VPI may readily be calculated. The elevations of the full stations of the proposed grade may then be determined. By knowing the elevations of the initial and proposed grades at any section and the existing cross section, the area of the excavation section may then be determined. Subsequently, the volumes between the sections and the total volume for the grade changes may be calculated. Considering Figure 15, the station of the VPI may be determined for any existing initial and end elevation and a trial grade combination. The elevation



The above terms represent:

E_BA = elevation of the point of initial ascent
S_BA = station of the point of initial ascent
E_VPI = elevation of the vertical point of intersection
S_VPI = station of the vertical point of intersection
E_EP = elevation of the final descent point
S_EP = station of the final descent point
G1,G2 = trial grade combination, left and right, respectively

Figure 15. Grade and Stationing

of the VPI may be determined from either the initial point of ascent or the final end point of descent.

$$E\_VPI = E\_BA + G1 \times (S\_VPI - S\_BA) \times 10 \tag{D.1}$$

$$E\_VPI = E\_EP + G2 \times (S\_EP - S\_VPI) \times 10 \tag{D.2}$$

The factor of 10 is required in both equations since the grade is expressed in percentage and the stations are in increments of 1000.

Permitting the initial station (S_BA) to be zero and setting the equations equal:

$$E\_BA + G1 \times S\_VPI \times 10 = E\_EP + G2 \times (S\_EP - S\_VPI) \times 10 \tag{D.3}$$

Factoring for S_VPI:

$$S\_VPI = \frac{(E\_EP - E\_BA) + G2 \times 10 \times (S\_EA) - S\_BA)}{(G1 + G2) \times 10} \tag{D.4}$$

The above station of the VPI is relative to the initial ascent point and its absolute station would be the addition of the S_BA.

Excavation Estimates for Grade Reduction

The computer program for this subsystem calculates the elevation of the initial design grade and the elevation of the trial grade combination for each 1000 ft station. Each of the trial grade combinations is selected by implementing a do-loop and decreasing the initial grade by one. Thereby, all trial grade combinations are analyzed.

The cross section data (existing elevations and the corresponding distances) are entered on separate data cards with each full station represented by two input cards for the left and right half sections. The area for each section is calculated by summing the areas of the two half sections. The volume is calculated as the product of the distance between the sections and the average of the areas using the average end area method. To correspond with the dual card arrangement of the cross section data, the initial and proposed grade centerline elevations are arrayed as half sections.

The area of each half section is calculated by one or several models depending upon two comparisons. The first comparison is between the extended side slope elevation using the input horizontal distance and the input elevation. If the elevation of the extended side slope is greater than the input elevation, the program transfer to models FOUR or FIVE, computes the area, and terminates the area calculations for that half section. Model FIVE is selected if the previous horizontal input distance is greater than one-half the base width. The selection and area calculations of the models are explained subsequently.

Glossary of Grade Reduction Variables

Common variables which are included in the computer program's area calculations are:

AREA = area calculation from each model;

ARE = storage location for summing the area of each model for totaling the combined area of the half section;

B = one-half the distance of the base width;

BP = storage location of the previous computed BPD. This is equal to EE(I) for the first area calculation;

BPD = elevation of the road section for each input DIST(I,J);

DI = storage of the previous horizontal distance;

DIS = horizontal length of the area section;

DIST(I,J) = corresponding distance from the centerline of the "J" point of the half section "I";

EE(I) = centerline elevation of the proposed grade combination for the "I" half section;

ELEV(I,J) = elevation of "J" point of the half section "I";

SS(I) = centerline elevation of the initial grade for the "I" half section;

SSF = side slope factor or the ratio of horizontal distance to vertical height of the side slope;

TP = storage of the previous ground elevation;

TPI = input ground elevation or SS(I); and

TPIT = elevation of extended side slope using DIST(I,J).

Five Area Models of Grade Reduction

Model ONE: For an area where the input distance is less than one-half of the base width ($DIST(I,J) \leq B$). From Figure 16:

$$\text{Area} = 0.5 \times (TPI + TP - BPD - BP) \times DIS \tag{D.5}$$

where

$$DIS = DIST(I,J) - DI \tag{D.6}$$

Model TWO: For an area that straddles the point where the side slope initiates ($DIST(I,J) > B$ and $B > DI$). From Figure 17:

$$\begin{aligned}\text{Area} = {} & 0.5 \times (TPI + TP - (2 \times BP)) \times (B > DI) + 0.5 \\ & \times (TPI + ELEV(I,J) - BP - BPD) \times (DIST(I,J) - B)\end{aligned} \tag{D.7}$$

where

$$TPI = [(ELEV(I,J) - TP) \times (DIS\ (DIST(I,J) - DI))] \tag{D.8}$$

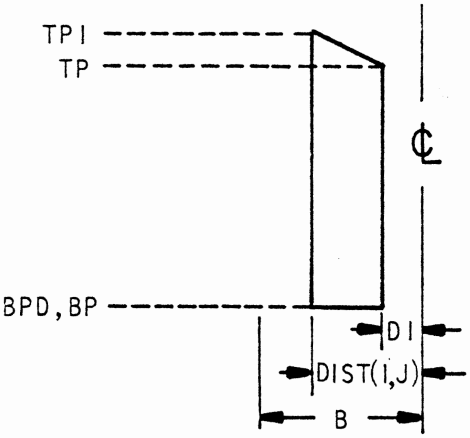


Figure 16. Model ONE

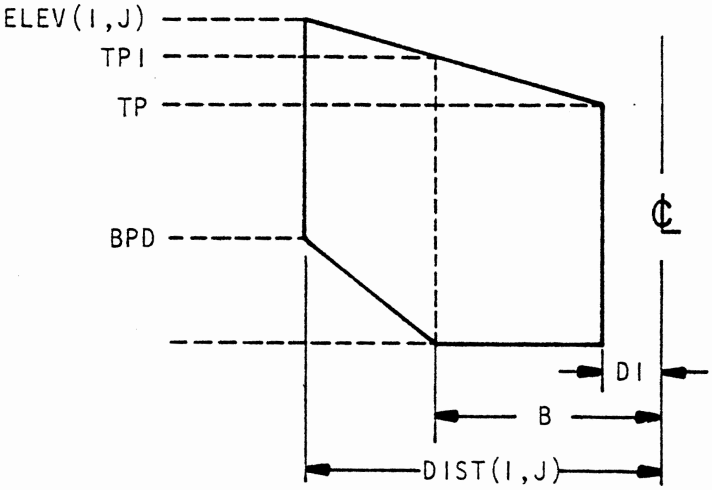


Figure 17. Model TWO

Model THREE: For an area that is a quadrilateral extending beyond the beginning of the side slope ($DI > B$). From Figure 18:

$$\text{Area} = 0.5 \times (TPI + TP - BPD - BP) \times DIS \tag{D.9}$$

where BPD is defined as

$$BPD = BP + DIS/SSF \tag{D.10}$$

Models FOUR and FIVE each terminate the calculations for the area of a half section. All remaining elevations and their corresponding distances for the half section are ignored. The program is structured to start the area calculations for the next half section data card after either model FOUR or FIVE is completed.

Model FOUR: For an area that is formed by a quadrilateral extending to the edge of the base width and a triangle extending from the beginning of the side slope to the slope stake. From Figure 19:

$$TPI = TP + (ELEV(I,J) - TP)\left(\frac{B - DI}{DIST(I,J) - DI}\right) \tag{D.11}$$

Finding the equations of the two intersecting lines and using BPD as the origin, X_SS may be found as the intersection of the two lines:

$$Y = \frac{1}{SSF} X\_SS \tag{D.12}$$

$$Y = \left(\frac{ELEV(I,J) - TPI}{DIST(I,J) - B}\right) X\_SS + (TPI - BPD) \tag{D.13}$$

Letting

$$M = \frac{ELEV(I,J) - TPI}{DIST(I,J) - B} \tag{D.14}$$

and substituting, the second equation becomes:

$$Y = M(X\_SS) + (TPI - BPD) \tag{D.15}$$

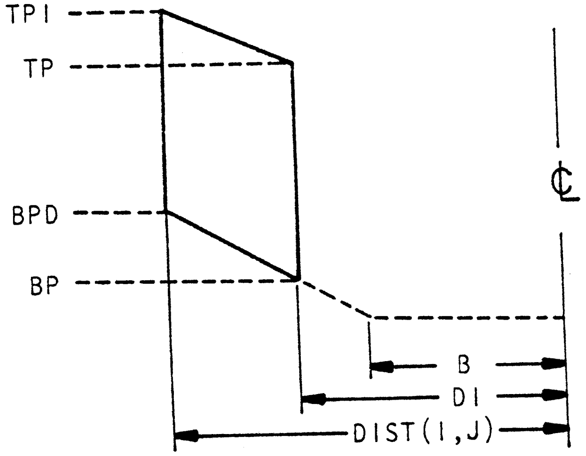


Figure 18. Model THREE

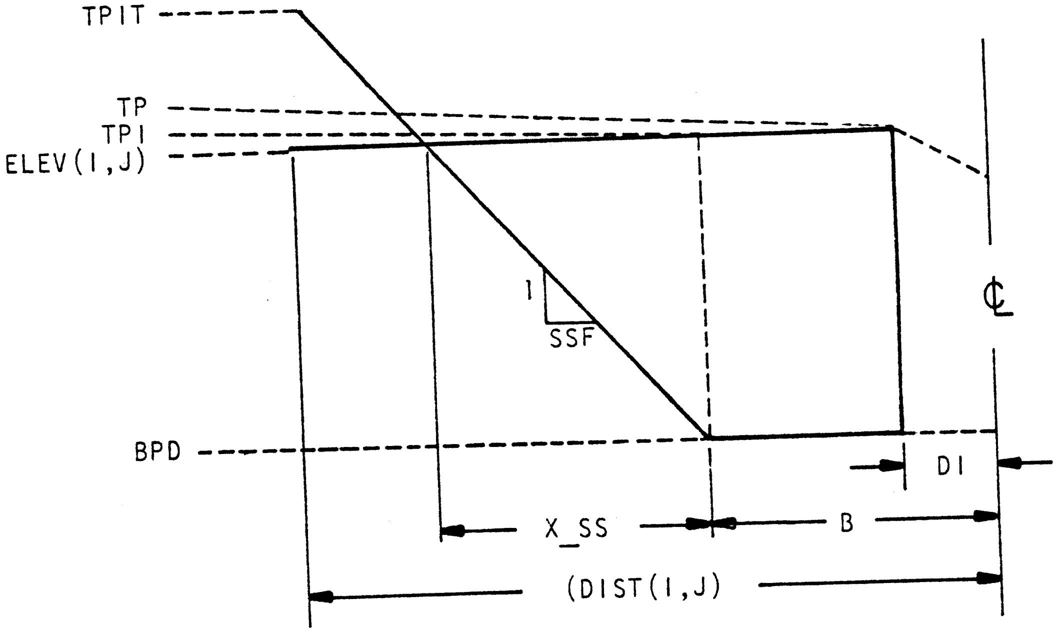


Figure 19. Model FOUR

Setting the two equations equal:

$$\frac{X\_SS}{SSF} = M(X\_SS) + (TPI - BPD) \tag{D.16}$$

and dividing each term by X_SS:

$$\frac{1}{SSF} - M = \frac{TPI - BPD}{X\_SS} \tag{D.17}$$

Factoring for X_SS:

$$X\_SS = \frac{TPI - BPD}{(\frac{1}{SSF} - M)} \tag{D.18}$$

$$\text{Area} = 0.5\ [TPI + TP - 2(BPD)]\ (B - DI) + 0.5\ (X\_SS \times (TPI - BPD)) \tag{D.19}$$

Model FIVE: For a remaining area that is formed after models TWO and THREE have been calculated from Figure 20:

$$M = \frac{ELEV(I,J) - TP}{DIST(I,J) - DI} \tag{D.20}$$

Similar to Model FOUR:

$$X\_SS = \frac{TP - BP}{(\frac{1}{SSF} - M)} \tag{D.21}$$

$$\text{Area} = 0.5\ [X\_SS \times (TPI - BP)] \tag{D.22}$$

Following the calculation of area by model FOUR or FIVE, the program then begins calculating the next half section (if there are any remaining).

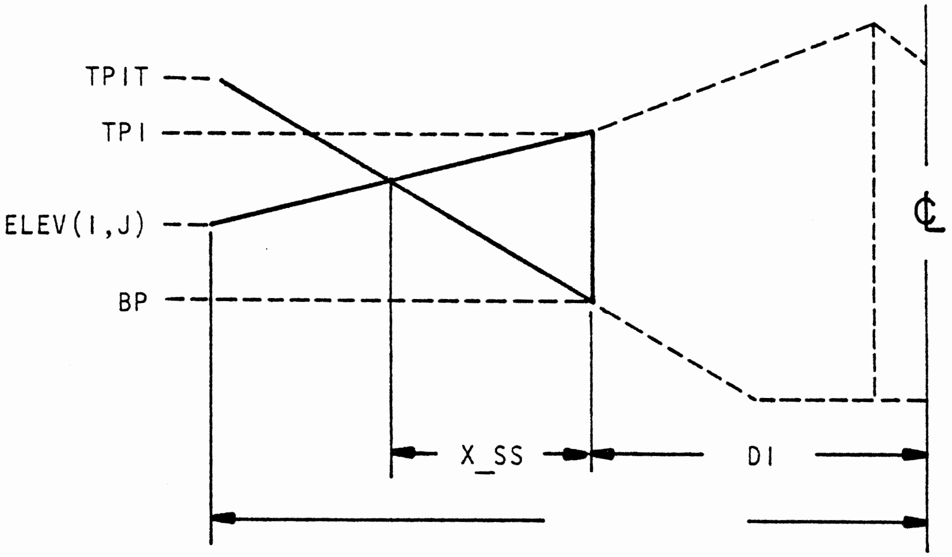


Figure 20. Model FIVE

VITA

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Doctor of Philosophy

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