Estimating Highway Vehicle Operating Consequences

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This paper presents an analysis framework for the process of estimating consequences of highway vehicle operation, and describes the ROADS model developed from it. It begins by suggesting a number of requirements for an ideal system. Factors affecting vehicle operation and performance are grouped by source and examined for types of relations to operation. From this, the structure of a theoretical model of the prediction process is derived. This structure is then examined with regard to several alternative approaches to its implementation.

A general description of a model specifically designed using the framework developed is presented. A major extension in this model is the combination of a vehicle performance model and a traffic congestion model. This provides the capability of seeing both the effects of vehicle performance on traffic congestion and those of congestion on vehicle performance.

•THE cost of vehicle operation, often estimated to be several times as great as the cost of building highways, has been of long-standing concern to highway transportation analysts and planners. Accurate vehicle cost information is difficult to obtain; no contracts are made or fees charged for highway transportation purely on the basis of roads driven. No real records are available to relate operating costs and consequences to specific highway design. The cost of vehicle operation remains one of the least understood aspects of highway transportation analysis.

This paper describes the design of a system to obtain the consequences of over-the-highway vehicle operation as related to highway design. This system is designed to work within a flexible and long-range logical framework, and to be usable by the highway engineer, the transportation planner, and the reseacher alike. A system based on work already done is illustrated rather than a totally new approach.

THE PROBLEM OF PREDICTING VEHICLE PERFORMANCE

A number of trade-offs between money spent on highways and money spent on vehicle operation are immediately evident. For example, savings in fuel consumption result from lower grades. Grade separation of intersections saves stops and hence fuel, tires, brakes, and time. It is in the interest of the public as a whole to optimize the use of resources for highways since it pays, either directly or indirectly, for highway transportation. The highway user benefits most from this, through lessened expenses and taxes, but others—property owners and users of transported goods—may also benefit. Two circumstances must exist before optimization of highway transportation should be attempted. First, the highway planner must realize his responsibility in the use of public funds as a whole. Second, and probably more important, much must be learned about the factors involved in the cost and benefits of highway transportation.

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This latter problem can be subdivided into two problems, one of data acquisition, and the other of data analysis. Analysis of costs and benefits is concerned with higher level network analyses, and will not be discussed here. Data acquisition, specifically of vehicle operating consequences, is the subject of this paper. One additional distinction is made in this report—that between consequence prediction and consequence evaluation. Because evaluation places explicit value ratings on consequences, it requires adopting a point of view and defining objectives, which cannot always be done at the data-collection level. Immediate evaluation ignores price differences between localities or countries. Also, especially in underdeveloped countries, the very existence of a project may upset the supply-and-demand equilibrium, causing prices to increase above original estimates. There is often no real need to separate consequences and costs, but to avoid the possible pitfalls for the theoretical discussion in this paper, it will be done.

A great deal of study has gone into many aspects of vehicle operation consequences, but most work has combined the prediction and evaluation steps by using estimates or standard values for costs. As a result, they have become known as "user costs" studies. The values often used, especially for fuel, are prices. [The danger here is that the price used for gasoline (about 30 cents) includes about 10 cents tax, which is collected for highway construction and does not reflect the cost of obtaining the fuel. The tax is really a user charge for highways.] Prices do not always reflect costs accurately. Also, costs may change over time and most of the "user cost" studies do not provide a way of updating values.

The accuracy of the predictions of consequences by many systems, it is to be hoped, can be improved with a better understanding of what the real sources are. Even for more deterministic consequences, such as fuel consumption, a comparison between studies made during this investigation shows that predictions can vary by more than 50 percent under identical circumstances. Little has been done to coordinate the variability of consequences resulting from traffic with those from other causes. The costs of delay must usually be considered implicitly in a highway design as separate from costs resulting from other consequences. Often, because of the difficulty in estimating them, important consequences such as accidents, comfort, or convenience are completely ignored or only lightly treated, as are many other situations or combinations of circumstances. Only situations for which the data were specifically taken can be studied. What is lacking is one comprehensive framework to combine these findings into a set of unified information useful not only for all design studies but also for guiding future research work in this area.

DEVELOPMENT OF A THEORETICAL FRAMEWORK FOR CONSEQUENCE PREDICTION

A framework for estimating vehicle and driver-traffic performance should be able to provide the different types of information necessary for decision-making at several levels. It should not include any decision-making beyond that of consequence prediction. Evaluation, optimization, and planning should be done with the results of predictions of vehicle operations in conjunction with predictions of other roadway economic and noneconomic factors.

The qualifications for such a framework can be considered, although they will vary with each particular situation. The most important should include the following:

· Wide Application—The models available today are of limited scope in application. This often renders them ineffectual or difficult to use in situations for which they were not specifically designed. Adaptability suggests that a multilevel set of methods might be used, each level having different applications and hence different accuracy requirements. Each level could then use the most reliable methods known for the data available. Multiple level also suggests that each level should be able to identify the important input parameters—the most relevant factors at that level which determine the consequences. A third consideration for wide application is the ability to handle uncertainty. At lower levels, less is known about the situation. Therefore some estimate of the uncertainty of predictions can be valuable, for example, in determining if a study is worth pursuing in more detail or whether an alternative should be sought.

· Natural To Use—The model should be easy to use. It should not require any unnatural formulation or decomposition of a problem. The user should be able to modify his formulation of problems easily to investigate alternate solutions. Accuracy should not be sacrificed for simplicity, but it should be relatively easy (compared to present methods) for the engineer to specify his problem.

· Economical—Extensive time or money should not be required to produce acceptable results. The economies that develop from its use should be orders of magnitude greater than the cost of using it. The development costs should also be considered in overall economy.

The foregoing requirements imply a system of use that minimizes the engineer's routine work in favor of his creative efforts. An example of systems designed to do just that are the recently developed problem-oriented computer languages. They attempt to maximize the ease of man-machine communication to provide the user with the full capabilities of the computer. The languages are designed to be as conversant in the area of application as is presently possible so that the user can specify his formulation naturally.

To understand how the requirements affect the internal methods for this framework and to develop a better understanding of the general characteristics of a theoretical model, the next sections examine the input or independent parameters of the vehicle operation consequences prediction problem, and propose a general structure for its solution.

Input Parameters

The number of input parameters affecting the consequences of vehicle operation is extremely large and under certain circumstances almost any one of them may become an important factor. To understand the source of operating consequences the independent parameters should be identified. Many of the input parameters to existing methods are not independent but are often functions of several factors, such as grade-climbing ability, which depends on vehicle power and weight, or speed-volume curves, which are aggretates of all drivers. Feedback can occur, especially over the long term when aspects of the inputs influence highway design decisions and consequently change the inputs. Poor highway designs combine with driver characteristics to cause accidents, causing similar designs to be avoided in the future.

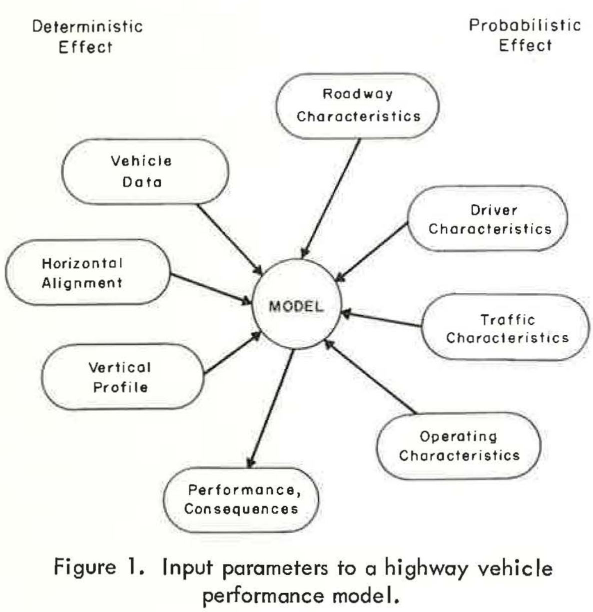

Figure 1. Input parameters to a highway vehicle performance model.

For convenience, various independent input parameters have been classified into several categories (Fig. 1):

Vehicle Data—This class includes such parameters as vehicle weight, engine power, fuel consumption rates, and vehicle resistance factors. Consequences also depend upon a multiplicity of other vehicle parameters, such as gear ratios, auxiliary loads, engine bore, stroke, compression ratio, maintained condition of vehicle and engine, and type, condition, and inflation pressure of tires. Of all these, weight is generally the most important factor in fuel consumption, and power is the most important in unrestrained speed.

Vertical Geometry—The vertical geometry of a road affects the gravity resistance a vehicle encounters when raising or lowering its weight along a vertical alignment. It may be expressed as grades or elevations, lengths of grades, and vertical curve information. The primary influence of vertical geometry is on speed and fuel consumption. It may also influence the driver's desired speed because it may limit sight distance and may also cause uncomfortable vertical accelerations.

Horizontal Geometry—The horizontal parameters of interest for vehicle performance are lengths of curves, their radii, and their superelevations. Curves have two primary effects on vehicle operation. Rolling resistance increases and centrifugal acceleration limits the speed of operation. Curves may also affect sight distance and consequently operation.

Road Characteristics—Almost anything describing the road other than its geometry can be included in this set: number of lanes, shoulders, medians, type of pavement and surface coefficients of friction and resistance, types of access, lighting, markings, restricting construction, etc—the external physical circumstances that affect the driver and his use of the vehicle.

Traffic Characteristics—Traffic data consist of vehicular traffic volume distribution over time or space, vehicle fleet composition (breakdown of types of vehicles and their numbers in the traffic), and certain facts about their origins and destinations. Traffic not only influences the driver's desires, and possibly, through accidents, vehicle performance, but it also generates total consequences, which are the sums of those for each of the individuals making up the traffic stream.

Driver Characteristics—A set of data describing each driver's pertinent physiological and psychological characteristics may not exist. If it does, no method is yet available to directly use such data in vehicle operation prediction. This data class includes such human descriptors as perception-reaction time, experiences,temperament, and decision abilities and criteria or judgment.

Operating Characteristics—This class includes essentially everything not included in others, but it usually represents those parameters that are time-dependent or legally imposed, such as weather conditions, speed limits and degree of enforcement, accidents, parking, and lane-use restrictions—passing lanes, one-way lanes, etc.

Vehicle data and horizontal and vertical alignment usually have a deterministic effect on consequences. Road, traffic, and driver and operating characteristics have primarily a stochastic effect on vehicle operation and consequences. In addition, the last three, especially traffic and driver characteristics, are stochastic in nature as well.

Since existing user cost methods cannot use most of the basic parameters, some modified and simplified parameters have been designed to approximate their effects. A few of these are shown in Figure 2 and described below.

The higher level category contains parameters that are generally independent of each other. The second level shows some derived parameters that have been developed either to implicitly account for some of the higher level factors or to simplify them by combining several into a single function.

Vehicle data may be estimated by analyzing the results of experiments with an average vehicle of a given type or class. The assumption is that operation of all vehicles of the same group will have similar consequences or at least average the same. Another category, power-to-weight ratio, has been shown to be an effective classification, especially for trucks. They probably have a more uniform type of driver and encounter less interference from other vehicles.

Average grades, and rate of rise and fall have been used to simplify the vertical geometry description. Rate of rise and fall is the arithmetic sum of the changes in elevation along an alignment divided by the total length of the alignment.

The combined effects of grade, length of grade, and power-to-weight ratios have been presented in some graphs (22,9), representing two classes of data. Other schemes simplify the accounting for horizontal curvature effects (3).

Because of uncertainty in drivers and traffic and operating characteristics, a number of derived parameters have been developed to estimate the distributions and averages of these characteristics. Annual Average Daily Traffic (AADT) and even Hourly

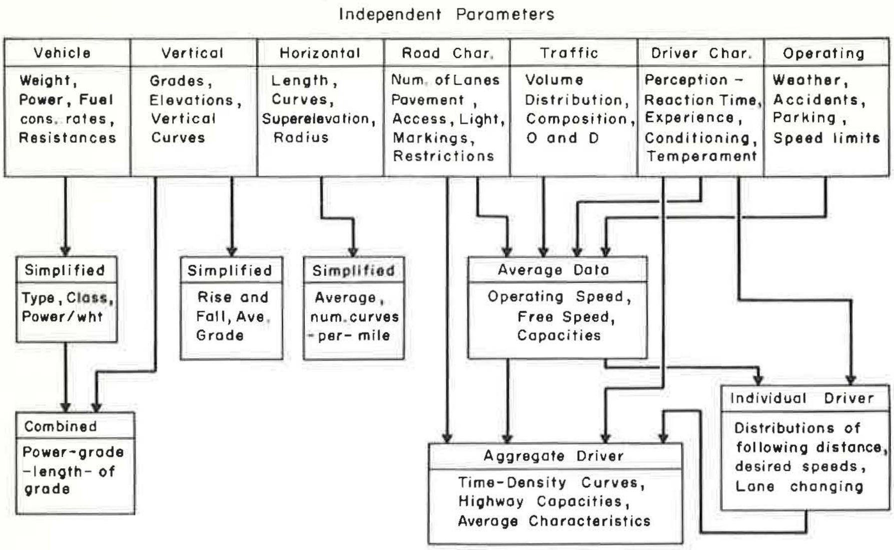

Figure 2. Input relations and forms.

Distributions of Traffic (HDT) are simplifications of the second-by-second fluctuations in traffic volume. Driver characteristics together with the vehicle data describe an integral system interacting as an entity with other driver-vehicle systems and the road. Consequently most of the input to many present models is really a combination of these two. Vehicle fuel consumption rates also imply something about the driver. In addition, driver parameters can be combined with those of other categories to get a better understanding of his behavior. Road characteristics combined with these produce desired (free) speed distributions or average free speeds. To include the effects of traffic, distributions of the following distances and of lane-changing and passing criteria are used. The average effects of road, traffic, and driver characteristics are measured by operating at average travel speeds, and the aggregates of these parameters are the capacity and time-density or time-volume curves (6).

Considerations for a Theoretical Model

To accurately predict consequences of motor vehicle operation, the large number of factors affecting this, coupled with their stochastic nature, would require continuous monitoring. Because of this sort of detail it is necessary to consider some of the possible restrictions on a model so that simplifications can be made. Highway planners and designers are not concerned with predicting consequences of a specific driver, vehicle, and road situation, but rather with the totals, averages, extremes, and variances of the consequences of large numbers of situations. This implies something about the nature of the simplifications. Some conclusions can be drawn by looking at each of the types of factors.

The designer is usually concerned with a specific roadway or type of roadway. Any given point on a roadway can have only one combination of horizontal, vertical, and roadway characteristics. Changes in these characteristics, with few exceptions, are deliberate and they are permanent until deliberately changed again. Therefore, once defined, the parameters can be used for all consequences predictions on a given part of a roadway.

Vehicles using roads appear to have a fairly continuous spectrum of characteristics. These can be simplified by classifying vehicles by some characteristics that yield fairly consistent consequences among all members of the class. Classification by vehicle type is one grouping that can be used. Types are defined by major descriptors such as compact auto, delivery van, and 2-S1 semi tractor-trailer combination. Vehicles of one type tend to have fairly consistent characteristics that are then represented by a somewhat fictitious "average" vehicle having characteristics that produce a set of consequences average for the group.

Another method of classification is by weight. This is usually the major vehicle factor in operation consequences. Classification by power-to-weight ratio tends to lump together those vehicles with similar performance in acceleration and grade-climbing ability.

The remaining three sets of parameters—operating, driver, and traffic—are mostly probabilistic in nature and present a different type of problem. The most common solution is to assume a uniform set of circumstances and use expected or average values in a model. The dangers of this assumption are not always clear, and lie in the nature of the mathematics random variables. As a simple example of this purpose, a random variable has a $\frac{1}{3}$ probability of being 1, 2, and 3. If y is defined as the function $y(x) = x^2$ then the following is true for a large sample of x:

$$\text{average, } x_a = \frac{1 + 2 + 3}{3} = 2$$

$$\text{average, } y_a = \frac{1 + 4 + 9}{3} = 4\tfrac{2}{3}$$

$$\text{However, } y\,(x_a) = 4 \neq 4\tfrac{2}{3}$$

Using the average value of a distribution of an input parameter will not always result in a prediction of the average consequences. If the consequences vary linearly with a parameter, however, the average value can be used. A study by Ruiter (16) indicates that fuel and time consequences do vary linearly with driver characteristics as reflected in average speed distributions. This implies that average driver characteristics can be used without much loss in accuracy and can be considered as defined by a function of position along the road, traffic density, and vehicle driven.

Several studies (6, 8, 22) indicate nonlinear variation of consequences with traffic density. Therefore, it appears necessary to consider each traffic situation separately. One method is to sum the lengths of time which have the same traffic flow rate. Consequences are assumed to be the same for identical flows. Little has been done to investigate the relationships between flow rates and consequences except to point out that a range of average speeds may exist at a given flow. In addition, vehicle mix in the flow, and in some cases the directional split, should be considered when choosing a situation that might be assumed to give identical consequences.

The relationships between operating characteristics and consequences are at present unclear. In general, these are influences on driver behavior and are reflected in operating behavior. A number of studies have been made on the effects of speed limits, parking, and accidents on consequences, but little can be said except for a few specific conclusions.

On the basis of the foregoing independent parameters, a general vehicle operation consequence prediction model must be sensitive to at least all of the more important of them. If vertical, horizontal, and roadway characteristics can be defined as a function of position along the road, traffic density as a function of a time-dependent distribution, vehicle fleet composition as a distribution over selected representative classes, and drivers as a function of all three, then a set of summations of consequences can be made over these three categories of independent parameters. This means that by summing the consequences for each vehicle class for each traffic density and composition, and for each different segment of a roadway, the total consequences incurred by the operation of all vehicles over the roadway can be estimated. This is shown in Figure 3. The actual order of looping depends on the precise method used for the consequence prediction.

The driver's desired driving speed free of any traffic (free speed) is a function of the physical features of the road, his knowledge of it, how rushed he is, his temperament, how well he can control the vehicle, and probably many more subtle psychological factors. In addition to these, his desired actions as a function of adjacent vehicles (traffic factors) and his acceleration and directional desires (lane changing, turning, etc.) are necessary to define his characteristics. The usable form of driver-related parameters is one modified by road, traffic, and operating characteristics. This form consists of three types of data: his desired speed, desired changes in speed, and desired direction.

Predict Vehicle Capabilities—The previous step examined the driver independent of what the vehicle could do for him. This step examines the vehicle independent of what the driver can do to it, specifically, the vehicle's speed capabilities as a function of its previous speed; the speed changes it can undergo as a function of its speed, road and other resistances, and power left for acceleration; and possibly its directional capabilities—how fast it can change lanes or turn.

Determine Actual Travel Possibilities—Combining driver behavior and vehicle capabilities modifies the driver's desires by the existing situation and imposes them upon the vehicle, which may or may not be capable of executing them. When the vehicle cannot perform as the driver desires, this of course must affect his driving desires, especially if it is an accident-producing situation. Also, the driver must act within the traffic constraints around him. He must slow down for other vehicles ahead when he feels it is not possible or safe to pass.

Predict the Consequences of Vehicle Operation—Once a prediction of the vehicle's operation is made, the consequences of this should theoretically be predictable. Besides fuel, time, oil, tires, and other physical consequences, the consequences should ideally include some measure of those occurring to the driver such as frustration and discomfort. Most difficult to predict may be the more stochastic consequences such as accidents. Probability distributions associated with the consequences could be useful in decision-making at higher levels of design analysis (10).

Alternate Approaches to Implementation of the Model

Three approaches to the problem of predicting consequences are found in the literature. Each can be used in the structure suggested above.

Tables or Graphs—This approach is used by most present methods. Tables and graphs are relatively quick and easy to use, and require little understanding of the behavior of vehicle performance. Relatively few calculations are necessary for the simpler methods, and the convenience of use to the highway designer is unsurpassed. The problem this method faces is the presentation of multidimensional results in two-dimensional graphs or tables. A computer capable of handling a multidimensional system could conceivably handle this approach fully, except that the size of the matrix increases very rapidly with increased dimensions. Even with some sophisticated matrix-reduction techniques, the number of variables for wide application appears so great that an unwieldy matrix seems unavoidable. The data collection for all the matrix elements is also no small problem, since the data as presented are essentially empirical and imply making a test to obtain data for almost every element. In addition, revision or updating could be quite difficult, since large portions of the matrix would probably need adjustment. Present tabular methods consider only a very few of the important factors and consequences.

Multiple Regression of Factor Analysis Equations—All that is required to use this approach is to supply input values to an equation. No table searches are required, although the user might have to choose between several equations. Only slightly more computation might be necessary to obtain final results than is required in the use of tables. Oppenlander's experiences in predicting speed for one small class of rural open-country Illinois roads (12) seem to indicate an immense data collection and reduction problem to produce a complete set of equations. While the final result is easy to use, the difficulties and expense of change and data collection may be even greater than for the tabular approach because of the additional data analysis necessary to prepare the equations.

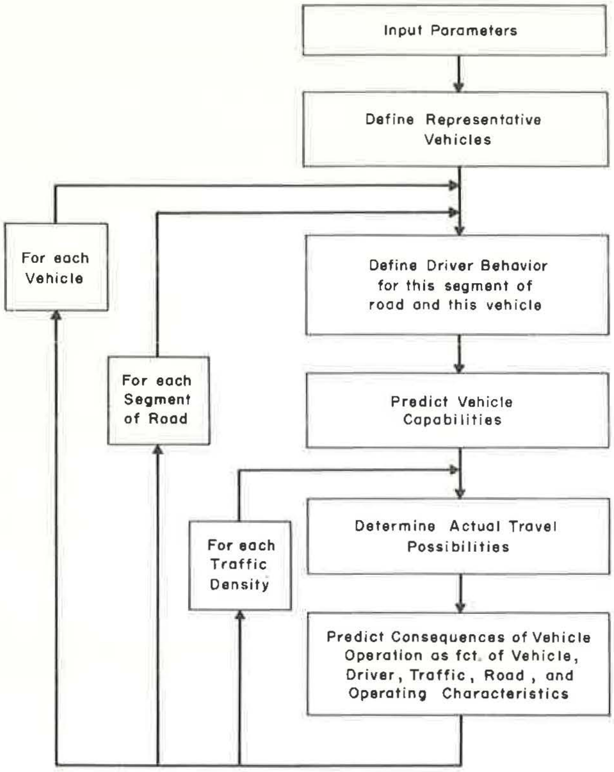

Figure 3. Steps in predicting vehicle operating consequences.

Structure of a Theoretical Model

Five theoretical steps occur in combining the input parameters for the actual preduction model (Fig. 3). (These are only general steps and do not necessarily need to be done in this order.)

Define Representative Vehicles—As indicated above, consequences vary greatly between different types of vehicles and even among similar vehicles. This step attempts to obtain an accurate measure of the variables affecting the total consequences of all vehicles using the road. Choosing vehicle groups of which members can be represented by one particular vehicle's characteristics seems to be the most practical way. Unfortunately, the assumption often is that one average vehicle, usually an automobile, or an average of a group can be used to predict the average consequences of all the vehicles. There is no evidence as yet to support this conclusion, and what can be deduced tends to show just the opposite. Thus, no single or small group of two or three vehicles should be used in more than a very rough prediction. A quick example may help to illustrate this. Many methods tend to neglect the importance and variability of truck consequences.

Grades under 8 percent rarely affect present American cars except in fuel and oil consumption. Truck consequences, on the other hand, are severely affected by grades of even small percents. The number of trucks and buses is increasing rather rapidly and now constitutes over 20 percent of all registered vehicles. Also, these vehicles, especially the larger ones, tend to cover more vehicle-miles per year. Larger combination vehicles travel an average of 60,000 miles per year vs 10,000 miles per year for autos. While combinations are less than 2 percent of registered vehicles, their estimated operating costs are four to five times as great per mile as those of autos. Multiplying cost per mile times miles per year indicates that these trucks alone incur about 20 percent of all highway operating costs, while other trucks incur another 25 percent. Considering the effects of trucks on auto traffic flow, it seems safe to say that over 50 percent of all operating consequences occur because of the operation of only 20 percent of all vehicles. Considering that less than 10 percent of these trucks cause half of all truck consequences, the variability of consequences as a function of vehicles can be seen. Since even the power-to-weight ratio factor provides no more than a rough estimate of this effect, summing over many types of vehicles seems necessary.

Define Driver Behavior—A vehicle's attempted performance on a road depends largely on its driver's desires and capabilities. These parameters include desired driving speeds, reaction to surrounding situations, and driver-vehicle interactions. Many studies have been performed on the driver to obtain knowledge of his performance in various driving situations and in the man-machine interactive system. It is not clear if much of the work available is usable in models for predicting vehicle-operating consequences.

Simulation or Theoretical Models—Most simulations are basically a cause and effect theoretical model. By establishing the relationships between consequences and the factors affecting them, considerably less empirical data are necessary. The main effort goes into model development rather than data collection. One saving factor is that much usable work has already been done by vehicle manufacturers and other researchers. Entirely new factors can usually be appended to the model just by adding the appropriate relationships. Additions to a model using this approach add to rather than multiply its size. Modifications involve only a recalibration rather than taking all new data. The simulation approach may be difficult to apply to subjective or nondefinable relationships. A rather large computational and logical effort for each problem is required to produce results. New computer systems now being developed could provide for tremendous ease of use, if the model and programs are structured properly.

The first two approaches are primarily empirical, the first presenting essentially raw measurements, the second performing an analysis of the raw data and presenting factored results. The last uses empirical data only to calibrate a theoretical model. The present state of the art would suggest that the best approach might be some combination of these.

Although highly dependent on the specifics of the model, some estimate can be made of the complexity of producing such a combination. Experience indicates that the complexity of a simulation model increases roughly in proportion to the number of factors included. The size of tabular models and the reduction of regression equations appear to increase as a higher order power or exponentially. The implications of this seem to be that tables or equations are better for preliminary or general analysis because simulations are too big or difficult. For highly detailed analysis, simulation is better. The difficult question is where the transition point between them lies. This will depend, to some extent at least, on the specific application and, most likely, it is in a continual state of change as more research is done. The trend today, with a greater realization of the complexity of the problem and more powerful models available, is toward ·re detailed analysis.

THE ROADS MODEL

The ICES-ROADS vehicle performance model results from the application of this investigation to the present methods of vehicle performance prediction. The model is designed for inclusion in the integrated computer system of civil engineering programs now being developed at M. I. T. (ICES). It is intended to be a practical application of a theoretical study of the principles and processes of the prediction of the costs and consequences of vehicle operation on roadways. It is designed for integral use in a highway location and design package (ROAD); however, considerations were made for its use with other ICES subsystems such as that for transportation planning (TRANSET).

Basically it consists of two models that have been coordinated to produce better and more comprehensive results than either could alone. These are a vehicle model and a traffic (or driver) model. The ROADS model is the only currently available method as comprehensive that operationally combines both of these (Fig. 4). For the first version of ROADS no new methods have been developed; however, a number of existing methods have been improved, made compatible, and linked together. The eventual plan is to expand both the scope and number

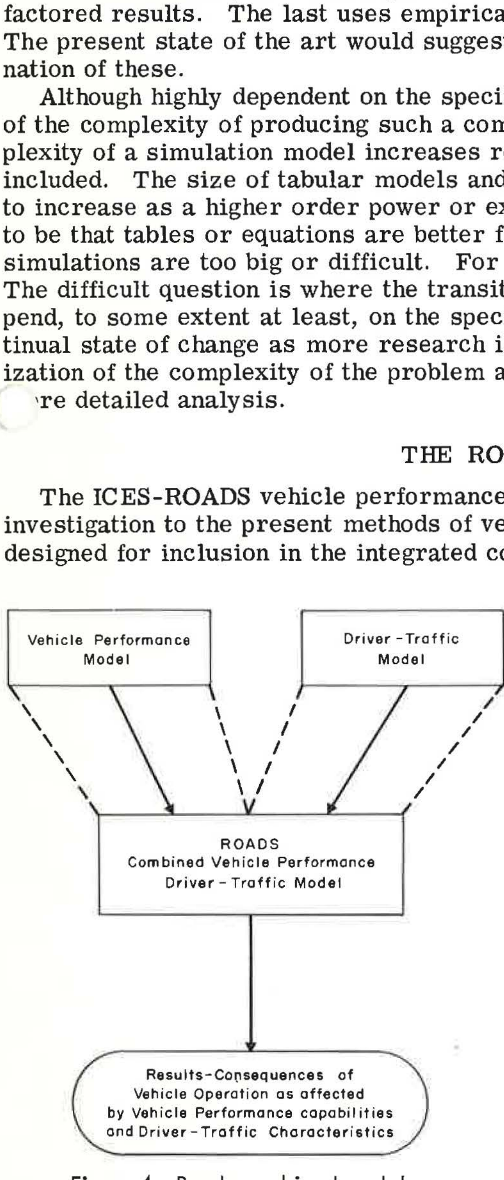

Figure 4. Roads combined model.

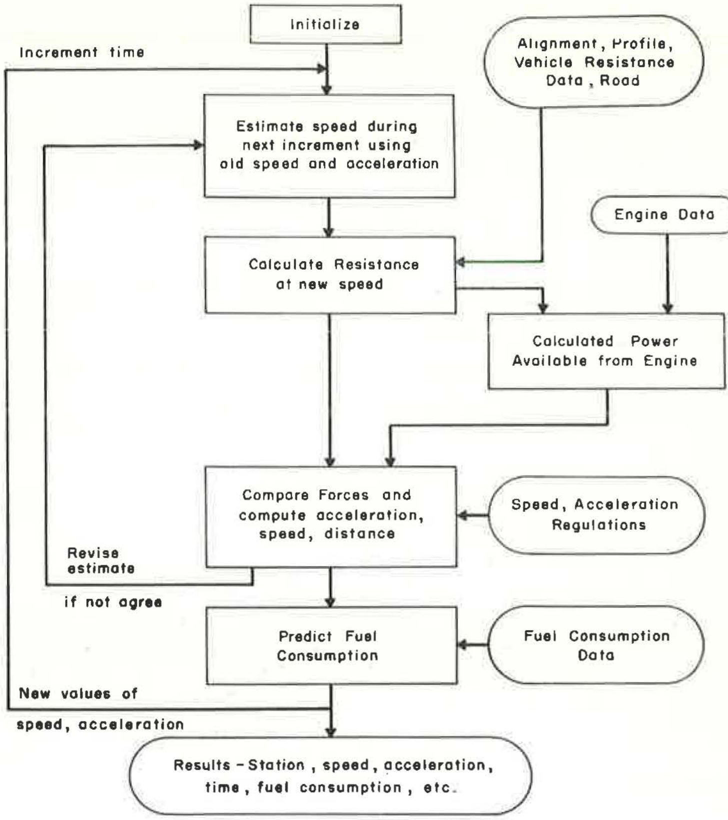

Figure 5. Vehicle model.

of consequences predicted, to provide several levels of accuracy, and hence speed and ease of use; and to improve the methods used and develop new, more effective ones.

The Vehicle Model

The vehicle model is essentially an expanded version of the M. I. T. vehicle simulation program. The model has been recalibrated to include some of the most recent data available (12). Definition of representative vehicles is part of the system to the extent that a library of detailed vehicle data is available to the user. He may choose from these or define new ones. Newly defined vehicles can be added to the library and all vehicles will be available to users by a short identifying name, for example, vehicle AVE AUTO.

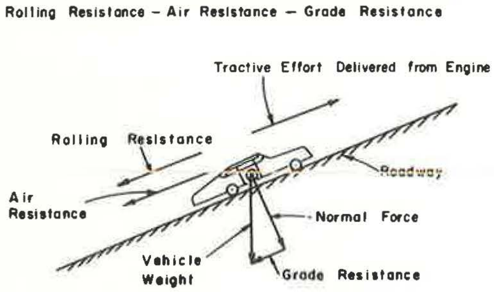

Figure 6. Simplified free body diagram of vehicle and roadway.

The model (Fig. 5) is basically a general model for internal-combustion, piston-engine powered highway vehicles, although it does have some restrictive inherent characteristics, such as only being applicable at present to gasoline engines. It first predicts the vehicle speed for the next time increment as a function of the previous speed and rate of acceleration. The resistance at this new velocity is computed according to Figure 6 and the power required is compared with that available. If require-

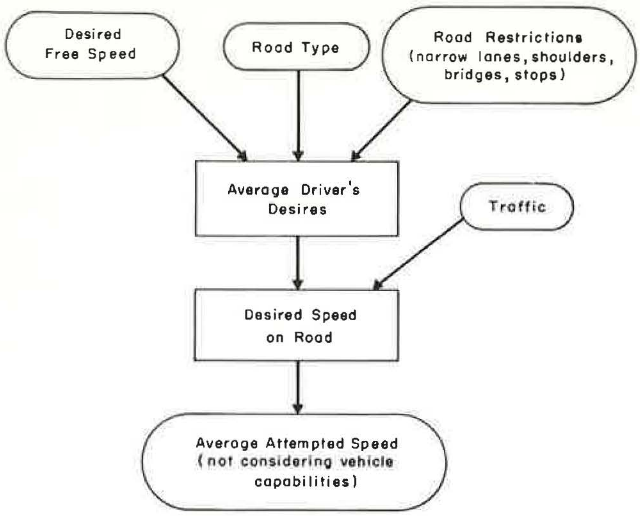

Figure 7. Driver-traffic model.

ments are too great, only that power available is used and a new acceleration and speed is computed. Speed is also compared to the maximum allowable speed and adjusted accordingly. Next, fuel consumption is predicted on the basis of actual energy consumed during this time increment. This is done by obtaining from a generalized table a unit fuel consumption as a function of engine speed and power output. The use of only one table is the cause of the current restriction that engines be those of average design and compression ratio, and that they consume gasoline. By providing a choice between several such tables, this restriction could be removed.

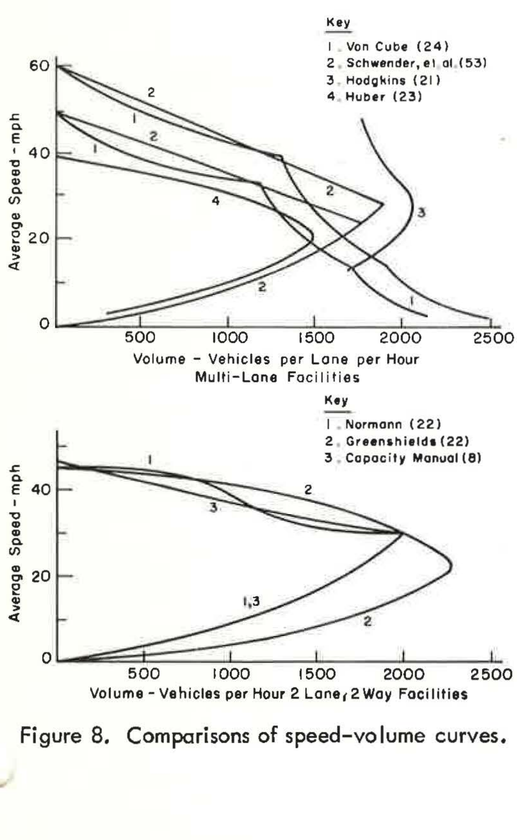

Figure 8. Comparisons of speed-volume curves.

Driver-Traffic Model

A tabular driver model is used in the first version. Most of an average driver's characteristics are derived from the program user's descriptions of the road, vehicles, and traffic conditions. A description of what the user thinks an average driver's free speed (speed with no traffic) would be on a particular road is necessary. At present there is no adequate model that considers enough of all the important parameters producing this critical aspect of a driver. It is hoped that later models will derive this from primary data by either a regression or a thoretical model.

The model presently is designed to predict the general aspects of driver performance and its effects on consequences (Fig. 7). One is the driver's effect on average vehicle speed. This is done through generalized travel-time traffic-volume curves (Fig. 8). Two types of input are required to use these: road description and traffic information. For purposes of identifying separate sets of these curves, roads have been categorized into nine general

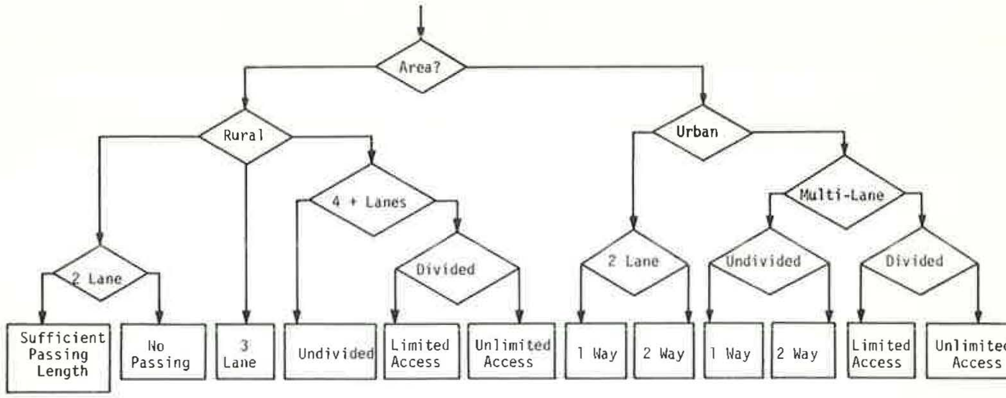

Figure 9. Roadway type identification process.

types (Fig. 9). Roads are classed by six different descriptions which the user inputs—urban or rural, number of lanes, divided or undivided, limited or unlimited access, passing or no passing, and one or two-way traffic. In addition, such factors as lane width and side restrictions are converted to volume adjustment factors. Free speed input by the user will also be adjusted because the time-volume curves are for the ideal case of wide lanes and no side restrictions. To use these in more restrictive cases, the input free speed needs to be adjusted upward.

The second input for the time-volume curves is traffic information This includes not only volumes but also the vehicle mix and number of hours of each volume. The user may input total volume and percent of each type of vehicle or he may input each vehicle by name and its volume. All remaining volume will be assigned to a vehicle previously designated to be assumed. Traffic volumes are adjusted for different types of vehicles

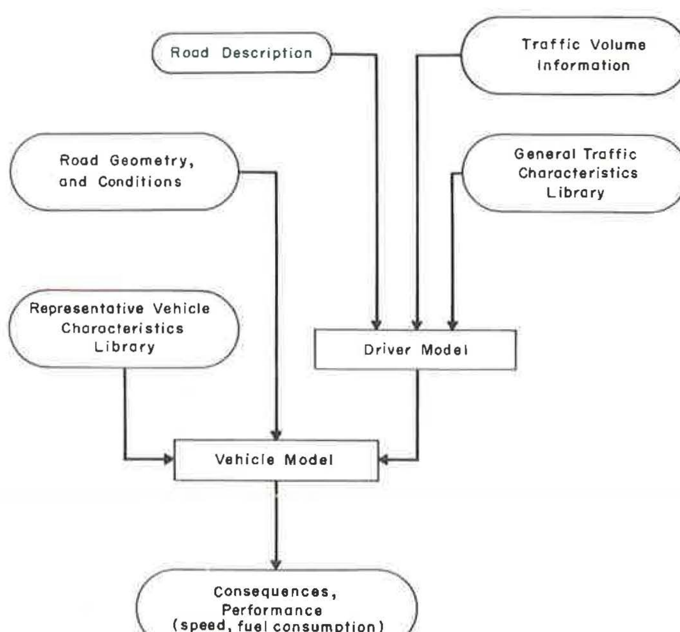

Figure 10. Complete model.

because the time-volume curves used are for equivalent units of automobiles only. A truck is given a car-equivalent factor based on the difference between its speed and that of a car on a particular portion of a road. This will be used to simulate such traffic-clogging effects as slow trucks on long steep grades where cars could go much faster, except for the trucks.

The Combined Model

To understand better just how the various types of vehicles have varying effects on traffic flow as a whole and consequent average travel time, we can examine what might be considered the interactive or modified traffic model (Fig. 10). Vehicles, for a particular volume level and portion of the road, are ordered by their weight-to-power ratios. The lowest-powered vehicles are simulated first (those with the highest weight/power). The car equivalence factor is computed by comparing the speed of this vehicle to what an auto could do if all the traffic were automobiles. The critical assumption is that the lower-powered vehicles receive no additional interference from higher-powered ones other than the fact that they are there. They will not be slowed down because of higher-powered vehicles' inability to move faster. Driver characteristics are input with the road description as free speeds. Other aspects of driver characteristics are implicit in the model.

Input of the vertical and horizontal alignment is the same as for the highway location and design model; in fact, the user may reference alignment already specified for that model. The input form will be the same as for COGO, another subsystem of ICES and a widely known command language used in solving civil engineering geometric problems.

Initial values for vehicle speeds, vehicle car equivalences, and adjusted volumes are estimated on the basis of previous performance or some expected value, and then corrected later when necessary. Station limits are set from the limits of traffic volume data. This will normally be a greater distance than if station limits were set for changes in roadway data. This allows a longer simulation before resetting the model r a new vehicle. Between each set of traffic station limits all traffic volumes will be simulated for each vehicle at that volume level, starting with the lowest-powered vehicle. The controlling speed for each vehicle will be obtained from the time-volume curves after the volume has been adjusted for the slow vehicles and roadway width restrictions; the vehicle model will then attempt to operate the vehicle at this speed, predicting overall time and fuel consumption.

The time prediction should at this point be correct; however, neither the vehicle nor the driver model has accounted for the increase in fuel resulting from the driver's oscillating around the average speed because of variations in traffic flow. Very little can be found in the literature to account for this. However, one set of tables (22) presents operating costs as a function of attempted and actual speeds. Therefore, if fuel consumption is adjusted by the ratio of these two costs at the free and average speeds for the road section under consideration, the resultant consumption should more accurately reflect the effects of the traffic-caused variations in speed.

The final results can be prepared as tables or plots of consequences vs volume, vehicle, projection year, or stationing, or various combinations of these, depending on the user's choice. Consequences can be priced at unit costs if the user specifically requests this.

CONCLUSIONS AND RECOMMENDATIONS

The primary conclusions drawn from this research are as follows:

1. The process of predicting vehicle operation consequences should be given stronger consideration in the total economic analysis process of highway planning and design. Evaluation of the predicted consequences should be considered as a separate step.

2. Five basic steps can be identified in the prediction of vehicle operating consequences. These are independent of the specific method of analysis and are included, either explicitly or implicitly, in all existing complete methods. The five steps are (a) definition of representative vehicles, (b) prediction of driver behavior for each vehicle and segment of roadway, (c) prediction of vehicle performance capabilities, (d)

determination of actual travel possibilities for each traffic volume, and (e) prediction of the consequences of vehicle operation for each vehicle, each road segment, and each traffic volume level.

3. Input parameters to prediction models can be classified as being either deterministic or probabilistic. Vehicle and alignment characteristics are deterministic in their influence, while driver, traffic, operating, and roadway characteristics are generally probabilistic. Average values can be used for most input variables; however, some vehicle, traffic, and roadway characteristics should be considered in more detail for predictions in specific situations.

4. The framework described in this paper can be used to help determine the priority of future research objectives and structure for predicting the consequences of vehicle operation. Research should be tailored for the intended use of the model and emphasis should be placed on those of the above five steps that are presently weakest. Research should be planned to fit into the above framework and to interface with other models and components. For example, much useful work in predicting vehicle performance capabilities and operating consequences is available for use in a detailed, accurate model. Each of the other areas currently requires additional research. Also, the work must be coordinated more effectively so it can be used together.

5. Existing methods of predicting vehicle-operating consequences or user costs follow the basic framework derived in this paper. Many simplified models have been developed for easy reference and use by highway designers, planners, and others not expected to be experts in the field of predicting vehicle operation. Recent advances in computer technology can now make more advanced research available to these users.

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