HIGHWAY RESEARCH RECORD

Number 245

Economic Factors Influencing Engineering Decisions

4 Reports

Subject Area

15 Transportation Economics
82 Urban Community Values

HIGHWAY RESEARCH BOARD

DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

Washington, D.C., 1968 Publication 1392

Price: $1.80

Available from

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Department of Economics, Finance and Administration

R. C. Blensly, Chairman
Oregon State University, Corvallis

HIGHWAY RESEARCH BOARD STAFF

Kenneth E. Cook

COMMITTEE ON HIGHWAY ENGINEERING ECONOMY
(As of December 31, 1967)

C. H. Oglesby, Chairman
Stanford University, Stanford, California

William G. Adkins
Malcolm F. Brenan
Paul J. Claffey
Paul D. Cribbins
Charles W. Dale, Secy.
Richard DeNeufville
A. C. Estep
Monroe L. Funk
Evan H. Gardner
R. J. Genereux
David M. Glancy
Eugene L. Grant
R. G. Hennes
Edwin C. Lokken
Littleton C. MacDorman
Marvin L. Manheim
William C. Pendleton
Paul O. Roberts, Jr.
Richard M. Soberman
James W. Spencer
John J. Suhrbier
Arvin S. Wellborn
Robley Winfrey

Foreword

This RECORD consists of papers in the general area of engineering economy necessary to make planning decisions. Three of the papers deal with methods of evaluating travel time. The fourth paper discusses vehicle operating costs in relation to the improvements of roadway design.

Authors Evans and Treadway develop a model for calculating travel time delay caused by trucks ascending grades on two-lane highways. The model simulates various headway distributions and traffic compositions. A sample calculation of travel-time delays incurred by passenger cars and small trucks resulting from slow-moving, heavy-laden trucks on long steep grades is included. Curves illustrating travel time delays on grades for different given traffic characteristics and highway geometrics were derived from the delay model.

Author Thomas attempts to estimate the value of travel-time savings by comparing motorists' choices between toll-road and free-road facilities in their trips to and from work. Data were collected by motorist interviews and test-vehicle measurements, and used independently to estimate the value of time. The study recommends the use of \$2.82 per person per hour as value of travel-time savings for commuter trips of more than 10 minutes or five miles in length.

Lisco's paper, presented as an abridgment, analyzes modal choices collected as part of the Chicago "Skokie Swift" Mass Transportation Demonstration project. Findings indicated that commuters place a \$2.00 value on the extra comfort afforded by their own cars over that provided by transit. Other findings were that transit fares were relatively unimportant in modal choice, and the discomfort value attributed to walking has a significant effect on modal choice.

Prokopy's paper is concerned with the design of a system to obtain the consequences of over-the-highway vehicle operation as related to highway design. The paper describes the process and briefly shows how a model can be developed from it. A major component is the combination of vehicle performance and traffic congestion models, which provides a method for evaluating effects of vehicle performance on traffic congestion, and vice versa.

Contents

Economic Analysis of Truck Climbing Lanes on Two-Lane Highways

EUGENE G. EVANS and THEODORE B. TREADWAY,
Pennsylvania Department of Highways

A simplified model that calculates travel time delay caused by trucks ascending grades on two-lane highways is presented. The model simulates various headway distributions and traffic compositions. A sample calculation of travel time delays incurred by passenger cars and small trucks resulting from slow-moving, heavy-laden trucks on long steep grades is included. Curves illustrating travel time delays on grades for different given traffic characteristics and highway geometrics were derived from the delay model.

•APPROXIMATELY 90 percent of Pennsylvania's highways are two-lane and carry relatively low traffic volumes. These highways may have adequate future traffic capacity for years if truck climbing lanes would be added on the more critical grades in hilly and mountainous terrain where truck volumes are high and resulting delays are excessive.

Because the highway construction backlog and current highway needs far exceed the operating capital available for highway improvements, it is imperative that highway appropriations be allocated so as to yield the greatest possible return to the motoring public. Such a savings to the highway user may be in the form of reduced operating costs, lower travel time losses, reduced accident costs, etc.

E. H. Gardner and J. B. Chiles of the Pennsylvania Department of Highways have developed a "sufficiency rating by investment opportunity" technique for determining the optimum improvement for all sections of highway within the state system (4, 5). The program presently considers generalized improvements such as widening, resurfacing, reconstruction, and route relocation. The program does not, however, include subprograms that would permit the justification by economic analyses of such geometric elements as truck climbing lanes, highway interchanges, and auxiliary lanes.

In conjunction with the sufficiency rating by investment opportunity program, the model contained herein has been developed to compute travel time delay caused by heavy-laden trucks on grades. The rate-of-return analysis was used to evaluate the economic feasibility of adding a truck climbing lane on a given grade. Variables included in the traffic simulation and delay model are as follows:

1. Hourly directional traffic volumes,
2. Percent of trucks in the traffic stream,
3. Average composition of trucks by weight-horsepower ratio,
4. Composite percent of grade, and
5. Either length of grade or elevation differential (arithmetic difference between elevation at crest and elevation at toe of grade).

Some of the parameters used in the traffic simulation model were obtained from previous research results. Vehicular speeds, traffic composition, and truck weight-horsepower ratios were obtained from speed and loadometer studies. Other factors such as headway distributions and free-flowing vehicular speeds on grades were obtained from field measurements and observations.

Paper sponsored by Committee on Highway Engineering Economy and presented at the 47th Annual Meeting.

The validity of the "time lost" (delay) model is currently being verified by field measurements. A before-after study of a truck climbing lane has also been initiated, which will provide another check on the delay model and on truck climbing lane feasibility.

OBJECTIVE

This study was conducted to determine the economic feasibility of adding truck climbing lanes on two-lane highway grades in mountainous terrain. The economic analysis was based on the increase in travel time (delay) experienced by road users in passenger cars and small trucks while traveling on ascending grades in mountainous terrain. This delay is caused by heavy-laden trucks (trucks with a relatively high weight-horsepower ratio) moving up long mountainous grades at a necessarily slow rate of speed. Travel-time delay was converted into a monetary value to estimate the feasibility of constructing truck climbing lanes.

Vehicle-operating costs and accident costs were not included in this analysis because of the difficulty in assigning accurate and realistic values to these parameters. It is to be hoped that a future economic analysis will include travel time delay costs, vehicle-operating costs, and accident costs in the feasibility study.

DEVELOPMENT AND APPLICATION OF MODEL

The truck climbing lane model has been developed for both rural and urban highways. Some of the basic assumptions may need to be altered, however, to accommodate highway and environmental conditions in a specific area. Assumptions included in the model are as follows:

1. Passing maneuvers are prohibited on mountainous grades.
2. Passenger cars maintain a constant speed on the grade if they are not delayed by a truck.
3. All vehicles enter the grade at a given speed and resume this speed beyond the crest of the grade.
4. Length of grade = elevation differential (100) ÷ percent grade. This relationship is accurate for small percents of grade, and in most cases grades are 10 percent or less.

Traffic simulation was used to generate traffic distributions from which the economics of adding climbing lanes were analyzed. This technique enables the engineer to synthesize intricate and sophisticated traffic problems in the office or laboratory and minimizes the need for conducting field studies. Simulation analyses for complex conditions are usually less expensive and less time-consuming than studying actual field systems. Now with the availability of high-speed computers, the engineer can analyze complex traffic characteristics and movements which may previously have been impractical.

When simulating stochastic events such as traffic movements on a highway, every event must be explicitly defined. When variables in the simulation model are realistically defined, traffic flows synonymous to field conditions are more easily obtained.

In this study traffic was simulated for only one lane (uphill traffic) because of the assumption of no passing on a grade. The no-passing assumption eliminated interference caused by opposing streams of traffic and greatly simplified the simulation model. Because of horizontal and vertical sight distance restrictions, which are prevalent on the vast majority of highway grades in rugged and mountainous terrain in Pennsylvania, this assumption was considered valid.

The composite headway distribution developed by Schuhl and modified by Kell was used to synthesize traffic flow (9, 12). The model describes a headway distribution such that free-flowing and restrained vehicles are intermixed in the traffic stream. By using this intermixing technique, the vehicle headway distribution realistically approximates headway spacings as they exist in the field.

For low traffic volumes the Poisson headway distribution closely describes the field vehicular flow, whereas the shifted exponential headway distribution approximates traffic flow under high volume conditions. The Schuhl distribution combines both free-flowing and restrained vehicles regardless of the magnitude of the traffic volume and is applicable when both low and high traffic volumes are encountered.

The following nomenclature is used in describing the model:

A = parameter describing traffic flow (9)
B = number base of computer used
BHPW = horsepower delivered by the engine to the clutch at wide open throttle, hp
C = parameter describing traffic flow (9)
E = number of trucks delayed by the lead truck
F_0 = net initial force on a truck at the start of a highway section, lb
F_t = thrust force on a truck due to engine torque, lb
g = gravitational constant (32 ft/sec/sec)
G = grade of highway, percent
GVW = gross vehicle weight, lb
H = minimum headway for restrained vehicles, sec
K = compositional class of vehicle
L = horizontal distance along a highway, ft
L_1 = deceleration distance, ft
L_2 = length of grade minus deceleration distance, ft
L_3 = acceleration distance, ft
L_4 = 4,000 ft minus acceleration distance, ft
M = parameter describing traffic flow (9)
Mod b^x = instruction to use only the low order or less significant half of the full (2x - digit) product (the remainder after dividing the product by b^x the maximum integral number of times)
n = number of vehicles in a queue
N = parameter describing traffic flow (9)
P = any random number
P_m = the m th random number
P_{m-1} = the previous random number
Q = portion of restrained vehicles in traffic stream, percent
R = portion of free-flowing vehicles in traffic stream, percent
S_0 = truck speed upon entering a highway section, mph
S_t = truck crawl speed, mph
t = headway, sec
t_f = free-flowing headway, sec
t_r = restrained headway, sec
T = time, sec
V = directional traffic volume, vph
W = minimum headway for free-flowing vehicles, sec
X = number of digits in a normal word on the particular computer used
Z = constant multiplier for random number generator.

To achieve the intermixing of free-flowing and restrained vehicular headways the following technique was used (see Fig. 1):

$$t_f = W - M\,[\ln(1 - P/R)] \tag{1}$$

$$t_r = H - N\left[\ln\left(1\frac{(1 - P)}{Q}\right)\right] \tag{2}$$

where

$$M = \frac{4827.9}{V^{1.024}} \tag{3}$$

$$N = 2.659 - 0.120 \left(\frac{V}{100}\right) \tag{4}$$

$$A = -0.046 - 0.0448 \left(\frac{V}{100}\right) \tag{5}$$

$$C = e^{-10.503 + 2.829(\ln V) - 0.173 (\ln V)^2} - 2 \tag{6}$$

$$W = 0.95 \text{ sec} \tag{7}$$

$$H = N(C - \ln Q) \tag{8}$$

$$R = e^{\left(A - \frac{W}{M}\right)} \tag{9}$$

$$Q = 1 - R \tag{10}$$

Random numbers were generated by the power residue method (6):

$$P_m = Z\, P_{m-1} \text{ Mod } b^x \tag{11}$$

Random numbers from 0 to 0.999 were obtained for use in the free-flowing and restrained headway formulas. If the random number (P) was from 0 to R-.001, the number generated was used, and the free-flowing formula was used in computing the headway. If, however, the number generated was from R to 0.999, then (1 - P) was used, and the headway was determined from the restrained headway formula.

The number of headways simulated per hour was equivalent to the hourly traffic volume being considered. The summation of headways (time in seconds) simulated for one hour should theoretically be 3600 sec. Because the sum of the headways

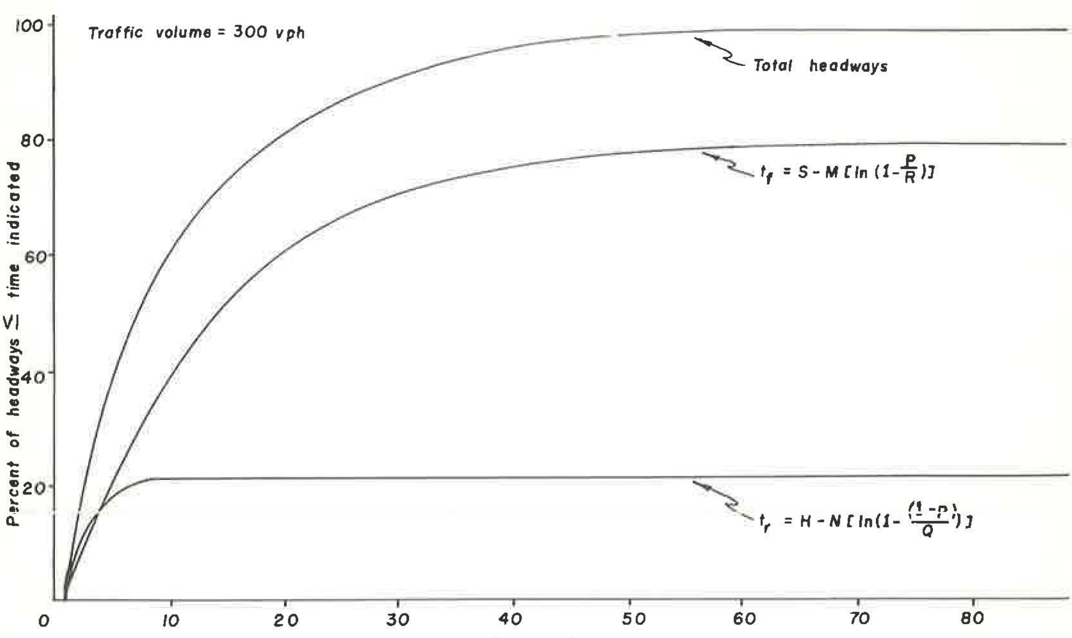


Figure 1. Composite exponential headway distribution.

generated could vary considerably from 3600 sec, a tolerance of ± 5 percent was specified for the hourly summation of headways. If this tolerance was not met, a new hourly headway distribution was generated. Headway distributions were generated until the tolerance limit was satisfied.

Minimum headways behind trucks on level terrain were specified at 3 sec to account for the length of the truck and also to account for the fact that some drivers are reluctant to follow a truck closely. On ascending grades minimum headways were specified at 5 sec behind trucks and 3 sec behind passenger cars. The reason for specifying longer headways on grades was that reduced truck operating speeds occur in hilly and mountainous terrain (see Fig. 2).

For example, if a truck is crawling up a grade at 10 mph (approximately 15 ft per sec), it will travel 75 ft in 5 sec. If the truck is 50 ft long, then the distance from the rear of the truck to the front bumper of the following vehicle is 25 ft.

Another random number distribution was generated to determine the composition of the traffic stream. The composition consisted of passenger cars (or the equivalent), medium trucks, big trucks, and giant trucks, and was identified as follows (17):

1. Passenger car—passenger car or a two-axle truck,
2. Medium truck—3 and 4 axles,
3. Big truck—5 or more axles,
4. Giant truck—No one group of trucks, on the average, has these characteristics, but this truck class was included so that extremely heavy trucks could be accommodated if necessary.

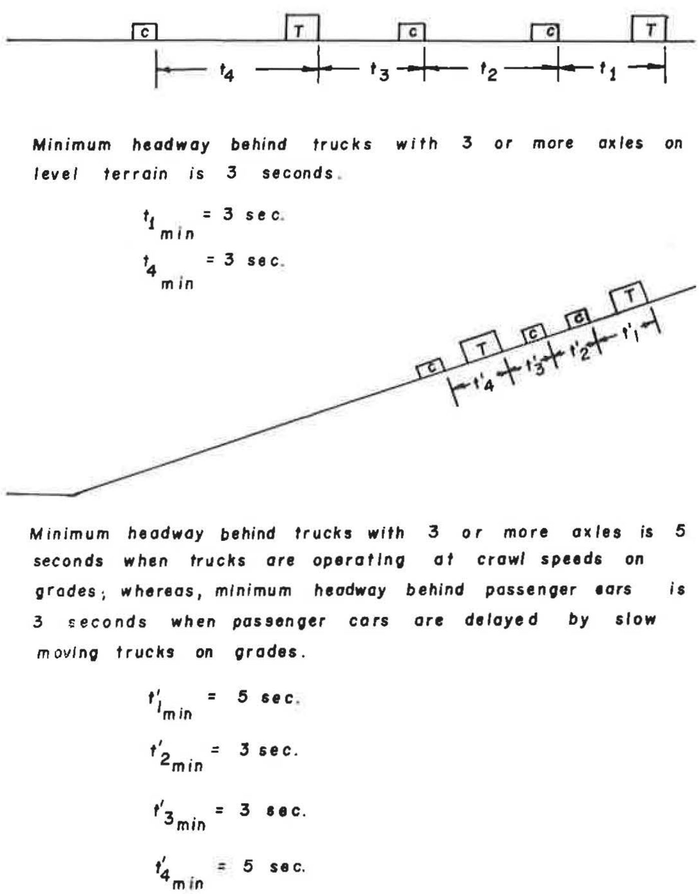


Figure 2. Minimum headways.

Operating characteristics of vehicles are largely determined by their weight-horsepower ratio. The weight-horsepower ratios associated with the above classes of vehicles are as follows:

Vehicle Code	Vehicle Type	Weight-Horsepower Ratio
1	Passenger car	Less than 200
2	Medium truck	200
3	Big truck	300
4	Giant truck	400

Firey and Peterson found that it was possible to assume that all trucks weigh 50,000 lb and to vary the truck horsepower to obtain the desired weight-horsepower ratio (3). The inherent errors involved by making this assumption were found to be negligible. The respective horsepowers for different given weight-horsepower ratios are as follows:

Weight-Horsepower Ratio	Weight (lb)	Horsepower
200	50,000	250
300	50,000	167
400	50,000	125

A tolerance limit for trucks of ± 10 percent was specified for the generation of vehicle composition, and the composition was rejected until this tolerance limit was satisfied. A flow chart depicting the generation of headways and composition of vehicles is presented in Figure 3. Any percentage of trucks, by class, may be specified in the model, but values in 10 percent increments would often be used because more accurate traffic composition data are not available.

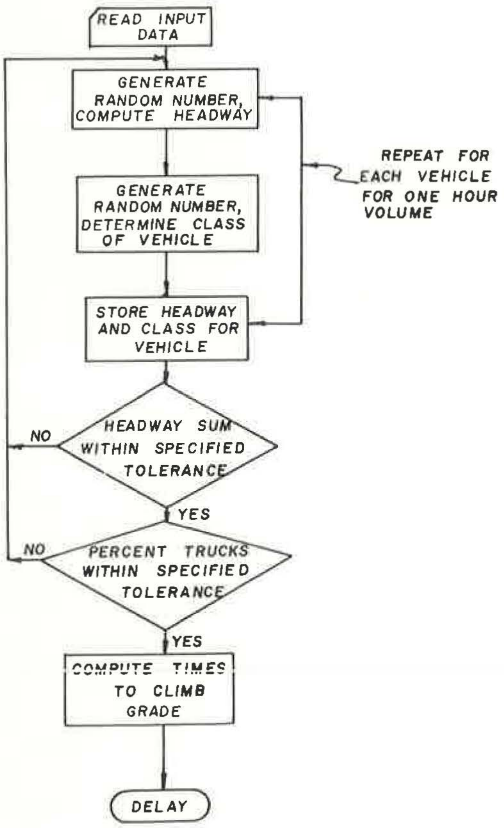


Figure 3. Generation of headways and truck composition.

Random numbers were again generated by the power residue method to determine the composition of the traffic stream. For example, consider the following vehicle composition designation:

90 percent—Passenger cars or passenger car equivalents,
10 percent—Trucks (50 percent medium trucks and 50 percent big trucks).

Numbers generated from 0.000 to 0.049 would represent medium trucks; numbers generated from 0.050 to 0.099 would represent big trucks; and numbers generated from 0.100 to 0.999 would represent passenger cars.

The total distance analyzed was from the toe of the grade to 4000 ft beyond the crest of the grade. The inclusion of 4000 ft beyond the crest was to enable trucks to accelerate to their normal operating speeds.

The time required for a passenger car to negotiate a grade is equal to the length of grade plus 4000 ft divided by the speed at which the grade is negotiated. The time required by a free-flowing truck to negotiate a grade depends on the weight-horsepower ratio of the truck, the approach speed at the bottom of the grade, and the percent of grade. Gear ratios may also have an effect on the grade-climbing ability of trucks, but this factor was not included in the analysis because of the vast number of gear ratios made available by truck manufacturers. Other factors that were neglected were climatic condition and elevation above sea level.

Crawl speeds of trucks for specific weight-horsepower ratios are given in Table 1.

TABLE 1

TRUCK CRAWL SPEEDS[a]

Vehicle Type	Grade, %	Crawl Speed, mph
Medium trucks	4	37.0
BHPW = 250	5	31.0
GVW/BHPW = 200	6	26.5
	7	23.0
	8	21.0
Big trucks	3	31.0
BHPW = 167	4	24.0
GVW/BHPW = 300	5	21.0
	6	17.5
	7	15.5
	8	13.5
Giant trucks	3	23.0
BHPW = 125	4	18.0
GVW/BHPW = 400	5	15.5
	6	13.0
	7	11.5
	8	10.5

[a]From Firey and Peterson (3).

The time required by a truck to negotiate a grade plus 4000 ft is equal to the sum of the following (see Fig. 4): deceleration time + crawl time + acceleration time + (4000 ft - acceleration distance) ÷ normal operating speed.

The computation of the time required for a truck to climb a grade plus 4000 ft is as follows:

$$F_0 = \frac{(BHPW)550}{S_0} - 532 - \frac{GVW(G)}{100} \tag{12}$$

$$T_1 = \frac{(GVW)(S_t - S_0)\,1.467}{F_0\,(g)} \tag{13}$$

$$L_1 = \frac{S\,(GVW)(S_t - S_0)(1.467)^2}{F_0\,(g)} + \frac{(GVW)(S_t - S_0)^2(1.467)^2}{2(F_0)\,(g)} \tag{14}$$

$$T_2 = \frac{\text{Length of grade} - L_1}{1.467\,(S_t)} \tag{15}$$

$$L_2 = \text{Length of grade} - L_1 \tag{16}$$

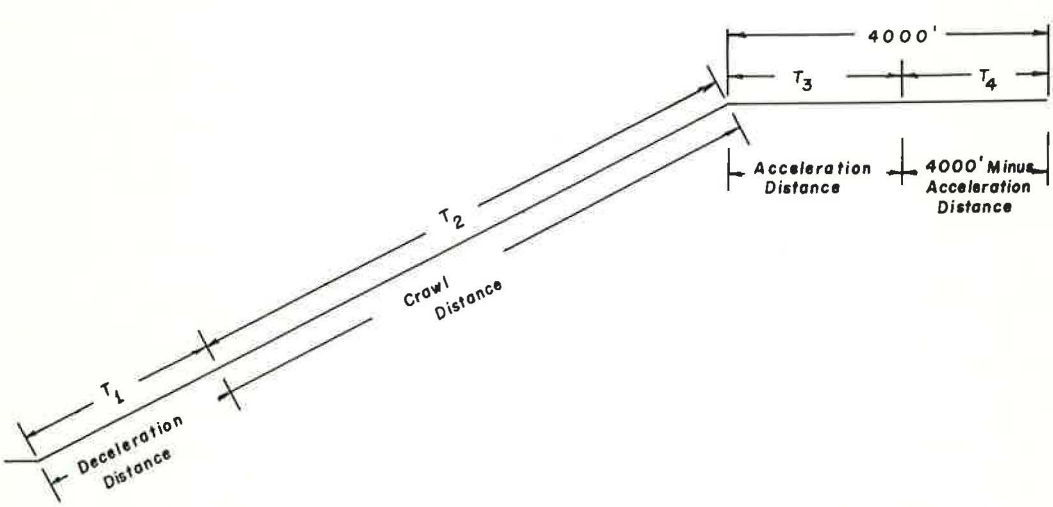


Figure 4. Distance and time increments in climbing a grade plus 4000 feet.

$$F_t = \frac{BHPW\ (550)}{1.467\ (S_0)} \tag{17}$$

$$T_3 = \frac{(GVW)\ (S_0 - S_t)\ 1.467}{F_t\ (g)} \tag{18}$$

$$L_3 = \frac{S_t\ (GVW)\ (S_0 - S_t)\ (1.467)^2}{F_t\ (g)} + \frac{GVW\ (S_0 - S_t)^2\ (1.467)^2}{2(F_t)\ (g)} \tag{19}$$

$$T_4 = \frac{4000 - L_3}{1.467\ (S_0)} \tag{20}$$

$$L_4 = 4000 - L_3 \tag{21}$$

The total time required for a truck to climb a grade plus 4,000 ft is

$$\sum_{i=1}^{4} Ti = T_1 + T_2 + T_3 + T_4 \tag{22}$$

The "time lost" formula, which calculates delays incurred on a grade, is as follows:

Time lost by a driver in the nth passenger car or light truck = (time required by the lead truck in a queue to climb grade plus 4, 000 ft) - (time required by a passenger car or truck with lower weight-horsepower ratio to climb grade plus 4,000 ft) -

$$\left\{(t_1 + t_2 + \ldots + t_{n-1}) - [5 + E(5) + 3(n - 2 - E)]\right\} \quad (2\text{:}$$

The time lost formula accumulates travel time delay incurred by passenger cars and light trucks while climbing long mountainous grades. Deceleration characteristics of passenger cars and light trucks on mountainous grades were not included in the model. If passenger cars and light trucks decelerate from their normal operating speed to the crawl speed of heavy trucks and maintain the minimum headway as specified in Figure 3, the resulting delay is the same regardless of the rate of deceleration.

By neglecting minute traffic-following characteristics of passenger cars and light trucks on grades, the calculation of travel time delay incurred on a grade was greatly simplified. A flow chart describing the accumulation of total travel delay is shown in Figure 5.

The time lost formula may be considered a "black box," as only the end product—total delay incurred by the road user—is of interest, and all intermediate minor traffic variations, such as headways maintained on a grade and speed variations, are taken care of.

Some models that have been developed to compute travel-time delay analyze the entire system (headways, speed of each vehicle, passings, etc.) at periodic intervals. Often these intervals are as short as 10 or 20 sec, and an analysis of this magnitude requires a substantial amount of computer time and is an expensive and complex operation. An analysis of the entire system at periodic intervals may be a necessity when passing maneuvers are permitted, but it was deemed unnecessary for this analysis.

Typical hourly delays calculated from the model for various traffic characteristics and geometric configurations are shown in Figures 6, 7, and 8. These delay curves demonstrate that the percent of trucks has only a minor effect on the resulting delay for grades of 6 and 8 percent and heavy traffic volumes. For high traffic volumes, near-saturation conditions have become imminent, and virtually every passenger car and light truck experiences delay; therefore, very little additional delay results by increasing the percentage of heavy trucks in the traffic stream. For traffic volumes of less than 50 vehicles per hour, the hourly travel time delay was found to be negligible.

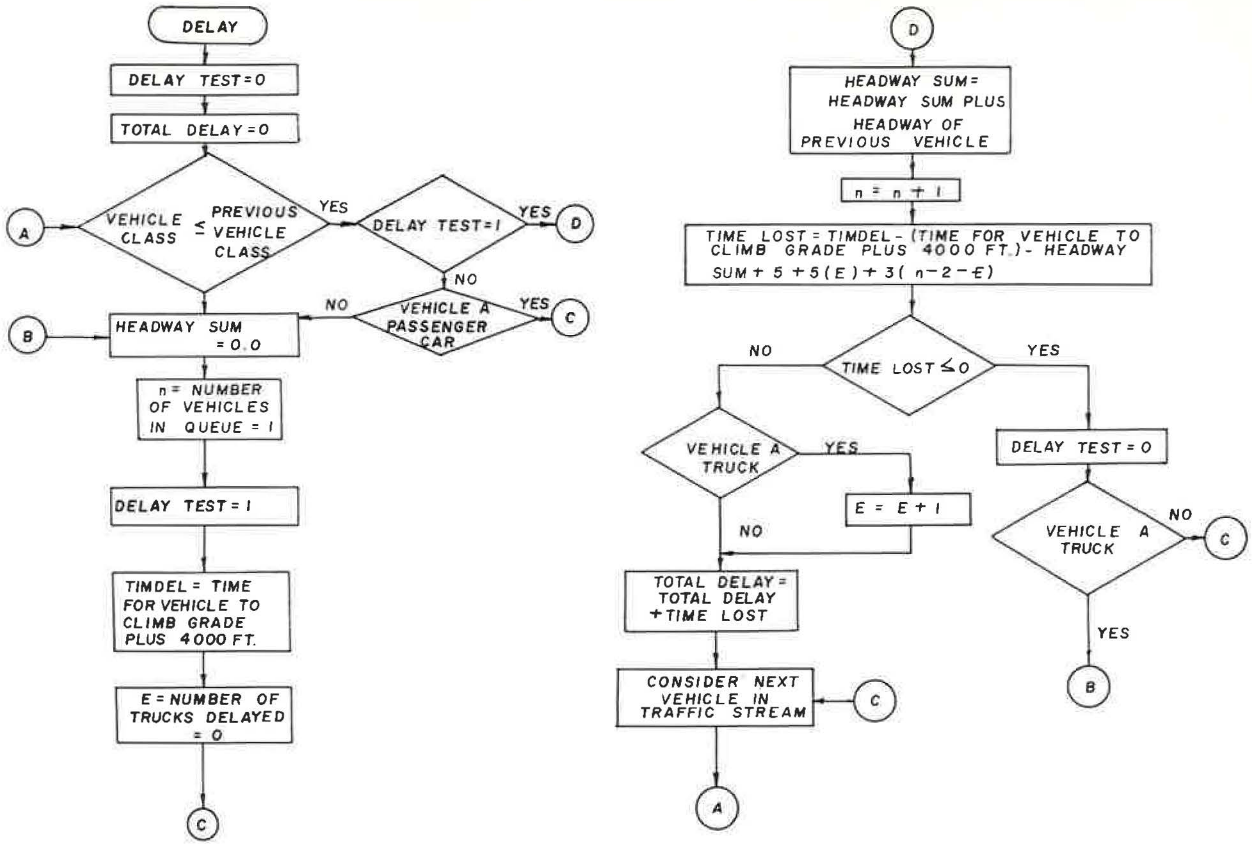


Figure 5. Calculation of travel time delay.

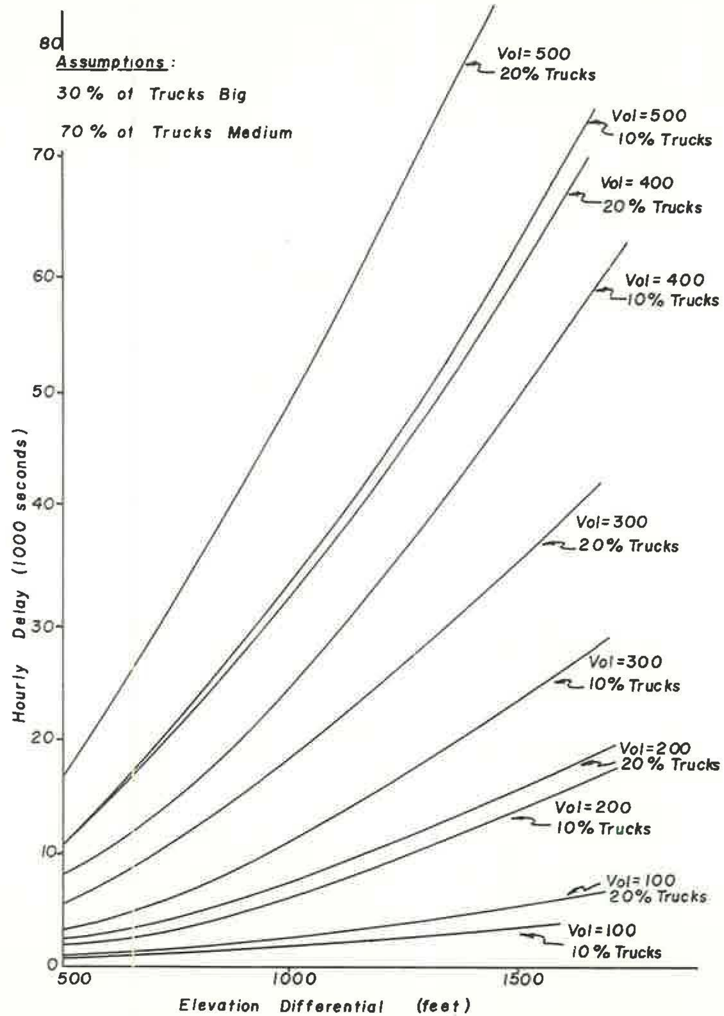


Figure 6. Hourly delay on a 3 percent grade.

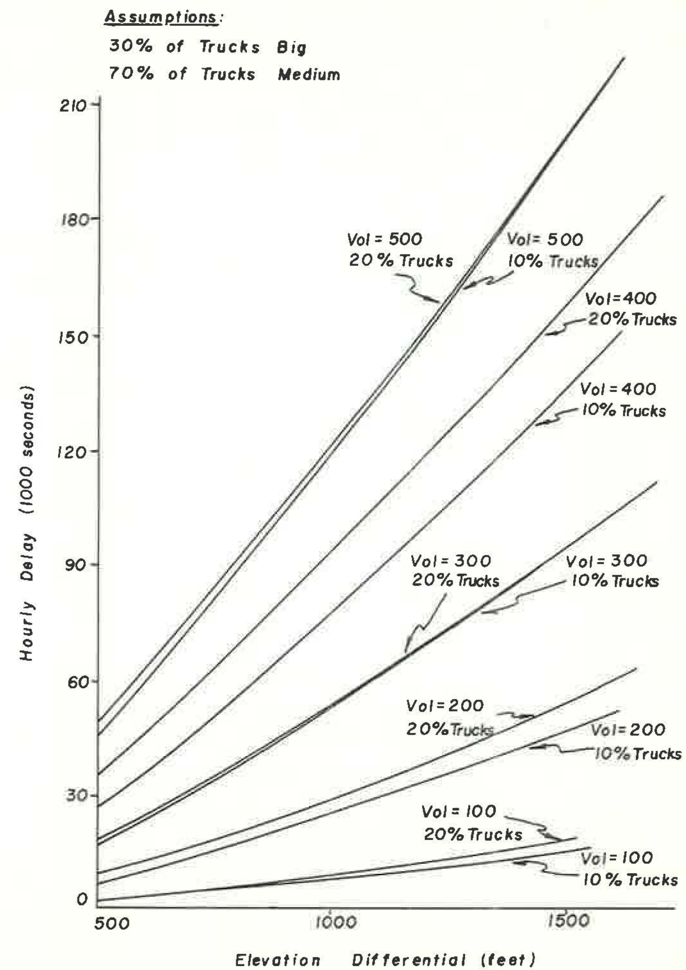


Figure 7. Hourly delay on a 6 percent grade.

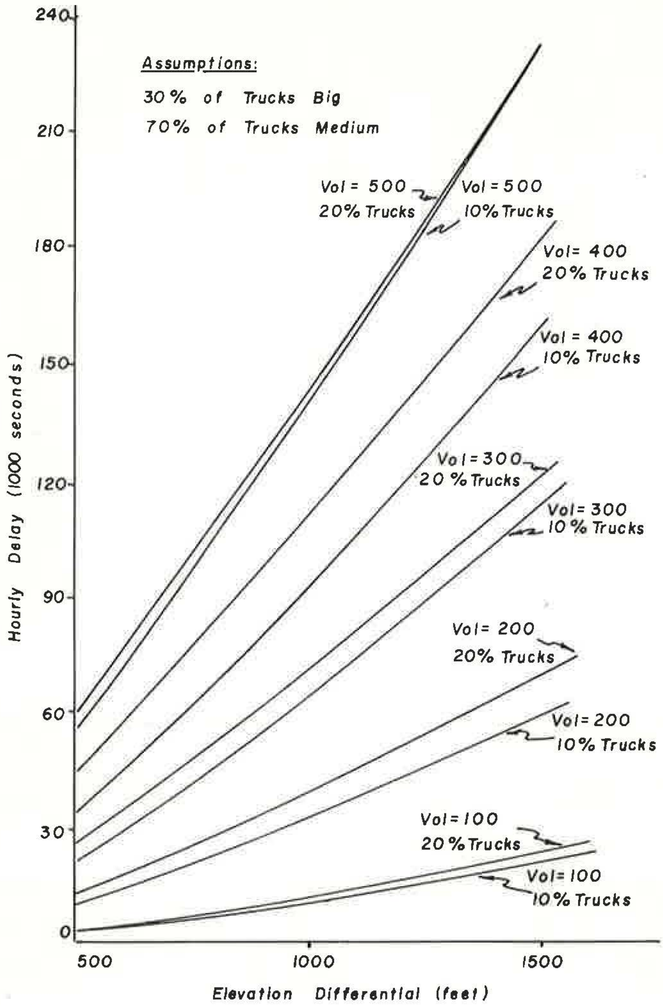


Figure 8. Hourly delay on an 8 percent grade.

The daily travel time delay from Figures 6, 7, and 8 was converted into monetary values that were used to obtain annual delay costs, which are given in Table 2.

PASSING MANEUVER CONSIDERATION

In reality, passing maneuvers are permitted over short segments of some grades where passing sight distance is available; therefore sample calculations were made to determine the magnitude of error involved in the travel time delay analysis by making the "no passing on a grade" assumption. In the sample calculations, an adequate passing sight distance was assumed over 20 percent of the grade and at the midpoint of the grade. When passing is permitted at the midportion of a grade, total delay incurred by road users is minimized (13).

For passing maneuvers to be imminent at the midportion of a grade, a traffic queue must have formed behind a truck at that point. Also the opposing traffic (downhill) lane must be free from oncoming traffic for a safe passing maneuver to be possible. Another assumption was that a period of 25 sec, which is commonly termed the critical gap, was required for the passing maneuver. No two passenger cars were permitted to pass a truck simultaneously. In other words, the first passenger car must have completed the

TABLE 2

DELAY COST CALCULATIONS

Year	Traffic Volume Growth Factor	Traffic Volume (daily)	Daily Delay (sec)[a]	Annual Delay Cost	Present Worth Delay Cost (Based on year 0)
0	0.03	3,200	88,000	$13,920	$13,900
1	0.03	3,300	92,700	14,670	13,700
2	0.03	3,401	97,500	15,420	13,500
3	0.03	3,502	102,300	16,170	13,300
4	0.03	3,602	107,000	16,920	13,100
5	0.03	3,715	113,000	17,870	13,100
6	0.03	3,828	119,000	18,820	13,000
7	0.03	3,941	125,000	19,770	12,900
8	0.03	4,054	131,000	20,720	12,900
9	0.03	4,181	138,000	21,830	12,700
10	0.03	4,308	145,000	22,940	12,500
11	0.03	4,435	152,000	24,050	12,200
12	0.03	4,563	159,000	25,150	12,000
13	0.03	4,707	172,000	27,200	12,000
14	0.03	4,851	185,000	29,250	12,000
15	0.03	4,995	198,000	31,310	12,000
16	0.03	5,140	211,000	33,370	12,000
17	0.03	5,300	220,000	34,510	11,600
18	0.03	5,460	229,000	35,650	11,200
19	0.03	5,620	238,000	36,790	10,900
20	0.03	5,780	247,000	37,930	10,500
Total					$261,000

[a]See Figure 7.

passing maneuver before a second vehicle could attempt to pass. A final assumption was that a truck was not permitted to pass another vehicle on a grade because of the excessive time required for such a maneuver. Even a truck with a lower weight-horsepower ratio was not permitted to pass a truck operating under a higher weight-horsepower ratio in the sample calculations because of the excessive time required and the hazard involved.

Using these assumptions, several hand calculations were executed to make a comparison of the true delay as a percent of the calculated delay (delay from the time lost formula). It was concluded that travel time delay, as obtained from the time lost formula, is not decreased appreciably if passing is permitted over a small portion of a grade. Results from the hand calculations are shown in the form of a calibration curve (see Fig. 9):

Traffic Volume	True Delay as a Percent of Calculated Delay
100 vph (one direction)	85 percent
200 vph (one direction)	90 percent

When traffic volumes approach 800 to 1,000 vph in both directions, passing opportunities become infrequent; therefore the loss of delay under high traffic volume conditions is insignificant. As traffic volumes become low (less than 50 vph on the uphill traffic lane), the resulting delay obtained from the time lost formula becomes negligible; therefore the delay at low traffic volumes may justifiably be disregarded. Also, at low traffic volumes, delay decreases if passing maneuvers are permitted on grades, which further substantiates that delay at low traffic volumes may be omitted from the overall delay analysis.

VERIFICATION OF TRAFFIC SIMULATION MODEL

To determine if the traffic simulation model properly described traffic behavior, field data were collected, analyzed, and compared with results obtained from the simulation model. The traffic headway distribution and truck speeds at the bottom of a grade were

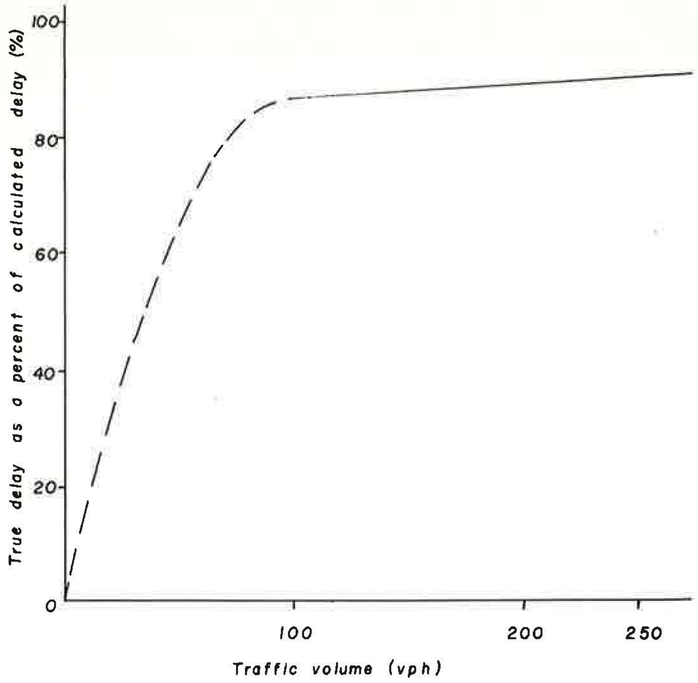


Figure 9. Calibration curve for travel time delay.

two critical elements in the economic analyses that were checked against field conditions.

The chi-square test for goodness of fit was used to determine if the theoretical traffic headway distribution closely approximated actual headway distributions on one lane of a two-lane highway. Results from the test showed that at the 99 percent level of confidence theoretical headways closely described headways obtained from field surveys.

Average approach speed data (vehicle approach speed at bottom of grade) were obtained simultaneously with the headway data by using a 20-pen event recorder. Average speeds on level sections of highway prior to entering grades were approximately 50 mph for passenger cars and 45 mph for trucks when horizontal and vertical alignment prior to entering a grade was not unduly restrictive. An observation from the field study was that many truck drivers "make a run" for grades if highway geometrics and traffic conditions permit.

The model for calculating delay incurred on a grade has been developed to accommodate any approach speed. Approach speeds may be altered for each grade considered if reliable speed data are available to substantiate such changes.

At some locations there may be speed zones or stop signs at or near the bottom of the grade. When these conditions exist, a much lower approach speed may have to be specified in the analysis. Also, travel times required by various types of vehicles to climb a grade were determined from field studies.

CALCULATION OF RATE OF RETURN

The rate-of-return economic analysis is suggested as a measure of the feasibility of adding truck climbing lanes. The calculation of the rate of return for projects being considered is as follows:

$$\mathrm{R.R.}^{x-n} = \frac{\mathrm{AUC}^{n} - \mathrm{AUC}^{x} + \mathrm{AMC}^{n} - \mathrm{AMC}^{x}}{\mathrm{cc}^{x} - \mathrm{cc}^{n}} \tag{24}$$

where

$R.R.^{x-n}$ = Rate of return of alternative x compared to null (existing);
AUC^n = annual user delay cost, existing route;
AUC^x = annual user delay cost, alternative x;
AMC^n = annual maintenance cost, existing route;
AMC^x = annual maintenance cost, alternative x;
cc^n = present worth, first construction cost existing route; and
cc^x = present worth, first construction cost alternative x.

In this analysis, however, annual user delay costs for the alternative are considered to be zero. Also, the present worth of the existing route would be zero if no improvements are scheduled. If these assumptions are made and if the maintenance costs are not considered, the rate of return would be as follows:

$$R.R.^{x-n} = \frac{AUC^n}{cc^x} \tag{25}$$

A capital recovery factor (CRF) is used to compute annual user delay cost. A 20-year CRF factor at 7 percent interest is recommended (5). For example:

Percent trucks—10
Percent grade—6
Elevation differential—1000 ft
Length of grade—3.16 mi
Cost of constructing one mile of a truck climbing lane (assumed)—$150,000
Number of years over which the delay cost is summed—20
Total present worth delay cost (see Table 2)—$261,000
Present worth delay cost per mile of highway—$82,000
Interest rate—7 percent
CRF—0.094393
Delay cost per vehicle per hour—$1.56
Annual road user delay cost = $82, 600 (0.094393)
= $ 7, 800

The rate of return is calculated as follows:

$$R.R.^x = \frac{7,800}{150,000}$$

$$= 0.051 \text{ or } 5.1 \text{ percent}$$

Future traffic volumes were calculated by using the compound interest formula:

$$V_f = V_p (1 + gf)^n \tag{26}$$

where

V_f = future traffic volume,
V_p = present traffic volume,
gf = yearly traffic volume growth factor, and
n = number of years in future that traffic volume is desired.

For example:

Present daily traffic volume—3200
Traffic volume growth factor—0.03
Number of years in future for which traffic volume is desired—10

$$V_f = 3200\,(10 + 0.03)^{10}$$

$$V_f = 4308 \text{ vehicles per day}$$

RESULTS AND CONCLUSIONS

1. Truck climbing lanes were found to be economically feasible on two-lane highways only when traffic volumes and percentages of trucks are relatively high (greater than 10 percent) and grades are severe (greater than 3 percent), or when the construction cost of adding a climbing lane is relatively low.

2. Travel time delay as calculated by the time lost formula is highly conservative because (a) delays caused by slow-moving passenger cars on grades were not included in the delay analysis, and (b) crawl speeds of trucks observed in the field were normally not as great as crawl speeds used in the analysis.

3. Vehicle operating costs were not included in the analysis. Passenger-car operating costs on a two-lane highway normally are lowest on a 6 to 8 percent grade when the operating speed is approximately 25 mph (16). Passenger cars that are delayed by slow-moving trucks on grades have higher operating costs because of the forced reduction in operating speed.

4. Accident costs were not included in the analysis because of the nonavailability of accurate accident data. If accident costs could be determined and added to the economic feasibility analysis, climbing lanes may be more attractive.

5. Only the cost of adding an additional lane for uphill traffic should be included in the economic analyses. In some cases where wide shoulders are available, reconstruction or stabilization of the shoulder may be all that is required. In most cases, however, the entire width of the pavement is reconstructed or resurfaced and this cost is compared with delay cost in the economic analyses. The use of this total cost should be avoided when comparing construction cost with delay cost.

6. Further research is needed on truck crawl speeds, delay caused by slow-moving passenger cars on a grade, accident costs caused by vehicles passing slow-moving trucks on a grade, vehicle operating costs on grades, and truck weight-horsepower ratios.

REFERENCES

1. Byington, Stanley R. Simulation of Vehicular Delays on Two-Lane Rural Highway Grades. MSCE thesis, Texas A and M University, 1963.
2. Dunn, Robert F. Motor-Vehicle Performance on Ascending Grades. HRB Bull. 104, p. 12-20, 1955.
3. Firey, Joseph C., and Peterson, Edward W. An Analysis of Speed Changes for Large Transport Trucks. HRB Bull. 334, p. 1-26, 1962.
4. Gardner, Evan H. The Congestion Approach to Rational Programming. HRB Bull. 249, p. 1-22, 1959.
5. Gardner, Evan H., and Chiles, James B. Sufficiency Rating by Investment Opportunity. Highway Research Record 87, p. 1-28, 1964.
6. Gerlough, D. L. Simulation of Traffic Flow. HRB Special Report 79, p. 97-118, 1964.
7. Highway Capacity Manual. HRB Special Report 87, 1965.
8. Huff, T. S., and Schrivner, F. H. Simplified Climbing-Lane Design Theory and Road-Test Results. HRB Bull. 104, p. 1-11, 1955.
9. Kell, James H. Analyzing Vehicular Delay at Intersections Through Simulation. HRB Bull. 356, p. 28-39, 1962.
10. Loadometer Survey. Pennsylvania Dept. of Highways, 1964.
11. Normann, O. K., Schwender, Harry C., and Granum, James O. New Methods of Capacity Determination for Rural Roads in Mountainous Terrain. HRB Bull. 167, p. 10-37, 1957.
12. Poisson and Traffic. The Eno Foundation for Highway Traffic Control, 1955.

13. Siedman, David R. Optimal Placement of Passing Bays. Unpublished, 1963.
14. Speed Study Report, Pennsylvania Dept. of Highways, 1963.
15. Willey, William E. Truck Congestion on Uphill Grades. HRB Bull. 104, p. 21-33, 1955.
16. Woods, K. B. Highway Engineering Handbook. McGraw-Hill, 1960.
17. Wright, John W., and Tignor, Samuel C. Relationship Between Gross Weights and Horsepowers of Commercial Vehicles Operating on Public Highways. Presented at the SAE National Transportation, Powerplant, Fuel, and Lubricants Meeting, 1964.

Value of Time for Commuting Motorists

THOMAS C. THOMAS, Stanford Research Institute

The value of travel-time savings for commuting motorists is estimated from the behavior of motorists in eight areas of the country who faced a choice between a toll road and a free road in their trips to and from work. The value of travel time is calculated from the estimated coefficients of toll and travel-time variables in route-choice models for these motorists. The route-choice models are nonlinear and estimated by least squares techniques. Data on the characteristics of the alternate routes were collected by both motorist interviews and test-vehicle measurements, and each was used to estimate independently the value of travel time. This study recommends the use of \$2.82 per person per hour as the value of travel-time savings for commuter trips of more than ten minutes and more than five miles in highway economy studies.

While the main objective of the study was to measure the value of travel time, the scope of the analysis included study of a wide variety of possible factors affecting route choice—for example, measures of route congestion or safety, family income, and sex of the motorist. In addition, special attention is given to a critique of both the methodology used in estimating the value of travel time and the use of the estimates in highway economy studies.

•INCREASED use of private automobiles makes economic analysis of highway improvement proposals an area of vital concern. Highway planners, faced with heavy demands for highway facilities and constrained by limitations on funds available for construction, are adopting the techniques of economic analysis to assist them in making better decisions on the expenditure of these funds. Economic analysis justifies highway improvement projects, develops priorities for the construction of highway projects within a political jurisdiction, and determines features of engineering design and layout for projects.

Economic analysis considers the effects of highway improvements both on the highway agency, in terms of increased costs for construction and maintenance of improved highways, and on the highway users, in terms of reduction in accidents and congestion and savings in travel time and vehicle operating costs. To include these effects in economic analysis, all benefits must be stated in dollar values.

One of the most important benefits is savings in travel time. A significant portion of proposed highway projects is directed toward savings in time, rather than savings in motor vehicle operating costs. Consequently, converting time savings from hours to dollars is critically important in both economic and engineering analyses of alternative highway locations and designs. The factor used to make this conversion is called the "value of time."

Even though a value-of-time factor has been used for years in highway economic analysis, relatively little reliance can be placed on the accuracy of the values chosen. The most common value—\$0.86 per person per hour—can be justified only in that it

Paper sponsored by Committee on Highway Engineering Economy and presented at the 47th Annual Meeting.

represents current opinion of a logical and practical value. Research into the value of time has increased in recent years, but even the latest efforts are unsuccessful in determining values that can be used with confidence in a variety of situations.

In view of the widespread importance of the value of time to highway planning and design, an extensive program of studies was undertaken. The study described herein represents the most recent phase of a contract research program that has been conducted for the U. S. Bureau of Public Roads over a period of years by Stanford Research Institute. In studies completed earlier, the history of the value of time was first documented. This review contained not only a qualitative review of past writings, but also a quantitative review of the work of researchers who built models to measure the value of time and attempted to measure it. The problems encountered in previous studies vary, but in general they were caused either by inadequate theoretical specification of the model and its variables (such as the implied assumption that motorists have an accurate idea of operating costs) or by the necessity to use data already collected for other purposes (such as for origin-destination studies) instead of data generated specifically for use in estimating the value of travel time.

After this review, a number of theoretical analyses were undertaken in an attempt to develop a theory of the value of time. Several mathematical models were then constructed, and a series of behavorial science and route-choice prediction experiments were accomplished. These efforts prepared the way for the present study in which we attempted to establish the feasibility of measuring the value of time and the value of traffic impedances.

ESTIMATION OF THE VALUE OF TIME AND TRAFFIC IMPEDANCES

Theoretical analysis, supported by experience of others, led to the following requirements: First, because the research was focused on highway engineering economy, we believed that it was necessary to study choices made by highway users between alternative highways. This led to a determination to study route-choice decisions. Second, we needed to obtain good confidence limits on the calculated values of time and impedance. This required that the cost differences between alternative routes be accurately known by the motorist, which led to the selection of toll-road compared with free-road route choices. Third, to minimize the loss of information that results from aggregating data on different trips into groups of "average" trips, it was decided to study individual motorists, which implies a rather high-cost experiment. Fourth, we felt that we should study a decision situation that is important to motorists. Commute travel, which requires a significant expenditure for tolls or loss of travel time over a period of a year, satisfied this requirement. The next step in the research was to develop a mathematical model or estimation technique for route choice.

Route choice is estimated as a function of a linear combination of explanatory variables such as those indicating the differences between the routes in travel costs, travel times, and traffic impedances:

$$\text{Route choice} = f(a_0 + a_1\, \Delta\,\text{cost} + a_2\, \Delta\,\text{travel time} + a_3\, \Delta\,\text{traffic impedance})$$

where a_0, a_1, a_2, a_3 are the coefficients of the explanatory variables. The values of a_0, a_1, a_2, and a_3 are calculated to minimize the errors in estimating motorists' route choices.

This function provides the basis by which motorist' route choices can be "explained" by the characteristics of their alternative routes and the characteristics of the motorists themselves.

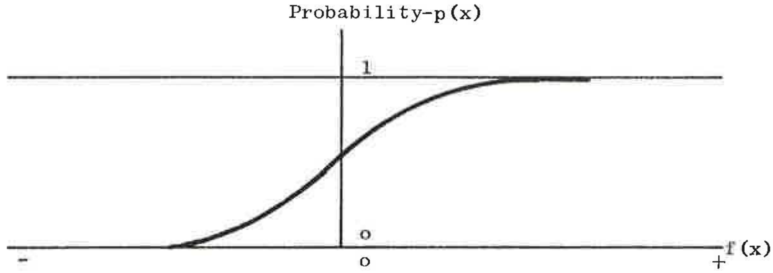
Next, the estimated coefficients are used to calculate the value of travel time and of traffic impedances. The value of travel time is defined as the ratio of a_2/a_1 and the value of traffic impedances as a_3/a_1. This definition implies that a motorist's route choice will not change when an increase in Δ cost by one unit is offset by an a_2/a_1 unit decreases in Δ travel time, or an a_3/a_1 unit decrease in Δ traffic impedance. Thus if Δ cost is in units of cents and Δ travel time is in units of minutes, a 1-cent increase in the cost of the road can be offset by an a_2/a_1-minute decrease in travel time.

The mathematical formulation of the functional relations between route choice and the linear combination of explanatory variables is based on the logit function, which can be expressed in the following form:

$$p(x) = \frac{e^{f(x)}}{1 + e^{f(x)}}$$

where p (x) = the probability of taking the free road, e = the base of the natural logarithms, and f (x) = a function of motorists and route characteristics.

A curve of the logit function is as follows:



In this curve, f (x) is plotted on the abscissa and p (x) is plotted on the ordinate and ranges from 0 to 1. The curve shows that when f (x) is large in the positive direction, the probability of taking the free road is close to 1, and when f (x) is large in the negative direction, the probability of taking the free road is close to zero. When f (x) = 0, the probability of taking the free road is 0.5 or 50 percent.

The route characteristics were used to form the x_is in f (x) in four ways: as the difference between routes, the difference multiplied by the magnitude of one characteristic, the ratio of the route characteristics, or the natural logarithm of the ratio of the route characteristics. Motorist characteristics such as income category and sex of driver were also included in the formulations of f (x).

Two basic sources of data were used in the study: route measurements by a test vehicle and motorist interviews. The test vehicle measured the traffic flow of the motorist's route. This vehicle was equipped with a fifth wheel to measure velocity and trip distance and a control panel containing switches and buttons to record descriptive data on the trip, such as the cause of acceleration, deceleration, or turn, the speed limit, type of road, type of traffic flow, nature of roadside construction, and special characteristics coded to the instructions and maps that specified the trip.

Data recording was automated to the extent that data for each second of the trip could be directly processed by computer. A ¼-inch tape recorder was used in the car, and the data recorded on this tape were later converted to standard computer tape. Recordings by the second provided a description of the alternative routes from which a large number of variables could be formed. The data were used to create common measures of route characteristics, such as travel time and distance; a number of impedance measures, such as number and size of speed changes; the portion of the trip spent at various fractions of the speed limit; and time spent at speeds less than 10 mph.

The interviews determined the principal and alternative routes each commuter used in driving to and from work. They measured motorists' perceptions of the characteristics of the toll road and the free road, such as time and cost, and their reactions to driving in general. They also provided data on motorists' personal characteristics, such as family income, age, sex, and model year of the car.

The objective in designing the questionnaire was to obtain the "richest" possible set of descriptors of the motorist and his route. Therefore, not only was a variety of

TABLE 1

CHARACTERISTICS OF THE SAMPLE

Area: Farthest Point—Work Location	Employer	Number of Route Choices[a]	Questionnaire Data	Test-Vehicle Data	Toll Road	Free Roads (Major Roads Only)
Saco, Me.—Kittery, Me.	Portsmouth Naval Shipyard	116	Yes	Yes	Maine Tpk.	US 1
Newburyport, Mass.—Kittery, Me.	Portsmouth Naval Shipyard	83	Yes	No	N.H. Tpk.	US 1
Milford, Conn.—Bridgeport, Conn.	General Electric Housewares and Wire and Cable Divisions	98	Yes	No	Conn. Tpk.	US 1 Conn. 122
Norristown, Pa.—Valley Forge, Pa.	General Electric Missiles and Space Center	127	Yes	Yes	Penn. Tpk.	US 202 Alt. Penn. 23 Penn. 363 Alt. US 422
Downingtown, Pa.—Valley Forge, Pa.	General Electric Missiles and Space Center	52	Yes	Yes	Penn. Tpk.	US 30 Penn. 113 Swedesford Rd. Penn. 23
Baltimore, Md.—Aberdeen, Md.	U.S. Army Proving Grounds	102	Yes	No	J.F.K. Memorial Tpk.	US 40 I-83 Md. 7 I-695
Dallas, Tex.—Arlington, Tex.	Six Flags Over Texas Industrial Park	110	Yes	Yes	Dallas-Fort Worth Tpk.	US 80 Jefferson Blvd. Texas 183 Loop 12
Fort Worth, Tex.—Arlington, Tex.	Six Flags Over Texas Industrial Park	124	Yes	Yes	Dallas-Fort Worth Tpk.	US 80 I-820 US 20 I-35W

Note: Average characteristics of commuters in sample—No. of passengers per car, 1.6; family income level, $9,200; model year of car, about 1961; sex of driver, 90 percent male, 10 percent female.

[a]Most, though not all, motorists provided both a morning and evening route choice.

questions included, but also two measurement techniques—line-scale ratings and forced-choice comparisons—were used for motorists' perceptions of route characteristics, such as the comparative safety of the alternative routes. A number of questions were eliminated during pretesting because of the low reliability of answers. In its final form, the interview took 40 to 60 minutes per commuter.

Commuters in eight areas were chosen for the route-choice sample. The characteristics of the sample are shown in Table 1. In three of the areas, interview data only were collected.

A conflict arose between the requirement to estimate the decisions of individual motorists and the resources needed to make test-vehicle measurements of travel time and traffic impedance of each motorist's alternative routes. Because both travel time and traffic impedance vary with the season, the day of the week, and the time of day, too many test-vehicle measurements on each route would be required if motorists were selected randomly. However, by selecting groups of commuters who work at the same location and have overlapping routes, it was possible to achieve major economies in the required number of test vehicle trips to create the physical measurements by combining overlapping segments of the trips. While this technique made the study feasible, it eliminated the possibility of a random sample. In all, 812 commute trips were analyzed.

The coefficients of the route-choice models were estimated from the data using maximum likelihood techniques. Since several hundred variables could have been formed from the available data, the number of variables used in any one model had to be restricted. It was decided that route variables based on questionnaire responses and test-vehicle measurements would not be combined in one route-choice model. These two approaches to route measurements were considered as distinct and independent and were used to provide separate estimates of the value of travel time and traffic impedance. Within each of these two sets of route characteristics, correlations were run between the motorists' route choices and the route variables—singly and in combination. This provided an indication of the empirical importance of the route variable that was then matched against its theoretical importance to select a subset of variables. Motorist characteristics were treated the same way. From the subsets of motorist and route-explanatory variables, route-choice models were specified and estimated.

Thirty-seven models were estimated that used route variables based on the test-vehicle data. The best route-choice model of the 37 models had an f(x) as follows:

	Coefficient	Variable
f(x) = 9.15	-0.236 (0.066)	Income category of motorist—categories 1 to 8
	-0.105	Model year of car—'58, '59, '60, . . .
	-1.29 (0.36)	Sex of driver—1 equals male and 2 equals female
	+0.0554 (0.012)	Toll per person—in cents
	+0.0028 (0.0003)	Difference in travel time—in sec

Numbers in parentheses beneath the coefficients are the standard errors of the coefficients. This model correctly estimated route choice for individual motorists 75.8 percent of the time. The percentage was calculated from the estimated p (x) for each motorist. If p (x) turned out to be greater than 0.5 the motorist was estimated to take the free road, and if it was less than 0.5, the toll road. The estimates were then compared with the actual choices.

Twelve models based on route characteristics taken from interview data were estimated. The best route-choice model based on the five-area interview data for which test vehicle measurements were also available had an f (x) as follows:

	Coefficient	Variable
f (x) = 3.48	-0.410 (0.089)	Income category of motorist—categories 1 to 8
	+0.025 (0.033)	Model year of car—'58, '59, '60, . . .
	-1.12 (0.44)	Sex of driver—1 equals male and 2 equals female
	+0.0488 (0.014)	Toll per person—in cents
	+0.00522 (0.00048)	Difference in travel time—in sec

This model correctly estimated route choice for individual motorists 84.5 percent of the time.

The best route-choice model based on the full eight-area interview data had an f (x) as follows:

	Coefficient	Variable
f (x) = 3.86	-0.432 (0.077)	Income category of motorist—categories 1 to 8
	+0.0499 (0.011)	Toll per person—in cents
	+0.0053 (0.0004)	Difference in travel time—in sec

This model correctly estimated route choice for individual motorists 85. 6 percent of the time.

Two criteria were used to select the best model in each set:

1. The coefficients of income, toll per person, and all the route-characteristic variables, such as difference in travel time, had to be significant at the 95 percent confidence level when compared to their standard errors.
2. The higher the percentage of correct predictions, given criterion 1, the better the model.

The unique characteristic of all three best route-choice models is that none contains a route characteristic variable other than difference in travel time. This is despite the fact that models were developed with a wide variety of traffic impedance variables in a number of combinations. The exclusion of traffic impedance variables from the route-choice model can be interpreted as (a) assigning little importance to a reduction in traffic impedance, independent of travel time, or (b) stating that nearly all the important reductions in travel impedances are included in the associated reductions in travel time. The second interpretation assumes that the difference in travel-time variable is highly correlated with the traffic-impedance variables, so that a separate coefficient cannot be reliably estimated. However, if this were true, the coefficient of the difference in travel-time variable should change, and the ratio of its coefficient to its standard error should decrease as travel-impedance variables are added to the route-choice model. This does not happen. Therefore, the first interpretation appears to be correct. According to this interpretation, a reduction in a traffic-impedance variable such as Δ deviation from speed limit is important only for the reduction in travel time it may bring. If it does not result in lower travel time, it has little or no importance to the motorist and does not affect route choice in a statistically significant manner.

Value of Travel Time

The value of travel time is calculated as the ratio of the coefficients of difference in travel time and toll per person. For the units in which the coefficients are expressed, the ratio must be multiplied by 36 to obtain an answer in dollars per hour. Initially, attention is directed at the values of time calculated from two best route-choice models for the five areas to facilitate comparisons.

From the best model based on test-vehicle data, the value of travel time was estimated to be \$1.82 per person per hour ($0.0028 \times 36 \div 0.0554$). The 95 percent confidence limits of the value of time range from \$1.04 to \$2.60 per person per hour.

From the best model based on motorists' reported route characteristics covering the same areas as the test-vehicle data, the value of travel time was estimated to be \$3.84 per person per hour ($0.00522 \times 36 \div 0.0488$). The 95 percent confidence limits of the value of time range from \$2.82 to \$4.86 per person per hour.

Standard errors of the calculated values provide confidence limits on their magnitude for each model, that is, for the particular set of explanatory variables for which the coefficients were estimated. However, these confidence limits apply only to values calculated from data from the same population using the same model. They provide no information on the changes in the calculated values (and hence the value of time that might occur) as other explanatory variables are added or subtracted from the route-choice model. Since large changes in the coefficients are possible when there is intercorrelation between the potential explanatory variables, the stability of the coefficients (and hence their ratios) will be analyzed as explanatory variables are introduced or removed from the discriminant function. This provides a clue to whether a consistent effect of the variable is being measured or whether only an unstable best fit has been determined that changes with the particular set of variables used to construct the model.

For the two best models that estimate the value of time from the five-area data, the test of stability takes on a special interpretation. The other variables to be introduced are all different formulations of the traffic-impedance variable. Therefore, the test can be rephrased: Is the value of time that is estimated when the value of traffic impedance is set at zero changed when the route-choice model is also formulated to estimate a value of traffic impedances, that is, when traffic impedance variables are included in the model?

For the model using test vehicle road measurements, the ratio of the coefficients of Δtravel time to the coefficient of toll per person is 0.05. The ratios of the coefficients for the models are the value of time in cents per person per second. Examination of the variations in this ratio when one additional variable is added (either in the form of a delta or a total variable) shows that the ratio of the two coefficients varies from a low of 0.04 to a high of 0.053. Thus, with the introduction of one additional variable, the variation in the value of Δtravel time stays well within the 95 percent confidence limit.

For the model using interview data for road measurements, the ratio of the coefficients of Δtravel time to the coefficient of toll per person is 0.107. Introduction of other variables into the discriminant function—not only singly but in groups of up to five additional variables—causes the ratio of coefficients to vary from 0.113 to 0.0866. Thus, the maximum variation with the introduction of other explanatory variables is well within the 95 percent confidence limit for the value of Δ travel time.

In summary, both the best model using test-vehicle data and the best model using interview data to measure road characteristics provide stable estimates of the value of travel time that significantly differs at the 95 percent confidence level from the $0.86 per person per hour value most commonly used in highway economy studies. In addition, the two estimates are significantly different from each other at the 95 percent confidence level.

Before analyzing the deviations of both estimates from a hypothesized true value of time, one argument will be considered for summarily rejecting the perceptual estimate without further analysis. This argument asserts that the value of travel time based on physical data must be used, since highway economy studies are based on physical data.

Nature of Value of ΔTravel Time and Its Use in Highway Economy Studies—The theoretical framework for the value of travel time is the motorist's indifference curve. Within this framework, the value of time to a motorist is the slope of the indifference map in the plane formed by the money-used and time-used axes. This slope of the indifference map can be interpreted as a value of travel time that the motorist holds only if the variables of money used and time used are the ones he perceived, that is, if it is his indifference map. Specifically, in this analysis the toll per person and Δtravel time quantities used should be the quantities the motorist perceived when he made his route-choice decision. Therefore, the only question is: Does the test vehicle or interview data on road characteristics better represent the motorist's perceived quantities when he made the decision? There is only one value of time—the motorist's. The best model is determined by how well it estimates the value of time, not its data source.

However, after the value of time has been estimated, there may be some question about how properly to estimate the difference in travel-time variable for use with the value of time. If motorists consistently perceive Δtravel time as higher or lower than is actually the case, they will estimate their benefits higher or lower than the product of their value of time and their actual time savings. However, given that the motorist's values are used, it seems appropriate for a public official to base benefits on the best available estimates of travel-time changes. This is the same benefit the motorist would calculate if he were informed of the "true" travel time difference.

Therefore, returning to the question, Can either value of Δ travel time be rejected based on the nature of the data used in its estimation?, the conclusion is that neither estimate can be rejected. Both must be analyzed.

Comparison of Test-Vehicle and Interview-Based Estimates—Neither the test-vehicle nor interview data provide a precise estimate of the travel time perceived at the point of the route-choice decision. Interview data have a bias toward the road taken, that is, the motorist consciously or unconsciously tends to make the road appear better in response to a question than it was previously perceived to be. Analysis of the data indicates that the magnitude of this bias is about 1 to 2 minutes upward in Δtravel time if the free road is taken and about 1 to 2 minutes downward if the toll road is taken. It is easy for this level of bias to be incorporated into the reported magnitudes of Δtravel time because motorists tend to report travel-time differences in multiples of 5 minutes. About 92 percent of the estimates were rounded to multiples of 5 minutes.

The measured data are in error, if for no other reason than that the motorist's perceptions do not always correspond to the actual travel time. Thus, even if the measurement were exact—which is unlikely, given the small number of measurements—they would still be in error in estimating the Δtravel time perceived at the point of decision. Analysis of the data indicates that the measured data probably are equal to the perceived Δtravel time at the time of decision on the average, that is, the measured data are unbiased. However, the effect of the differences between perceptions and measurements is to increase the variance of the travel time distribution from what it would otherwise be.

The effect of the bias in interview data and the errors in measured data on the coefficient of travel time in the route-choice model is shown in Figure 1. The effect of the bias and errors is compared to the coefficient that would hypothetically be estimated without bias or errors in the data. In each of three examples, the explanatory variables other than Δtravel time are assumed to be held fixed. It is assumed that 200 motorists have faced different Δtravel times and made a decision between the toll and free roads.

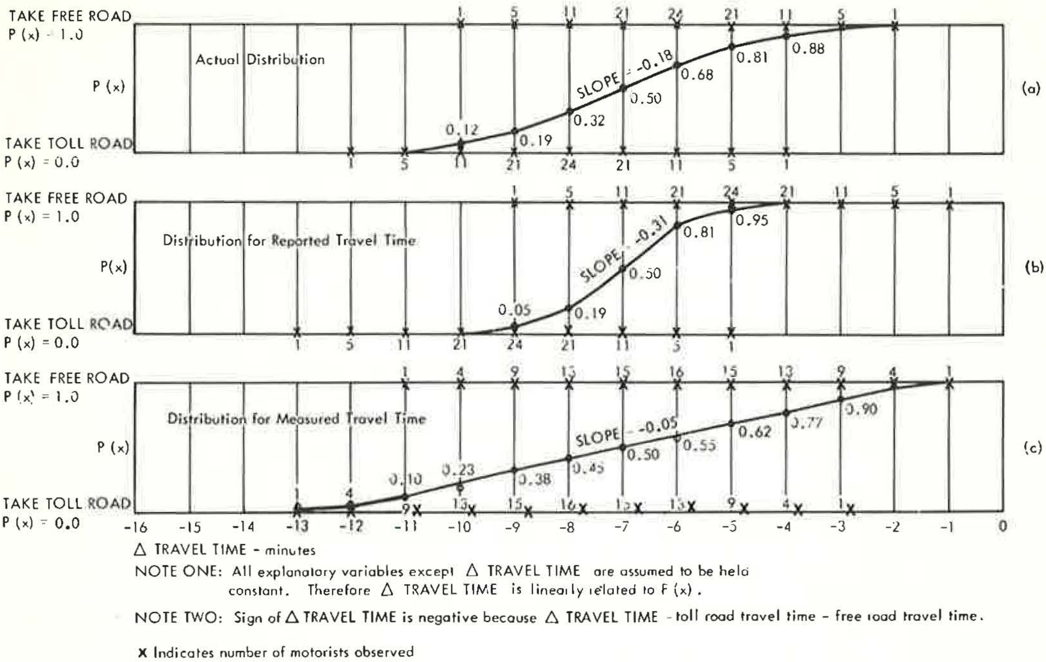


Figure 1. Effect of biases and errors on the coefficient of Δtravel time.

Of these, 100 chose the toll road. They are shown by X's on the toll-road choice line, indicating the Δtravel time they faced. The other 100 motorists are shown in the same way on the free-road choice line. The number above the X's indicates the number of X's—the number of motorists that faced that level of Δtravel time and made the indicated decision.

For comparative purposes, the analysis concentrates on the slope of the S-shaped curve in its midrange. Since all explanatory variables except Δtravel time are assumed to be held constant, changes in Δtravel time are linearly related to changes in f(x). Therefore, the larger the absolute magnitude of the slope in the midrange (which is common to each graph), the larger the absolute magnitude of the coefficient of Δ travel time; the smaller the absolute magnitude of the slope, the smaller the absolute magnitude of the coefficient of Δtravel time. Since toll per person is known without error, its estimated coefficient is nearly uniform for all models; therefore, the larger the coefficient of Δtravel time in absolute magnitude, the larger the value of Δtravel time, and vice versa.

Figure 1a shows a hypothesized distribution for the Δtravel time perceived at the time of the route choice The approximate slope of the S-shaped curve between -6 and -8 min is -0.18, that is, a change in p(x) of -0.18 for each 1-min change in travel time. The coefficient of Δtravel time from these data is assumed by definition to provide the true coefficient of time. The S-shaped curve is pictured as trying to minimize the sum of the squares of the deviations for each integral Δtravel time. This would require that the curve go through the mean of the observations at each integer (shown on the graph). While the actual S-shaped curve fitted to the data will not go through the mean for each integer, it will be close to these means in the midrange, where the largest number of observations were made.

Figure 1b shows a hypothesized distribution of travel time reported in the interviews. This is the same distribution used in Figure 1a, except 1 min is subtracted from the Δ travel time of each toll-road user and 1 min is added to each free-road user. The effect of this bias on the estimating of an S-shaped curve is to raise its approximate slope in the -6 to -8 min range to -0.31. This increase in the absolute magnitude of the slope is due to the additional separation in the toll-road and free-road motorist distributions caused by the biases. This bias makes discrimination between toll-road and free-road users easier. Better discrimination corresponds to a higher slope of the S-shaped curve, which provides a quicker change in p (x) from the toll road to the free road as Δ travel time increases. Therefore, the value of time based on interview data is estimated to be higher than the true value of time.

Figure 1c shows a hypothesized distribution of travel time measured at the time of the survey. The mean of each distribution is kept the same as in Figure 1a—at -6 min for the free road and -8 min for the toll road. The only change is an increase in the variance of each distribution, that is, a spread due to errors between the perceived Δ travel time at the point of decision and the measured Δ travel time. The effect of the increase in the variance is to lower the approximate slope of the S-shaped curve between -6 and -8 min to -0.05. The larger variance has increased the overlap of the two distributions and made the discrimination task more difficult. This corresponds to a lower slope in the midrange of the S-shaped curve, which provides a slower change in p (x) from the toll road to the free road as travel time increases. Therefore, the test-vehicle-based value of time is estimated to be lower than the true value of time.

The analysis shown in Figure 1 leads to the conclusion that the value of Δ travel time based on the test-vehicle data of $1.82 per person per hour is low and that the corresponding estimate of $3.84 per person per hour based on interview data is too high. The correct value of time lies between these two values.

It was not possible to derive estimates of the relative magnitude by which each type of estimate was in error. However, both simulation and analysis hold some promise. At this point in time, a simple average of the two values of time would appear to provide the most reasonable compromise estimate based on the five-area data.

Additional Evidence on the Value of Time—Additional interview data on commuters' route choices were available for three areas. Despite the dissimilarities between the route choices in these three additional areas and the original five areas, there was no significant difference between the two sets of data in the commuters' decision structure (as approximated by the model). Specifically, the coefficients of toll per person and Δ travel time estimated from the two sets of data were different by less than a single standard error of each coefficient. Therefore, the difference in the value of time calculated for both areas is not statistically significant.

The two sets of data were combined, and a route choice model estimated for the eight areas. Results were as follows:

1. Using the same variables as in the best five-area model using interview data, the value of the difference in travel time was estimated to be $3.72 per person per hour with a standard error of $0.84 At the 95 percent confidence level, the value of the difference in travel time ranges from $2.07 to $5.37 per person per hour.
2. If the two explanatory variables—sex of the driver and model year of the car—are eliminated (as was indicated by their lack of statistical significance) and the route choice model is reestimated, the value of the difference in travel time is estimated as $3.82 per person per hour with a standard error of $0.84. At the 95 percent confidence level, the value of Δ travel time ranges from $2.17 to $5.47 per person per hour.

These results are very close to the calculated value of the difference in travel time from the best five-area model with some widening of the confidence limits. The additional evidence of the three new areas strongly supports the existence of a uniform value of Δ travel time based on interview data. Also, the highly favorable nature of these results lends implicit support to the hypothesis that the value of travel time based on test-vehicle data for the three additional areas also would correspond closely to that of the other five areas.

Use of the Estimated Value of Δ Travel Time

The value of Δ travel time for the sample has been placed within the limits of $1.82 per person per hour (best five-area model based on test-vehicle data) to $3.82 per person per hour (best eight-area model based on interview data). There is no evidence for narrowing these limits further or placing the value of the difference in travel time (that is, the value of Δtravel time) closer to one limit or the other. Therefore, the simple average of the two values, or $2.82 per person per hour, is selected as the value of Δtravel time.

It is obvious that $2.82 per person per hour is not the value of Δtravel time for all motorists under all circumstances. In analyzing the subpopulation of motorists for whom this value is appropriate, one is limited because the sample was not random. Consequently, statistical confidence limits cannot be placed on the expected value of Δ travel time for motorists—not even for commuters facing a toll road-free road choice. In a statistical sense, knowledge is limited to the observations in the sample. Nevertheless, the value of Δtravel time of $2.82 per person per hour is based on the actual preferences displayed by commuters. Alternative values of time are based on judgment and current opinion. In these circumstances, it is our judgment that the value of time of $2.82 per person per hour should be used for all commuter trips greater than 10 min and longer than 5 miles.

The reason for restricting the recommendations to commuters is obvious: all the motorists in the sample were commuters. Likewise, the shortest trips in the sample took over 10 min and were longer than 5 miles. Another characteristic of the sample is that all the route choices involved toll road-free road alternatives. However, this does not appear to present a limitation to increasing the value of travel time to at least $2.82 per person per hour. If there is a bias against paying a toll just because it is a toll, the bias would operate to decrease the estimated value of Δtravel time from its true free road-free road value. The value of the time savings would have to be greater than the toll by the amount of the bias. This decreases the amount of toll that a motorist would otherwise be willing to pay and results in a lower value of Δtravel time for the motorist. Consequently, because of this bias, the value of $2.82 per person per hour may be too low. However, from other evidence developed in the study, the magnitude of this bias in the decisions studied is believed to be small.

The data have other peculiarities. The average income per family is high compared to all commuters, being approximately $9,200 compared with the overall average of $6,500. However, income is a variable in the route-choice model and its influence is estimated separately. Professional and blue collar workers are overrepresented and clerical workers are underrepresented. Metropolitan areas predominate. Government and defense industry workers are overrepresented. The possible effect of these and other characteristics of the data appears to be negligible in light of the magnitude of the difference between the currently used values of time and $2.82 per person per hour.

It is therefore recommended that the value of time for commuter trips of over 5 miles and 10 min be adjusted upward to the estimated value of $2.82 per person per hour.

CRITIQUE AND EXTENSION OF THE METHODOLOGY

The value of time is shown to have a number of desirable statistical characteristics for an estimated value. In addition, the number ($2.82 per person per hour) can be used in present procedures for calculating highway benefits. However, it is just this characteristic of the estimate—that it is a single number—that makes it most undesirable on theoretical grounds.

This section analyzes the characteristics of this estimate of the value of time that are independent of the amount of time saved, of the income level of the motorist, or of any other variable except type of trip, which is limited to commuters.

The linear form of f(x) used to estimate route choice makes the value of Δtravel time constant for all levels of time savings. However, both theoretical and empirical work in earlier Stanford Research Institute studies indicate that motorists are less sensitive to an incremental unit of time savings when total time savings are either very small or very large (1).

Figure 2a shows the theoretical relationship that is hypothesized. The slope of the relationship is low for both small time savings (labeled insensitive) and large time savings (labeled diminishing marginal returns) and is high in the midrange. Therefore, the linear approximation is low for some amounts of time savings and high for others.

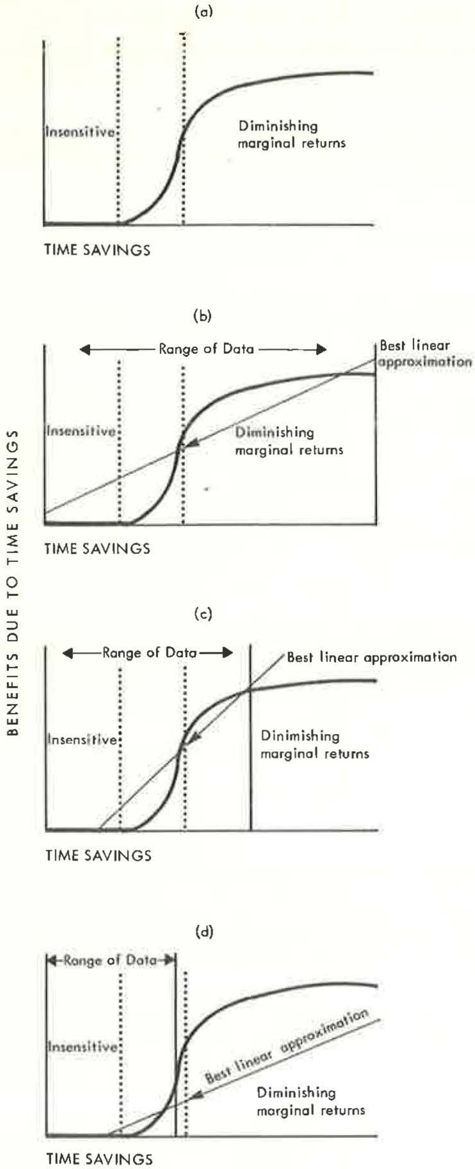


Figure 2. Relationships of benefits due to time savings.

Furthermore, the estimate of benefits obtained from multiplying time savings by the value of time is not necessarily equal to even the linear approximation. It is equal only if the intercept of the linear approximation on the benefits axis is zero.

Figures 2b, 2c, and 2d illustrate how the slope and intercept of the linear approximation may change as the range of data changes. The slope is low and the intercept positive when much of the data lie in the area of diminishing marginal returns (Fig. 2b). The slope increases and intercept decreases (to a negative value) as data become more evenly distributed over the three areas (Fig. 2c). Finally, the slope of the linear approximation decreases and the vertical intercept remains negative as the range of data excludes all diminishing marginal returns and part of the midrange (Fig. 2d). In Figure 2b, the linear approximation of benefits from time savings is higher by the amount of vertical intercept than that estimated from multiplying the value of Δtravel time by Δtravel time. In Figure 2c and 2d, the linear approximation of benefits from time savings is lower by the magnitude of the vertical intercept.

There are reasons to believe that Figure 2c or 2d portrays the actual situation in the sample. It was selected to provide a split in route choices and approximately one-third of the motorists reporting that the toll road is faster do not take it. Since motorists appear much more sensitive in their route choice to the level of time savings than to any other variable including toll per person, it appears that benefits due to time savings cannot be too high, or they would outweigh all other considerations and result in a higher proportion of motorists taking the toll road. It is likely, therefore, that few if any motorists are in the region of diminishing marginal returns.

Therefore, the use of the product of the value of travel time and travel time savings as an estimate of benefits may overstate the benefits compared with the linear approximation, which itself has over- and under-approximation errors.

Total Benefits

A quantitative estimate of the magnitude of the intercept of the linear approximation (as well as the effect of income on the value of time) requires an analysis of the motorist's total benefits from his route selection. This is necessary because the route choice is the observed event to which benefits can be related. The calculation of the benefit from time savings involves an allocation of part of the total benefits from the route choice to time savings and clouds the analysis.

The method of calculating the difference in total benefits for two alternative free roads can be conceptualized as follows: Assume that the characteristics of one road are better. On the better road, however, there is a toll booth with an operator that adjusts the amount of toll required from each motorist until the motorist becomes indifferent to the route he takes. Then the toll is lowered just enough for each motorist to take the better road. This toll, individualized for each motorist, equals the money value of the benefits he would have received if there were no toll—his benefits on the better free road.

The median benefit to the group of motorists is the toll that would make the median motorist indifferent. This toll can be obtained in a straightforward manner from route-choice model. The median motorist is indifferent to differences in the two roads when the probability of taking the free road is 0.5. But the probability of taking the free road is p (x) where

$$p(x) = \frac{e^{f(x)}}{1 + e^{f(x)}}$$

where $p(x) = 0.5$ and $f(x) = 0.0$.

If the route-choice model uses as explanatory variables toll per person plus motorist and route explanatory variables, then:

$$f(x) = 0 = k + a_T x_T + a_{1m} x_{1m} + a_{2m} x_{2m} + \ldots + a_{1r} x_{1r} + a_{2r} x_{2r} + \ldots$$

where

a_T is the coefficient of toll per person,
x_T is toll per person,
a_{im} is the coefficient of the ith motorist explanatory variable,
x_{im} is the ith motorist explanatory variable,
a_{ir} is the coefficient of the ith route explanatory variable,
x_{ir} is the ith route explanatory variable, and
k is the estimated constant term.

Therefore, the total benefits—x_T, or the toll per person required to make the median motorist indifferent—are

$$x_T = -\frac{k}{a_T} - \frac{a_{1m}}{a_T} x_{im} - \frac{a_{2m}}{a_T} x_{2m} - \ldots - \frac{a_{1r}}{a_T} x_{ir} - \frac{a_{2r}}{a_T} x_{2r} - \ldots$$

For the best model using test vehicle data, the total benefits become

$$\begin{aligned}\text{Total benefits per person} = {} & \frac{9.15}{0.0554} + \frac{0.236}{0.0554}\ \text{Income category} \\ & + \frac{1.29}{0.0554}\ \text{Sex of driver} \\ & - \frac{0.105}{0.0554}\ \text{Model year of car} \\ & - \frac{0.0028}{0.0554}\ \Delta\ \text{Travel time}\end{aligned}$$

Any mathematically equivalent expression for total benefits is permitted. A particularly appealing one, since Δ travel time is the only route variable describing the two free roads, is to use Δ travel time as the only explanatory variable with the other explanatory variables (based on motorist characteristics) operating as modifiers of the coefficient of Δ travel time. Stated mathematically,

$$\text{Total benefits per person} = (V^*)\ (\Delta\ \text{travel time})$$

For the best model using the vehicle data, the equality is preserved when:

$$V^* = -\frac{0.0028}{0.0554}\left[1 + \frac{9.15}{0.0028}\,\frac{1}{\Delta\ \text{travel time}} - \frac{0.236}{0.0028}\,\frac{\text{income category}}{\Delta\ \text{travel time}} - \frac{1.29}{0.0028}\,\frac{\text{sex of driver}}{\Delta\ \text{travel time}} - \frac{0.105}{0.0028}\,\frac{\text{model year of car}}{\Delta\ \text{travel time}}\right]$$

where 0.0028/0.0554 is the value of Δ travel time as previously defined, and the expression in brackets modifies it, based on the income category, sex of driver, and model year of car.

V* has the dimensions of total benefits per second saved. It not only incorporates the effects of the explanatory variables specifically in the model, but also the effect of the average of all other variables through the constant term. These other variables are not only the excluded variables, such as Δ distance and Δ speed changes, but also such variables as bias against the toll road for which no attempt was ever made to represent them explicitly in the route choice model. The multiplicity of factors involved in determining the magnitude of the constant term should be kept in mind as its effect is examined.

Estimates of Total Benefits to Motorists

Figure 3 shows total benefits vs Δ travel time for the model using test-vehicle data and the best area interview-data model. The relationships are for the median motorist. In the graph, explanatory variables other than toll per person and Δ travel time are held

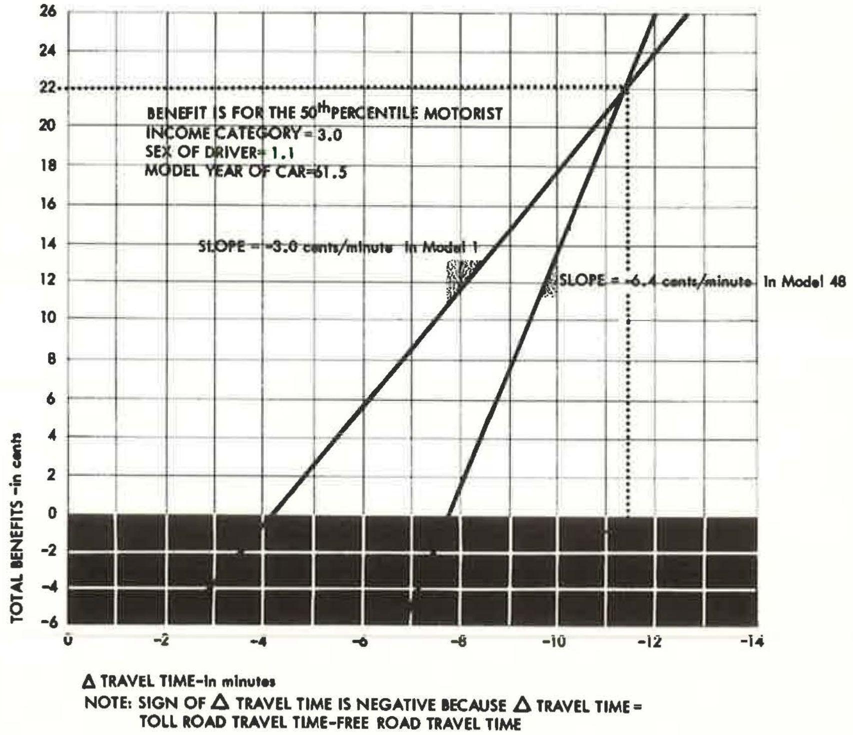


Figure 3. Total benefits vs Δ travel time for model 1 (best model using test-vehicle data) and model 3 (best area interview-data model).

constant. Income category is set at 3 ($6,000 to $8,000 a year), which includes the median for all automobile commuters. (The median value for all automobile commuters is about $6,500 as shown in Passenger Transportation Survey, 1963 Census of Transportation, Bureau of the Census, 1965.) The test-vehicle data model also uses the model year of the car and the sex of the driver as explanatory variables. These variables are fixed at their mean value in the sample, that is, a model year of 61.2 and a sex of 1.1 (10 percent females, 90 percent males). The slope of the lines in Figure 3 is the value of Δ travel time in units of cents per minute. Any point on the line relates travel-time savings to the equivalent total benefits to the motorist, given the fixed value of the other explanatory variables.

Figure 4 shows a different picture. The average model, which has a value of Δ travel time of $2.82 per person per hour, or 4.7 cents per person per minute, is shown by the solid lines for each income category from 2 through 5. The effect of an increase in family income of the motorist is to increase the total benefits equivalent to a fixed level of travel-time savings.

Total benefits are negative for some amounts of positive time savings (Figs. 3 and 4). For example, in Figure 4 the solid lines show that total benefits become negative for motorists in income category 3 when travel time savings are less than 6.7 min. This property—benefits dropping to zero before time savings—was depicted in Figure 2c and 2d as the most likely placement of the linear function used to approximate the theorized nonlinear relationship between benefits due to time savings and actual time savings.

The estimated relationship should not be used to calculate negative benefits. It is an approximation and should not be used outside the range of data in the sample. A toll of 5 cents per person is effectively the lower limit of the data. Therefore, the relationship should not be used to estimate total benefits of less than 5 cents. Similarly,

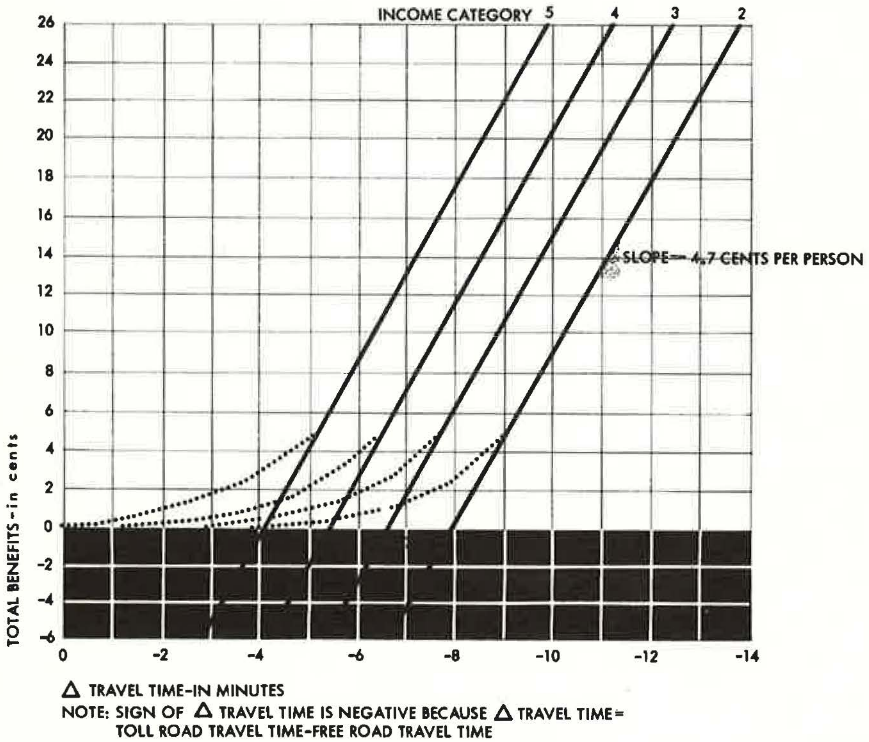


Figure 4. Total benefits vs Δtravel time, average model.

the relationship should not be extended above a toll of 30 cents per person, which is effectively the upper limit of the data. For total benefits less than 5 cents per person, a new relationship can be proposed,which theory suggests should eliminate negative benefits for positive time savings, intersect the origin, and have a monotonically increasing slope to the right of the origin. The dotted lines in Figure 3 indicate such a relationship. The required reduction in the slope to eliminate negative benefits for positive time savings makes total benefits less sensitive to time savings near the origin.

Once the slope of the linear portion of the relationship has been estimated, the range of reduced sensitivity is determined by its intercept. The magnitude of the intercept is determined by several factors. First, the income category of the motorist affects the placement and consequently the range of reduced sensitivity. For the model graphed in Figure 4, the range of reduced sensitivity for motorists in income category 5 is from the origin to time savings of approximately 5 min, and for motorists in income category 2, from the origin to time savings of approximately 9 min. Second, the placement is affected by the constant term in the route-choice model. The question therefore arises as to how accurately the constant term is known, that is, what the confidence limits on the constant are.

For both models, the standard error of the constant term is slightly larger than two units. But only a one-unit change in the constant term changes the intercept of the line with the Δ travel time axis by 6 min for the model based on test-vehicle data and 3.2 min for the model based on interview data. Therefore, the confidence limits on the placement of the line are very broad. The hypothesis that the intercept is actually zero—that there is no reduction in sensitivity—cannot be rejected at the 95 percent level. Thus the route choice models can provide statistically significant estimates of the marginal effect of both Δ travel time and the income category on total benefits, but not the intercept of the relationship. The wide confidence limits on the constant term may be due to the fact that the constant term reflects many factors, including the mean value of each explanatory variable, the mean value of the excluded explanatory variables of traffic impedances (to the extent that their mean affects route choice), and the mean value of other variables, such as toll road bias, that were never considered for inclusion in the route-choice model. The effects of the average magnitude of the excluded explanatory variables were analyzed, and the Δ distance in the models based on physical data had a noticeable effect. An adjustment for its average effect would lower the intercept of test-vehicle data model by about 0.5 min, but it has a negligible effect on the interview data model.

The estimated intercept based on toll road-free road choice data may be biased as an estimate of the intercept for a free road-free road choice. This bias if it exists is the negative effect on the motorist of the existence of a toll, independent of the level of the toll. Its existence could be tested by comparing the estimated relationship from a toll road-toll road choice. In this case, both roads would have a toll and any bias would cancel out. The difference in tolls would act as a measure of total benefits.

The only evidence available on the magnitude of the toll-road bias is inferential. In a hypothetical question, motorists were asked if they would pay a given amount for additional time savings. Most of them indicated thay they would not, even though the payment was considerably less per minute saved than what they were already paying. This discrepancy between word and deed is probably caused by the toll-road bias. It operates in a hypothetical question, where a verbal refusal to make the payment does not cost the motorist any actual benefits. However, when faced with real benefits, many more motorists pay the toll than their answers to the hypothetical question indicated. The inference can be drawn that the average toll-road bias in the actual situations may be quite small and exert only minor influence on the intercept.

Thus, while the total benefits approach is useful in examining the effect of the intercept and other variables in the route-choice model, the analysis is still based on a linearized estimator, that is, f(x). Within this study, the extent of the nonlinearity could not be determined. (A precise estimate of the intercept in the total benefits versus Δ travel time would have provided some insight.) However, the ramifications of a nonlinear relationship such as those shown in Figure 2 are quite striking and will be illustrated in a simple example.

Effect of Nonlinearity in the Relationships of Total Benefits to Time Savings

With a nonlinear relation, a reduction in the slope of the relationship between total benefits and Δ travel time compared with the linear portion will occur. If such a reduction occurs around the origin, the value of a minute saved depends on which minute it is—the first minute saved or the tenth. Stated another way, if the motorist has a reduced sensitivity to small savings in travel time, the average value of a minute is 1 minute or 10 minutes. In such a case, the accurate assessment of the benefits of time savings on a portion of the trip requires a knowledge of the travel-time savings for the entire trip.

By similar logic, the evaluation of the benefits of time savings from a highway improvement requires knowledge of whether it is a single isolated improvement or part of a series of improvements. In the latter case, the larger the total time savings of which the improvement is part, the greater the average value of a minute saved.

However, reduced sensitivity to small time savings would not only affect the data collection requirements for highway economy studies, but it would also create problems in specifying the proper methodology for the evaluation. The following example introduces some of the methodological complications:

Assume that the relationship between total benefits and Δ travel time is known. The question is then posed: What are the benefits to a motorist of the proposed improvement in the following example? The motorist must go from point 1 to point 2. At present, he has the choice of using either Route A or Route B. Route A is 10 minutes faster than Route B. The proposed improvement is to Route A. If the improvement is made, Route A will be 12 minutes faster than Route B. These conditions are shown in Figures 5 and 6.

Assume that the time savings of the proposed improvement are the only aspect of the improvement that affects the total benefits perceived by the motorist. Then one method of calculating the benefits (Method 1) would be:

Total Benefits of Improvement = f [travel time on Route A (improved) - travel time on Route A]

= f[2 min of travel time savings]

However, the relationship between total benefits and travel time was presumably estimated from data on the motorist's choices between two routes, both of which were available at that time. Therefore, it is equally logical to use the following method (Method 2) to calculate benefits: Total Benefits of Improvement = [total benefits of Route A (improved) compared with Route B] - [total benefits of Route A compared with Route B] = f [travel time on Route A (improved) - travel time on Route B] - f [travel time on Route A - travel time on Route B] = f (12 min of travel time savings) - f (10 min of travel time savings)

If the slope of the total benefits vs Δ travel time relationship were a constant for all amounts of Δ travel time, the two methods of calculating total benefits would produce the same estimate of total benefits. But if the slope is not constant because of reduced sensitivity to small time savings, for example, the results of the two methods will differ. For the modified relationship shown in Figure 4 (the dotted lines for benefits

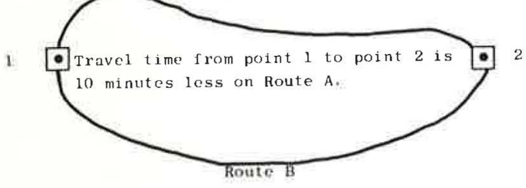


Figure 5. Present conditions.

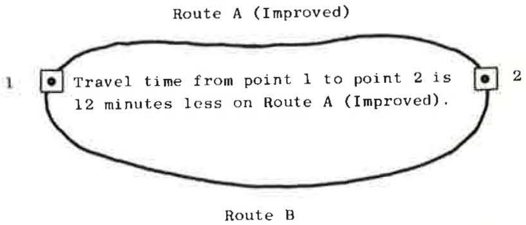


Figure 6. Conditions with proposed improvement to Route A.

of less than 5 cents), the first method of calculation would estimate total benefits of less than 1 cent. The second method of calculation would estimate total benefits of 9.4 cents. It is not just insensitivity to small time that will cause this result. The two methods will generally produce different answers when the slope varies. For example, if total benefits were a function of Δ travel time and (Δ travel time)^2, the relationship would be curvilinear, and the method of estimating total benefits also would be important.

The choice between the two methods is difficult. Both methods of calculating total benefits can be logically defended and both produce anomalous results under some circumstances.

The recommended use of $2.82 per person per hour as the value of travel time is based on the use of Method 2 and the assumption that total benefits before and after the improvement lie on the linear portion of the relationship between total benefits and travel time. This is the case shown in the example.

Under these circumstances, only the slope of the relationship in its linear portion need be known. The placement of the relationship will not affect the results. Since the extent of the reduced sensitivity is not known, it is impossible to specify quantitatively the route choices for which the assumption of linearity is valid.

The use of $2.82 per person per hour is consistent with Method 1 only if the range of insensitivity is assumed negligible; that is, the graph of the total benefits vs travel time is approximately linear and passes through the origin. In this case, Methods 1 and 2 give the same results.

The recommended value of Δ travel time bypasses the problems of estimating total benefit in the face of reduced sensitivity through a plausible assumption on the method of estimating highway benefits. However, this problem will almost certainly become important as the empirical basis for the value of time expands.

By making a more precise estimate of the value of time than has previously been possible, this study has transformed the question, "What is the correct number of the value of time?" to "What is the functional form and parameters of the value of time?". The second question will be more difficult to answer, but being in a position to ask the mc sophisticated question indicates considerable progress.

REFERENCE

1. Haney, Dan G. The Value of Time for Passenger Cars: A Theoretical Analysis and Description of Preliminary Experiments. Stanford Research Institute, May 1967.

Discussion

DENNIS NEUZIL, Assistant Professor of Civil Engineering, University of Delaware—Because this report has presented rigorously derived values for the value of time to commuting motorists, and because similar information for other types of trips does not exist, the Stanford Research Institute values will probably be used for other trip purposes as well. When faced with a lack of information for certain phenomena, there is a tendency to use data from related phenomena that have been well substantiated. While this practice may not be desirable, it is not uncommon.

For example, one state highway department has already made use of the Stanford Research Institute travel-time values in the analysis of a proposed rural Interstate highway located in a scenic mountaninous area abounding in recreational activities. Citing the Stanford Research Institute study, the highway department used a value of $1.72 per person per hour—slightly less than the $1.82 per person per hour average value based on actual cost differences and time savings found in this report. Thus a value slightly reduced from that found for urban work trips is being used in the economic analysis of a highway for which work trips will not be the dominant trip type, and where the alternatives differ significantly in length, gradient, and cost.

At the risk of sounding redundant, then, it should be emphasized that the values of time reported in this study are for commuting motorists, that is, for urban work trips, and may not be valid for other types of trips. For rural highways, where the combination of recreational, tourist, and pleasure-drive trips is often the major component of average daily traffic, and where average trip length is greater than in urban areas, one would expect a lower overall value of time to apply.

During the discussion of this paper, a significant statement was made concerning the application of time values for non-toll road travel to the effect that, time costs should not be added to motor vehicle operating costs in order to arrive at a total road-user cost for benefit-cost ratio analyses, because these are not the same type of costs. Unlike operating costs, time costs do not represent an economic transaction: while there is a per-mile expenditure for fuel, oil, tires, etc., there is no actual expenditure for travel time. Although we may impute a time cost to the motorist, he does not actually pay this "cost" from his wallet. This position has, I believe, much merit.

Highway economy analysts typically report only a single benefit-cost ratio for a proposed improvement. Because time costs are becoming larger relative to operating costs for many highway improvement situations, the limitations of our knowledge and the above considerations indicate that a better procedure would be to present a series of road-user costs, savings, and consequent benefit-cost ratios using, for example, the following format: (a) all time costs excluded (operating costs only); (b) including truck time costs; (c) including truck time costs plus, say, one-half of the passenger car time costs; and (d) all time costs included. This presentation could also be made with more than one assumption for the value of travel time.

When the results of highway economy studies are presented in the above manner, those who will review and pass judgment on the several alternatives for a given highway improvement will have the opportunity to note the sensitivity of the economic feasibility of the alternatives to the assumptions regarding travel-time costs, as well as to make their own judgment as to the proper handling of time costs. This format would add little to the cost or effort of conducting the economic analysis but would significantly increase its utility.

Value of Commuters' Travel Time—A Study in Urban Transportation

THOMAS E. LISCO, Chief Economist, Chicago Area Transportation Study

ABRIDGMENT

•TYPICAL suburban commuters are willing to pay at a rate approaching 50 percent of their wage rate to save time on their trips to work. Further, when overall door-to-door commuting times are equal between travel modes, these same commuters place a $2.00 value on the extra comfort afforded by their own cars over that provided by transit.

These are two of the most important results of a modal choice study conducted on household interview data collected as part of the Chicago "Skokie Swift" Mass Transportation Demonstration project. This study, which used minutely derived times and costs for alternative trip modes, inferred from actual choices made by commuters the values they placed on the various factors entering into their choices. It simultaneously measured the effects of different commuter characteristics, such as income, on the choices made. The analytical tool used was multiple probit analysis, a tool similar to logit analysis, and one which fits curves appropriate to the modal choice problem.

The results have very strong implications both for mass transportation planning and for its pricing. Among other things, the study indicates that the actual comfort provided by the transit vehicle can be very important in contributing to commuter satisfaction. It also shows that transit ridership by commuters should be very unresponsive to fare changes. With typical commuters valuing time at 4 or 5 cents a minute, and comfort at $2.00 a day, the transit fare becomes relatively unimportant in the modal choice decision. This, in turn, implies that most transit systems can probably be self-supporting simply through charging economic fares.

Two other results deserve mentioning. The first is that, given the values put on time and comfort by the commuters studied, their choices of transportation mode appeared to be both rational and consistent. Where automobiles were the better choice, people drove. Otherwise, transit was used. There was no evidence of an irrational commuter "love affair" with the automobile. The second result concerns walking time. A small supplementary study of parking lot prices in downtown Chicago indicated that at the margin, people who drive downtown are willing to pay 30 cents a block or 12 cents a minute to avoid extra walking. This extreme discomfort value of walking time would indicate that a two- or three-block difference in the placement of transit stations may be very important in determining mass transportation use.

Paper sponsored by Committee on Highway Engineering Economy and presented at the 47th Annual Meeting.

Estimating Highway Vehicle Operating Consequences

JOHN C. PROKOPY, Department of Civil Engineering, Massachusetts Institute of Technology

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.

Paper sponsored by Committee on Highway Engineering Economy and presented at the 47th Annual Meeting.

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.

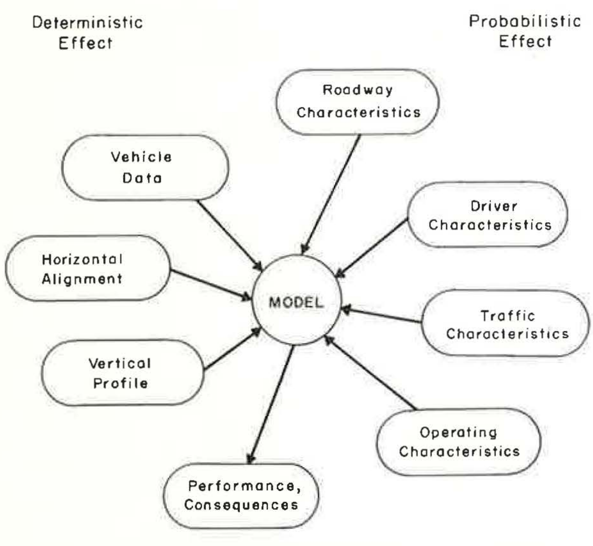


Figure 1. Input parameters to a highway vehicle performance model.

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

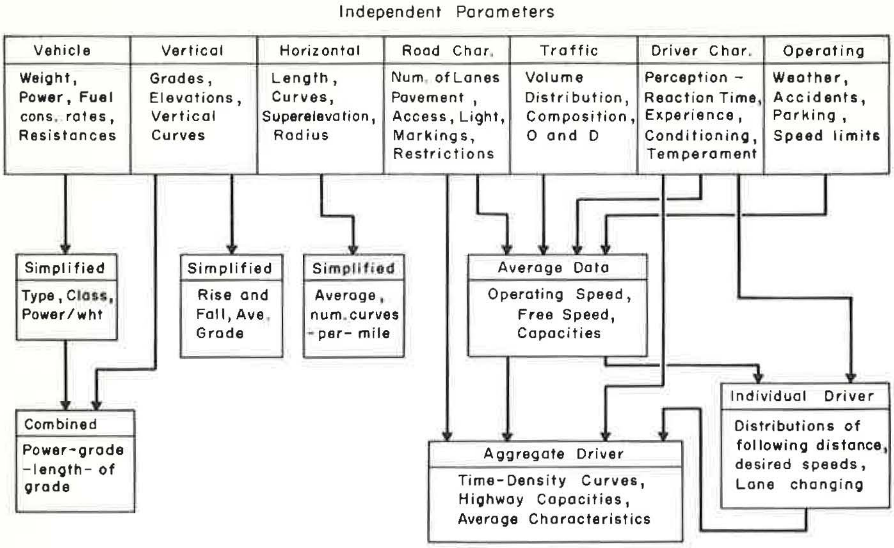


Figure 2. Input relations and forms.

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 addi-''on, driver parameters can be combined with those of other categories to get a better .derstanding 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.

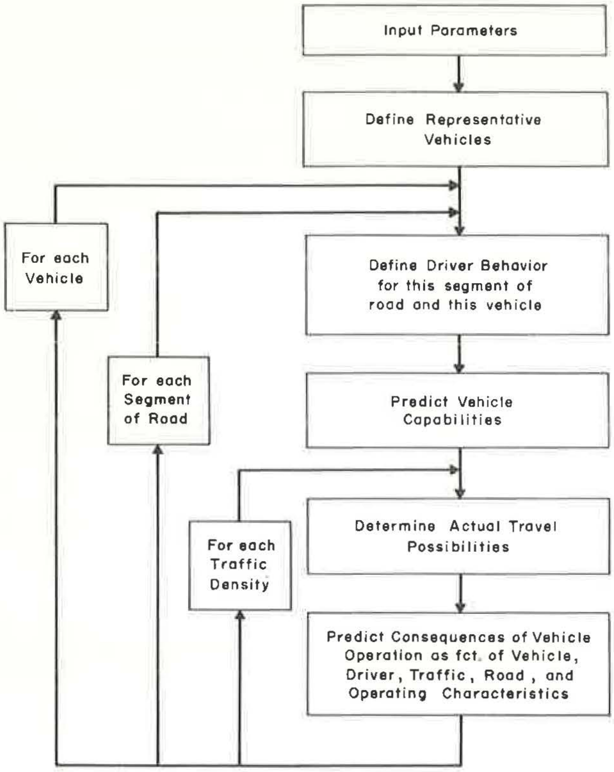


Figure 3. Steps in predicting vehicle operating consequences.

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

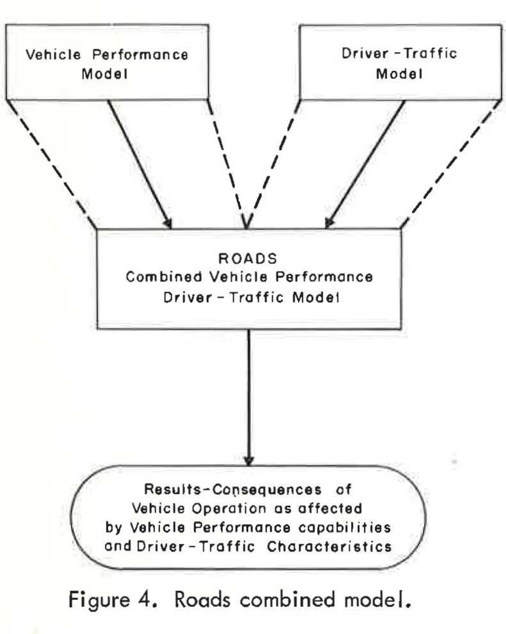


Figure 4. Roads combined model.

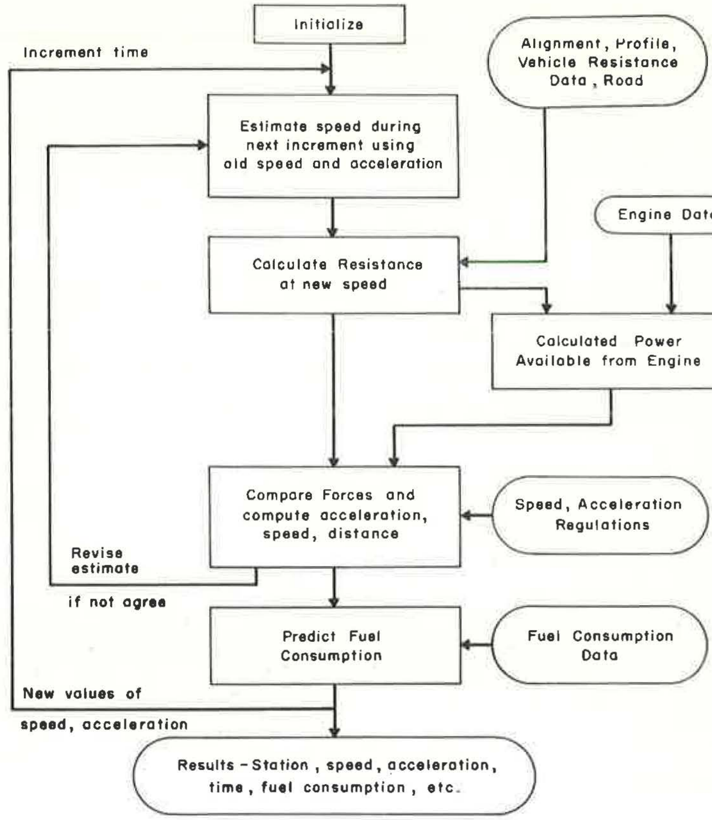


Figure 5. Vehicle model.

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.

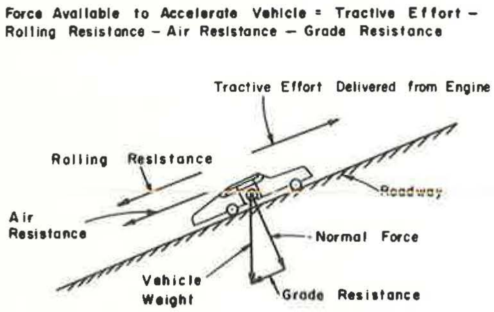


Figure 6. Simplified free body diagram of vehicle and roadway.

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-

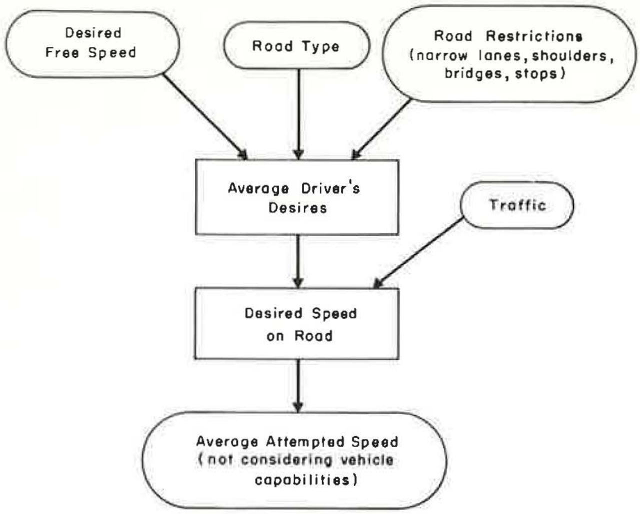


Figure 7. Driver-traffic model.

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.

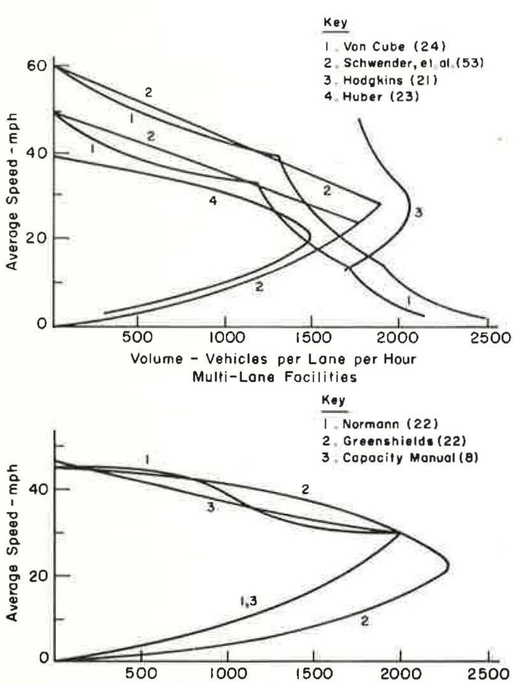


Figure 8. Comparisons of speed-volume curves.

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

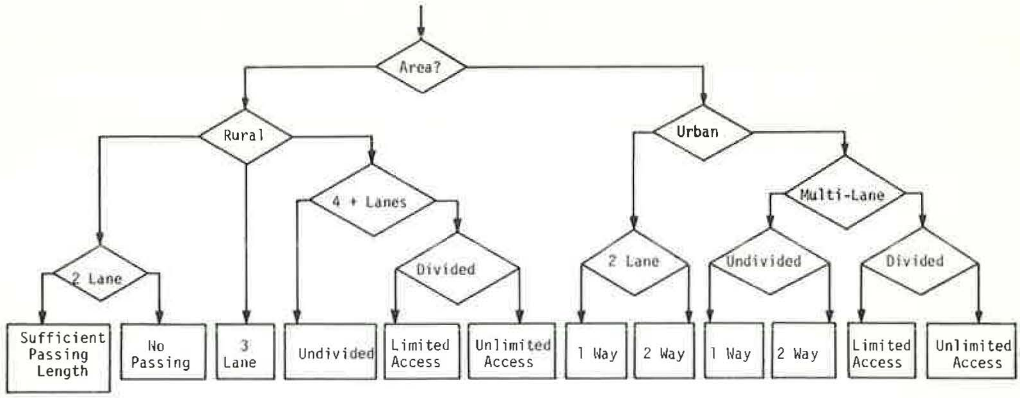


Figure 9. Roadway type identification process.

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

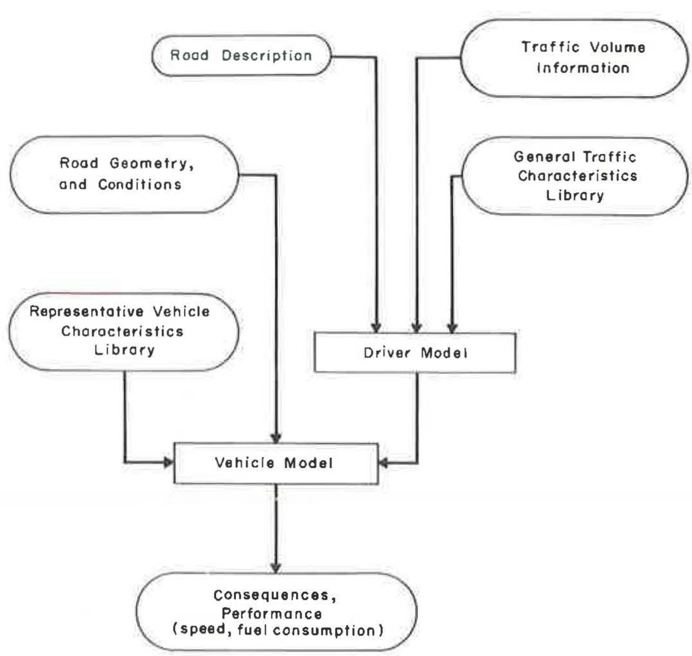


Figure 10. Complete model.

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.

ACKNOWLEDGMENTS

The author gratefully acknowledges the aid of the sponsors of the research of which this is a part: the U.S. Bureau of Public Roads, the Massachusetts Department of Public Works, and International Business Machines Corporation.

REFERENCES

1. Road User Benefit Analyses for Highway Improvements. American Association of State Highway Officials. Washington, D.C., 1960
2. Bone, A.J. Final Report of the Highway Transportation Demand Research Project. M.I.T. Civil Engineering Res. Rept. R65-24, 1965.
3. Byrne, J. J., Nelson, R.J., and Googins, P. H. Cost of Hauling Logs by Motor Truck and Trailer. U.S. Dept. of Agriculture, Forest Service, Portland, Ore., 1956
4. Claffey, P. Running Cost of Motor Vehicles as Affected by Highway Design. Interim Report, NCHRP Rept. 13, 1965.
5. Engineers' Guide to ICES COGO I. Civil Engineering Systems Laboratory, M.I.T., Aug. 1967.
6. Highway Capacity Manual—1965. HRB Spec. Rept. 87, 1965.
7. Irwin, N. A., and Von Cube, H. G. Capacity Restraint in Multi-Travel Mode Assignment Programs. HRB Bull. 347, pp. 250-289, 1962.
8. Johnson, W. F. The Use of Traffic Volume Data in the Evaluation of Highway User Costs. Unpublished SM thesis, M.I.T., 1964.
9. Liston, L. L., and Bielak, S. F. Comparisons of Empty and Gross Weights of Commercial Vehicles. Highway Research Record 26, pp. 1-23, 1963.
10. Manheim, M. L. Modeling Highway Location as a Hierarchically-Structured Sequential Decision Process. M.I.T. Dept. of Civil Engineering, pp. 65-83, Sept. 1965.
11. Miller, C. L., Lange, A. S., and Robbins, D. H. Research Report on the Vehicle Simulation and Operating Cost System. M.I.T. Civil Engineering Systems Laboratory. Pub. 143, 1961.
12. Oppenlander, J. C. Multivariate Analysis of Vehicular Speeds. Highway Research Record 35, pp. 41-74, 1963.
13. Prokopy, John C. A Framework for the Prediction of Highway Vehicle Operating Consequences. M.I.T. Dept. of Civil Engineering Res. Rept. R66-48, Dec. 1966.

14. Roberts, P. O., and Suhrbier, J. H. Final Report of the Highway Location and Design Research Project. M. I. T. Dept. of Civil Engineering Res. Rept. R66-9, Dec. 1966.

15. Roos, Daniel. ICES Systems Design—Objectives, Requirements, and Components. M. I. T. Civil Engineering Systems Laboratory Pub. T65-8, Aug. 1965.

16. Ruiter, E. R. The Effects of Random Traffic on the Accuracy of the Vehicle Simulation and Operating Cost System. M. I. T. Dept. of Civil Engineering Res. Rept. R63-3, 1963.

17. Saal, C. C. Time and Gasoline Consumption in Motor Truck Operation as Affected by the Weight and Power of Vehicles and the Rise and Fall in Highways. HRB Res. Rept. 9-A, 1950.

18. Schwender, H. C., Normann, O. K., and Granum, J. O. New Methods of Capacity Determination for Rural Roads in Mountainous Terrain. HRB Bull. 167, pp. 10-37, 1957.

19. Smith, G. L. Multigrade Vehicle Performance Simulation. General Motors Corp. Truck and Coach Div. Unpublished paper, Detroit, 1963.

20. Truck Ability Prediction Procedure. Society of Automobile Engineers, New York, 1957.

21. Suhrbier, John H. ICES ROADS I, Objectives and General Description. M. I. T. Dept. of Civil Engineering, July 1966.

22. Winfrey, R Economic Analysis. In Highway Engineering Handbook, K. B. Woods, ed. McGraw-Hill Book Co. 1960.