PREDICTING TRAVEL TIME AND FUEL CONSUMPTION FOR VEHICLES ON LOW-VOLUME ROADS

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A major experimental investigation of the effect of roadway characteristics and environmental conditions on traffic behavior was conducted in Brazil. Empirical relationships were developed for predicting free speeds on positive and negative grades. Free speed was found to be related to vehicle class, grade, surface type, and road roughness. These relationships have been incorporated into a computer program, TAFA, for predicting travel time, free speed, and fuel consumption on low-volume rural roads. Example applications of the model show its usefulness in evaluating operational and road maintenance strategies which are of interest to highway engineers and economic analysts.

The Brazilian Government and the United Nations Development Program are sponsoring a research project on the Interrelationships between Highway Construction, Maintenance, and User Costs. In one study area of the project, vehicle fuel consumption and traffic behavior experiments were performed. Regression equations were developed and incorporated into a computer model for predicting travel time and fuel consumption of vehicles traversing rural roads. The activities undertaken in this study are shown in Figure 1. The traffic behavior experiments and time and fuel algorithm are addressed herein. The fuel experiments are described in detail in another paper (1).

Traffic Behavior Experiments

Table 1 summarizes the 11 experiments designed to investigate the relationships between speed and specific environmental and roadway conditions. Sections were sought which were homogeneous with respect to grade, surface type and roughness. Equal emphasis was given to each of these factors. Figure 2 shows the design matrix for the acceleration and free speed on positive and negative grades experiments. This factorial was expanded for the horizontal curve experiment to include four radius levels: 20-100 m, 101-200 m, 201-400 m, and greater than 600 m.

In the free speed calibration experiment smooth paved and unpaved sections with varying grades were sought. The two grade levels used were less than 2% and greater than 5%.

The data collected in the remaining experiments were restricted to a few sections limited to studying a specific aspect of driver behavior. For example, in the night experiment, observations were made on five sections.

General Methodology

Observations of the vehicle population were made at fixed stations on the sections. Speeds were measured to the nearest kilometer per hour with radar speed meters. Vehicles were classified by the scheme shown in Figure 3 and observers estimated loads as empty, half full, full, or undetermined for all buses, utilities, and trucks. In addition, during the deceleration, dust, and calibration experiments the license number was recorded and time was measured to the nearest one tenth of a second with digital stopwatches.

A test fleet was used in the acceleration experiment since acceleration rates of the vehicle population could not be observed without influencing traffic behavior. This fleet, described in (1), included an economy car, two utility vehicles, a light gasoline truck, a light diesel truck, two medium diesel trucks, an articulated diesel truck and a rural bus. Test runs were made from zero to maximum speed using full power and timing gear changes to obtain maximum acceleration. Time and distance were photographically recorded at fixed time intervals.

The grade, curvature, and cross slopes of each test section were determined by the project survey crew and roughness measurements were made with a Maysmeter (2). Rainfall, temperature, and wind speed and direction were recorded hourly on all sections. Daily measurements of looseness, moisture content of the loose material, and spacing and depth of corrugations were made on gravel sections.

Free Speed on Positive and Negative Grades

Data Collection. Initially nine mirror boxes were used at intervals of 167 m to define stations of observation for three radar teams. In November, 1976, a policy of strict enforcement of a nationwide 80 kph speed limit was instituted. After this date, exposed radar units affected speeds. Subsequently, observations were made with hidden radar units, without the aid of mirror boxes, and the distance between stations was increased to 500 m.

Figure 1. Activities for completing study and model of traffic behavior and fuel consumption.

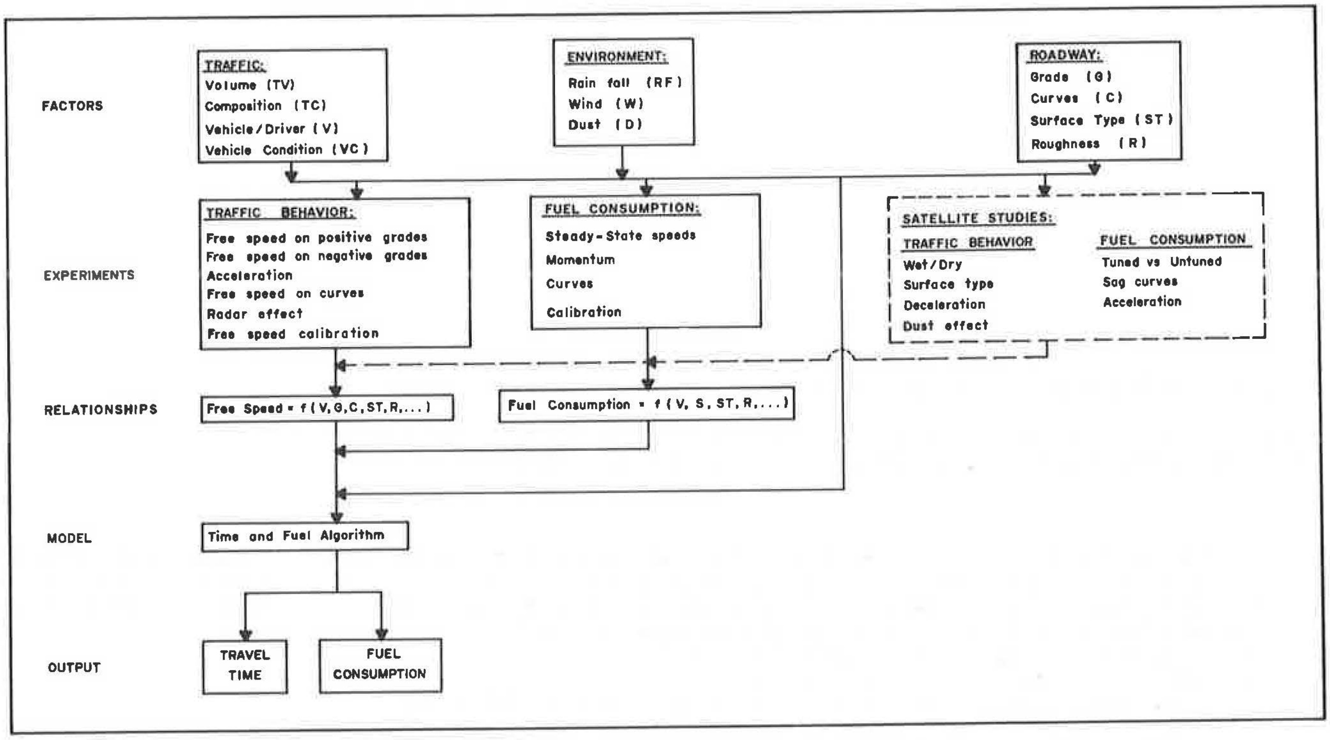


Table 1. Summary of the traffic behavior experiments

Experiment	Description
Free Speeds on Positive Grades	Determine the speed patern of vehicles climbing positive grades as a function of grade, position on the grade, surface type, and roughness. Observations made at 500m intervals on test sections 1 to 2 km long.
Free Speeds on Negative Grades	Same as above except observing traffic descending grades.
Free Speeds on Curves	Determine the speed distribution of vehicles traversing horizontal curves as a function of curve radius, grade, position on grade,surface type, and roughness. Spot speeds measured at the midpoints of curves
Acceleration	Determine the acceleration rate of vehicles climbing and descending grades as a function of vehicle type, load, grade, surface type, and roughness. A test fleet of vehicles was used to represent the vehicle population.
Free Speed Calibration	Collect independent data to verify the computer model. Spot speed and travel time collected on five sections, 3 to 5 km long.
Radar Effect	Determine if speeds are being affected by experiment methodology.
Wet/Dry	Measure the effect of rain on speeds. Curve test sections were used.
Deceleration	Determine the distribution of deceleration rates used by vehicles entering curves. Spot speed and time measured as vehicle starts to change speed, uses brakes, and enters curve. Observations made on paved roads with grades of 0, 2, and 3.6%.
Surface Types	Determine if the type of gravel surface affects speed. Observations made at the mid-point of long level tangent sections.
Dust	Collect data on the effect of dust on vehicle speeds and headways. Spot speed and travel time measured at three points on the test section. Dust measured by a photo-electric device.
Night	Determine the effect of darkness on speeds. Observations made on level tangent paved sections.

Figure 2. Design for acceleration and free speeds on positive and negative grades experiments.

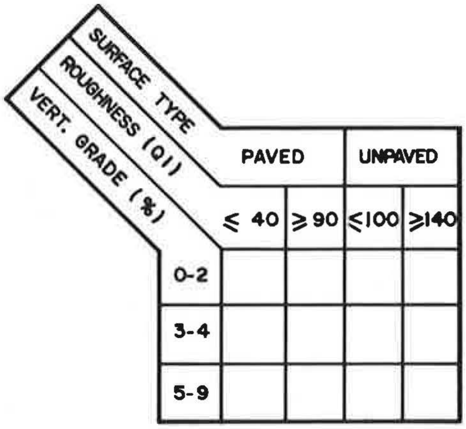
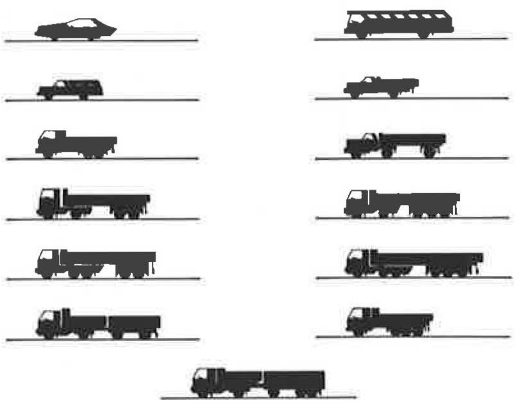


Figure 3. Vehicle classification scheme for traffic behavior experiments.



Test sections 2 km long were sought to provide sufficient length to observe the speed pattern on the grade. A minimum length of 1 km was accepted for some sections with grades greater than 4%.

Analysis of Free Speeds on Grades. The data for the trucks and buses obtained before the enforcement of the speed limit were not used in the analysis as they were significantly different from the speeds observed with the hidden radar. Over 100,000 observations remained for use in the analysis. Even with this quantity of data, it was necessary to group the vehicle classes shown in Figure 3 into cars, buses, utilities empty, utilities with load, trucks empty, and trucks with load for the analysis.

The mean speed per section, class, and station was the dependent variable analyzed. Unweighted analyses of variance, ANOVAS, were used to identified the important main effects and interactions. Examination of the data showed that no ANOVAS could be run to test surface type interactions. Thus, in the model, separate coefficients are estimated for the paved and unpaved sections.

The unweighted ANOVAS were only approximate tests since the number of observations per mean ranged from 1 to 1269. In the regression analysis, the data were weighted by the inverse variance of the mean. In all cases, the unweighted ANOVAS and the weighted regression analysis showed the same main effects and interactions to be significant.

The velocity at the last station was assumed to be the constant speed which would be maintained on a grade of infinite length. A regression equation was developed for this constant speed for both the positive and negative grade experiments. Data from the other stations were used to produce a speed change equation for each of the experiments.

Constant Speed on Positive Grades. The ANOVAS for the constant speed on positive grades showed that the class, grade, and roughness main effects, and the class-roughness interactions were significant for all sections. The class-grade interaction was also significant for the paved sections. The weighted regression analysis on 150 means produced equation 1 with $S_e = 4.1$.

$$S_p = ST_1(75.4 + 21.6V_1 + 13.0V_2 + 10.2V_3 + \sqrt{G}\,(-21.9 + 13.6V_1 + 15.2V_3 + 16.6V_4 + 12.5V_5) - R\,(0.0747 + 0.0675V_1)) + ST_2\,(95.9 + 38.1V_1 + 22.5V_3 + 18.1V_4 + 13.3V_5 - 25.4\sqrt{G} - R\,(0.108 + 0.072V_1 - 0.060V_2)) \qquad (1)$$

S_p is the estimated crawl speed in kilometers per hour and the other variables are defined in Table 2.

The equation shows that all classes react the same to roughness on paved roads except for cars for which the effect is almost doubled. The effect of grade on crawl speed for paved roads is shown in Figure 4. For all classes, as grade increases the crawl speed decreases, and the effect is greatest for trucks with load and buses. In comparing the two parts of the equation across surface type, one finds that at zero grade, the predicted speed is higher for unpaved roads than paved. The reason for this illogical conclusion is that the lowest grade analyzed for a gravel road was 2%, and thus predictions for unpaved grades less than 2% are extrapolations.

Speed Changes on Positive Grades. The ANOVAS for speed changes on positive grades showed the grade main effect was significant for all sections. The grade-class interaction was also significant for paved roads. The weighted regression on 622 means produced equation 2 with an $S_e = 4.05$.

$$\Delta S_p = GL\,(ST_1(-0.00534 + 0.00272V_1 + 0.00311V_3 + 0.00250V_4 + 0.00218V_5) - 0.000794ST_2) \qquad (2)$$

ΔS_p is the change in speed in kilometers per hour and all other variables are defined in Table 2. This equation is shown in Figure 5 for paved roads with a 6% grade and an arbitrary initial speed of 80 kph. On paved roads, trucks with load and buses decelerate at a higher rate than other classes. The deceleration rate on unpaved roads is constant for all classes and lower than on paved roads.

Constant Speed on Negative Grades. The ANOVAS for constant speed on negative grades indicated that class and roughness main effects were significant on all sections and that the grade main effect and grade-class interactions were also significant on paved sections. A weighted regression on 121

Table 2. Definition of variables in the free speed equations.

Variable	Value	Conditions or Units
ST_1	1	Paved roads
	0	Unpaved roads
ST_2	1	Unpaved roads
	0	Paved roads
V_1	1	Cars
	0	All other vehicle classes
V_2	1	Buses
	0	All other classes
V_3	1	Utilities empty
	0	All other classes
V_4	1	Utilities with load
	0	All other classes
V_5	1	Trucks empty
	0	All other classes
R	Roughness	QI (see Ref. (2))
G	Grade	Percent (100 rise/run)
L	Distance	Meters

Figure 4. Constant speeds on positive paved grades as a function of grade for a roughness of 30QI.

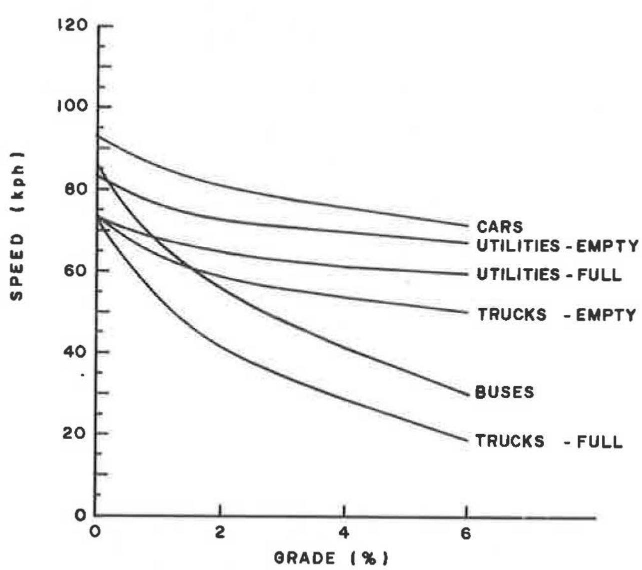
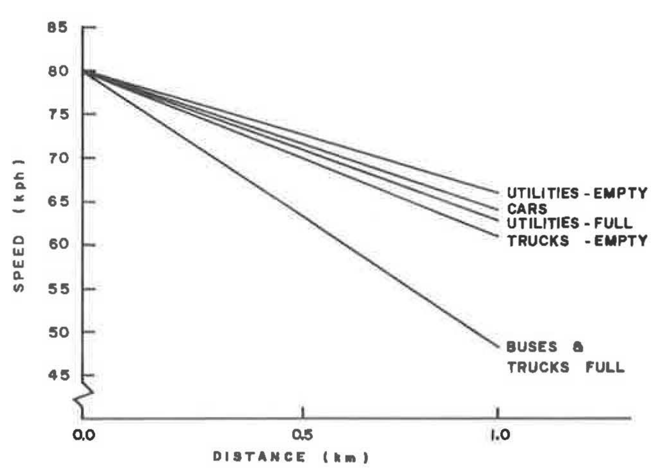


Figure 5. Speed change on positive grades.



mean speeds produced equation 3 with $S_e = 4.7$.

$$S_n = ST_1(76.2 + 17.4V_1 + 13.6V_2 + 5.6V_3 + 7.7V_4 - G\,(3.19 - 3.18V_1 - 3.71V_2 - 1.82V_3 - 2.86V_4) - 0.22R) + ST_2\,(79.8 + 7.8V_1 + 5.5V_3 - 0.25R) \quad (3)$$

S_n is the desired speed on negative grades in kilometers per hour and the other variables are defined in Table 2. The speed for each class as a function of grade is shown in Figure 6 for roughnesses of 30 and 80 QI on paved and unpaved roads respectively. Grade has no effect on unpaved roads and the effect is minimal for cars on paved roads. Buses showed a tendency to go slightly slower on steep grades than on flat sections. Trucks, both empty and with load, show the greatest tendency to go fast on paved grades; they change from the slowest vehicles on flat grades to the fastest on 6% grades.

Speed Change on Negative Grades. The ANOVAS for speed change on negative grades showed that the grade effect and the grade-class interaction were significant for paved sections and indicated that vehicles do not change speed when descending unpaved grades. Equation 4 was produced from a weighted regression of 381 mean speeds with $S_e = 2.02$.

$$\Delta S_n = GLST_1\,(-0.00198 + 0.00120V_1 + 0.00166V_2 + 0.00134V_3 + 0.00157V_4) \quad (4)$$

ΔS_n is the speed change of vehicles on negative paved grades and the other variables are defined in Table 2. Figure 7 shows that trucks use the greatest acceleration rate on paved negative grades, while buses and utilities with loads use the lowest acceleration rate.

Figure 6. Constant speeds on negative grades as a function of grade. Roughness equals 30 QI for paved and 80 QI for unpaved.

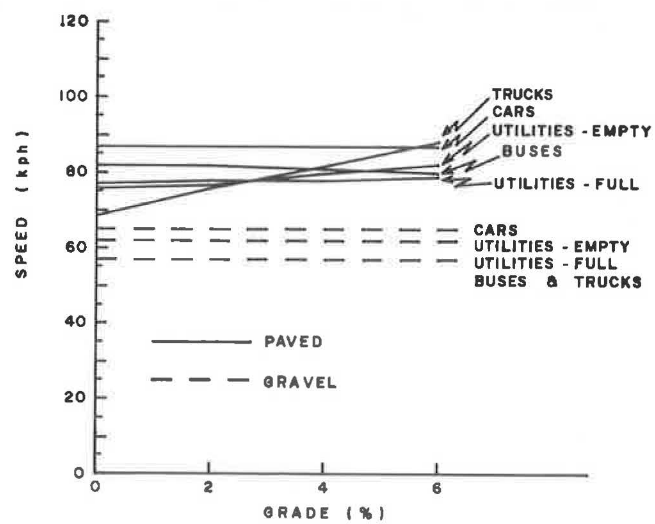
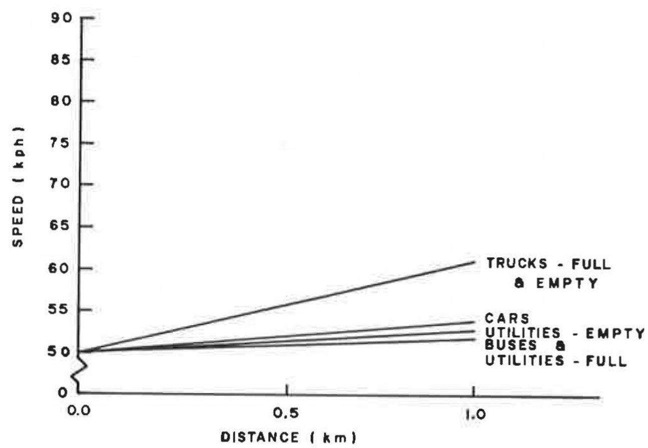


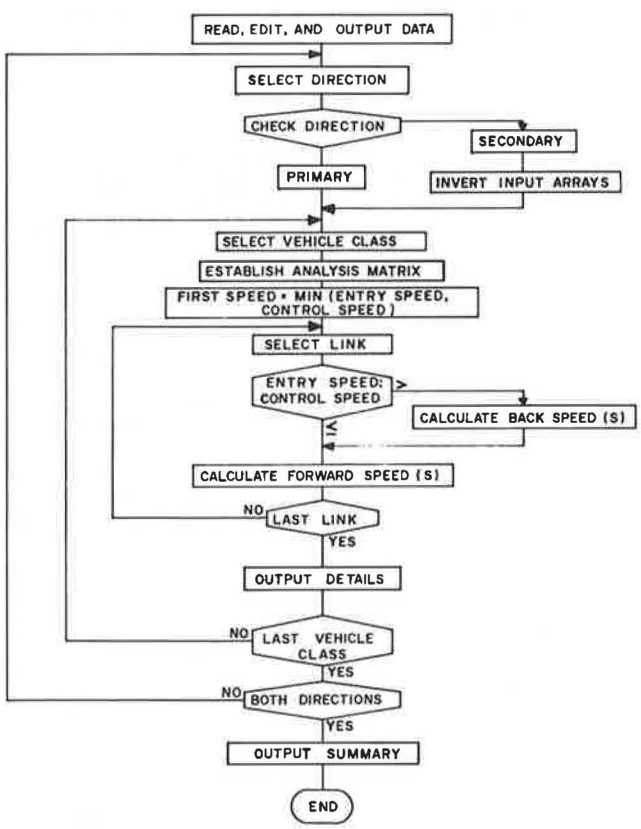
Figure 7. Speed change on paved negative grades.



Time and Fuel Algorithm

The relationships derived from the experimental program are incorporated in a computer model, TAFA, for predicting speeds, travel time, and fuel consumption for any low-volume rural road. The roadway is described to the model as a series of links which are homogeneous with respect to grade, horizontal curvature, surface type and roughness. Each vehicle class is sequentially processed along the road by the logic shown in Figure 8.

Figure 8. Logic used in the TAFA computer model.



Input to TAFA

The roadway characteristics are described in five arrays: grade, surface type, roughness, horizontal curves, and speed controls. The first three arrays are specified continuously along the road by giving the distances to points of change and the value of each characteristic as defined in Table 2. In the horizontal curve and speed control arrays the start and end distances are specified for each curve or zone along with the radius or control speed, respectively. The user can input the mean speed for a zone where exogenous influences control driver behavior.

The model can analyze six vehicle classes: cars, buses, utilities empty, utilities with load, trucks empty, and trucks with load. For each truck class the distribution of light gasoline, and light, medium, and heavy diesel truck types must be specified. Up to four power-to-weight ratios can be included for each class and type.

The Simulation Process

As shown in Figure 8, the first steps in the simulation process are to select the direction for analysis, and a vehicle class. The grade, horizontal curve, speed control, surface type, and roughness arrays are then combined to establish a matrix of homogeneous links. In preparing this matrix, a default speed control is assigned to each link where none is input. For links with curves, the minimum of the control speed for the link and the speed calculated for the curve is assigned to the speed control array.

The vehicle is entered onto the roadway with a speed equal to the minimum of the specified entry speed and the control speed for the first link. The desired speed for the link is calculated using the constant speed equation from either the positive or negative grade traffic behavior experiment. Due to a discontinuity in these equations the desired speed used for positive grades is the minimum of the speeds calculated with the positive grade equation and the negative grade equation evaluated at zero grade. The vehicle is then either accelerated or decelerated toward the desired speed. If the vehicle reaches the desired speed or control speed before the end of the link, then it is held at a constant speed for the rest of the link. The travel time and fuel consumption are then calculated.

The fuel consumption rate for the vehicle class is calculated as a weighted mean of the rate for each power-to-weight ratio. The weighted rate is then multiplied by travel time for the link to obtain the fuel consumption.

The vehicle is sequentially processed through each link, using the exit speed from one link as the entry speed to the next. However, if the entry speed to a link is greater than its control speed, the program back tracks along the road to find the point where deceleration must start in order to meet the speed constraint.

The logic is repeated until all of the links in one direction have been analyzed for the vehicle class. The speed, travel time, and fuel consumption for each link are printed if requested by the user. The next vehicle class is then simulated. When all classes have been processed the logic is repeated for the opposite direction if requested. Finally, speed, travel time, and fuel consumption for each vehicle class and direction are printed for the roadway.

Status of TAFA and Potential Uses

The logic for computing speed, travel time, and fuel consumption is complete and the model may be used for analysis if certain restrictions are understood by the user. Empirical relationships for free speed on positive and negative grades have been incorporated into the model, but assumed functions are used for other situations. For example, the rates given in the Transportation and Traffic Engineering Handbook (3) are used when a vehicle accelerates on a positive grade. The empirical relationships for fuel consumption at constant speed are used for all fuel calculations, but the estimates are modified when a change in speed is simulated.

To demonstrate some potential uses of the model, several example simulations have been run. The same roadway is analyzed in each example to demonstrate how operating and road maintenance policies affect travel time and fuel consumption.

The vehicle classes included in this analysis were cars, buses, and trucks with load. The trucks were divided into four types. The power-to-weight ratios and their distribution are given in Table 3.

The distribution of grades of the road used in the these examples is given in Table 4. The maximum grade on the road is 6% and the minimum radius of a curve is 100 m. The road has 44 km of gravel surface and 120 km of surface treatment.

Roughness of 30 and 80 QI were used for the paved and unpaved sections, respectively. Analyses were performed first assuming no speed control zones and then with speed controls of 80 and 50 kph on the paved and unpaved sections, respectively. The unpaved section of the road was then reanalyzed for roughnesses of 140 and 200 QI without speed control. The results of these five runs are shown in Table 5.

As would be expected, the inclusion of speed control zones had the greatest impact on cars. Their average speed dropped by 7% and this resulted in a fuel savings of 11%. The bus and truck classes showed only a slight reduction in overall speed. Fuel economy of the bus improved by 5.2%. The light gasoline truck economy increased by 4.0%, and the diesel truck economy increased by 6.7%.

Table 3. Vehicle characteristics used in the example problems.

Class	Type	Percent of class	Power to Weight Ratios (bhp/ton)					
			P/W	%*	P/W	%*	P/W	%*
Cars		100	41.4	70	35.0	30		
Buses		100	12.8	80	20.0	20		
Trucks	Lgt.gas.	20	26.4	70	50.3	30		
w/load	Lgt.dsl.	20	15.9	22	25.0	60	38.1	18
	Med.dsl.	50	6.3	50	15.1	50		
	Hvy.dsl.	10	6.1	90	17.0	5	22.0	5

* Percent of vehicles within the class-type combination with the specified P/W.

Table 4. Distribution of grades on the roadway used in the examples.

Grade Range							
	Max	+5	+3	0	-3	5	7
	Min	+7	+5	+3	0	-3	5
Percent of Route length		4	8	34	45	7	2

Table 5. Example problem results.

Situation	Cars		Buses		Trucks w/load		
	Speed kph	Gas km/l	Speed kph	Diesel km/l	Speed kph	Gas km/l	Diesel km/l
Entire road No control speed	72	11.9	56	3.8	48	2.4	1.5
Entire road W/control speed	63	13.2	53	4.0	46	2.5	1.6
Unpaved section, 80QI	66	12.6	56	3.8	56	2.6	1.2
Unpaved section, 140QI	52	13.1	44	3.8	44	2.8	1.7
Unpaved section, 200QI	38	9.3	30	4.7	30	2.6	1.9

Road roughness showed a major influence on speeds as shown in Table 5. On the unpaved sections, equal speeds were predicted for the buses and trucks while the cars were estimated to have higher speeds. The fuel economy of the cars showed an increase as roughness changed from 80 to 140 QI, then decreased when the roughness went to 200 QI. The buses experienced the same fuel economy at 80 and 140 QI, but a substantial increase at the high roughness level. The light gasoline truck's fuel economy did not substantially change whereas the fuel economy of the diesel trucks kept improving as the vehicles slowed down due to roughness.

Even though the TAFA model is yet to be calibrated, these example problems do demonstrate the capability of the model to analyze the effect of different operating and road maintenance policies. Others areas where the model will be useful include the evaluation of geometric standards, and strategies for paving roads, economic analysis for route selection, etc.

Summary and Recommendations

An experimental investigation of the effect of roadway and environmental conditions on traffic behavior was presented along with empirical relationships for predicting free speeds on positive and negative grades. In these relationships, free speed is a function of vehicle class, grade, surface type, and roughness. These relationships have been incorporated into a computer program for predicting speed, travel time and fuel consumption on rural roads.

Further work is needed in this area to complete the analysis of all the experiments described, and incorporate the relationships into the computer model. Finally, the model needs to be validated using data which are already available for Brazil. Application of the model outside of Brazil will require the execution of calibration experiments to establish the validity of the model.

References

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