COMPUTER SIMULATION OF HAULAGE TRACTOR TESTS

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Abstract

Haulage tractors have been tested by the South African Sugar Association Experiment Station for a number of years. These tests, consisting of a pto dynamometer test for engine performance and a road haulage test monitoring speed, load and fuel consumption over a known route, are time-consuming and expensive. In this paper a computer model is outlined, using various tractor parameters and traction mechanics to simulate these tests. The predicted results from the computer model are compared with the results obtained from the pto and road haulage tests.

Introduction

Computer modelling and simulation enable the researcher to carry out hypothetical field testing and although the results obtained from the prediction equations are only estimates, they allow the researcher to determine trends which result from changing the model input parameters. Furthermore, the effect of tractor and soil parameters on tractive and energy efficiencies can be studied by means of computer modelling without the cost, time and machinery which are necessary for field testing.

The computer program which has been developed, models the performance of haulage tractors along a particular route with varying gradients. The imposed loads can be changed to obtain results for the range of loads normally pulled by haulage tractors.

The inputs for the model are various tractor parameters such as the dimensions and geometry of the tractor, the torque-speed characteristics of the engine, and the lengths and percentage slopes of each gradient along the test-route. The traction model is based on the traction equations developed by Wismer and Luth[3], and the fuel and engine speed model is based on equations developed by Jahns[2]. The model gives the speed in km h^{-1} and fuel consumption in l h^{-1}. From this information the time, specific fuel consumption, and haulage capacity, which is a measure of productivity, are determined.

The results from the model were then compared with values obtained from field tests carried out on four different tractors. The tractors were tested over a standard test route from the La Mercy farm of the SASA Experiment Station to the Mount Edgecombe sugar mill, pulling loads varying from 2 to 13 tons. The materials and methods used in these tests are the same as those reported by Boevey and Meyer[1].

Initially, a pto dynamometer test is done to determine the power, torque and fuel characteristics of the tractor engine. The pto test is also carried out to check that the engine performance corresponds with its specifications. These results are entered into the computer model together with the required tractor and trailer dimensions. From these results, regression equations are obtained for plotting the haulage performance curves.

Development of the Model

The complete model is divided into three main parts. The first part deals with predicting the forces which act on the tractor-trailer unit and the tractive performance of the tractor. The second part predicts the engine speed and allows the forward ground speed to be determined. The third section of the model predicts the fuel consumption for each engine speed and torque loading. The second and third sections are closely related through analysing the torque, speed and fuel characteristics obtained from the pto dynamometer tests.

The tractive performance model is based on the equations of Wismer and Luth[3] for traction with pneumatic tyres and soils with both frictional and cohesive properties. The model will initially be used for hard surfaces such as tarred roads. The drawbar pull is determined from dimensions of the trailer, its mass and the load for each gradient along the test route. The equations determine the various weight transfers and calculate the gross tractive forces required and the amount of wheel slippage that is likely to occur.

Once the gross tractive force is known, the torque required at the rear axle and the engine, through the drive train, can be calculated. From this required engine torque, the engine speed can be determined by a set of equations used to plot the engine torque-speed curve. The tractor's ground speed is then calculated using the gear ratio, rear wheel size and percentage wheel slippage. These calculations are repeated for each available gear, and the gear resulting in the highest ground speed, which does not exceed the tractor's torque capacity, is selected. With the engine torque and speed now known, the fuel consumption in l h^{-1} is determined. These calculations are performed for each section of the test route and an average speed and fuel consumption are calculated for the whole route. These average speeds and fuel consumptions are determined for a number of loads and regression equations are obtained from these results. The regression equations are then used to plot the predicted haulage performance curves. A flow chart of the model is shown in Figure 1.

Model inputs

To predict the tractive performance, a number of tractor, trailer and test route parameters are considered. For speed and fuel consumption predictions the engine torque, speed and fuel characteristics, determined from the pto tests, are used.

Tractor, trailer and route parameters: the tractor inputs include tyre sizes, mass of the tractor, wheel base, centre of gravity, position of the drawbar, and all the gear ratios. The horizontal position of the centre of gravity in relation to the rear axle is determined by measuring the weight at the front axle, and the vertical position is determined by measuring the weight at the tractor's front axle with the wheels raised off the ground. The gear ratios and the tractor and trailer dimensions are obtained from the manufacturer's specifications. The mass and load of the trailer are assumed to be uniformly distributed over its length with the centre of gravity at the centre. The test route is divided into a number of sections which are demarcated by a change in gradient. The length of each section and its relevant percentage gradient are entered into the program.

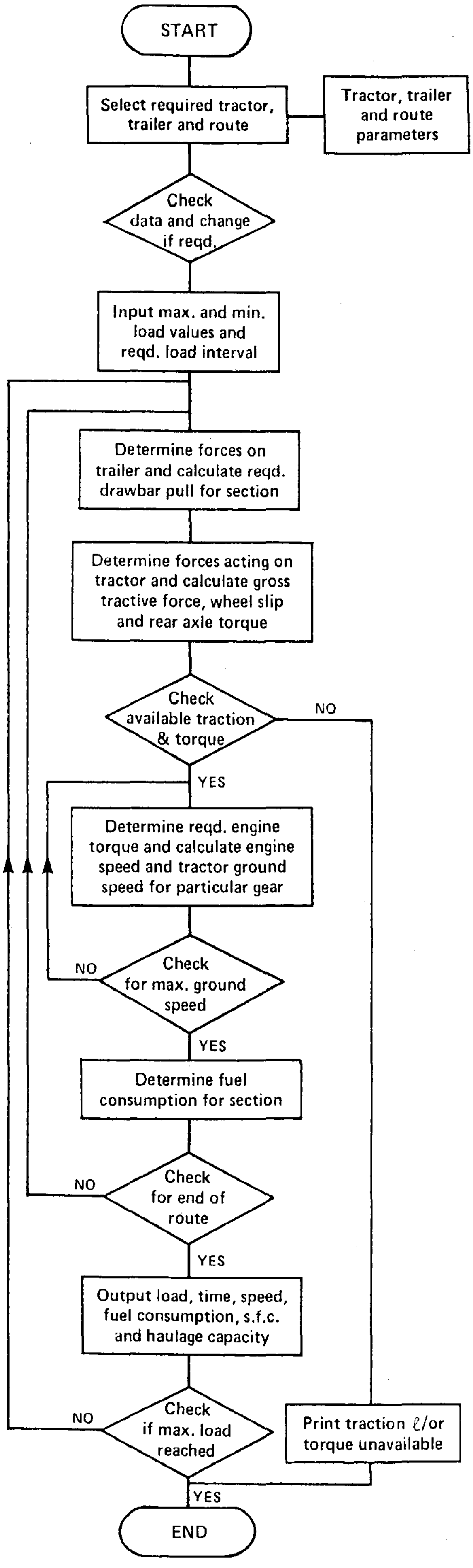

FIGURE 1 Flow chart of the computer model used for simulating haulage tractor tests.

Engine speed and fuel consumption inputs: submodels are used to predict the engine speed from the calculated torque load, and the fuel consumption from the torque load and predicted engine speed. These submodels are based on a method of plotting diesel engine performance maps (Jahns[2]) and they are discussed in a later section. The inputs to the program are the coefficients for the equations describing these engine performance maps which are obtained from the pto tests.

Determining the forces acting on the tractor and trailer

The information required to evaluate tractor field performance can be obtained from static equilibrium force analyses. It is assumed that the accelerations are zero and that the following conditions apply:

- the ground surface is assumed to be planar and non-deformable
- the motion of the tractor is regarded as two-dimensional
- rotational motion of the front wheels is neglected
- aerodynamic forces are neglected.

To determine the required drawbar pull the trailer is analysed as a separate unit. The program includes options for both single and tandem trailers with the analysis for both being the same.

The forces are broken into their vertical and horizontal components with respect to the road surface, which when summed and combined determine the drawbar pull (P). The trailers are assumed to have single axles and the trailer wheel loads R_1 and R_2 are determined from the gross load and the geometry of the trailer.

A complete tractor and trailer unit is composed of different arrangements of towed and driving wheels. A wheel located on an unpowered axle is considered a towed wheel. Axle torque is assumed to be zero by neglecting bearing friction. The traction prediction equations are limited to tyres which operate at a nominal tyre inflation pressure. This pressure is defined as the pressure which produces tyre deflections of appropxímately 20 % of the undeflected section height. The equations are developed for tyres with a tyre width/diameter ratio (b/d) of approximately 0,3. The towed force of a wheel, or its rolling resistance, is predicted from:

$$\frac{TF}{R} = \frac{1,2}{Cn} + 0,04 \qquad \ldots\ldots (1)$$

where TF = towed force of wheel, kN
R = dynamic wheel load, kN
Cn = wheel numeric, $\frac{CI \cdot b \cdot d}{R}$
CI = cone index, cone penetrometer resistance as defined in ASAE Recommendation R313·1, kN m^{-2}
b = unloaded tyre section width, m
d = unloaded overall tyre diameter, m

When these equations are used for hard road surfaces the Cn value will be large and the towed force is equal to 4 % of the wheel load. The rolling resistance is attributed to tyre flexing and scrubbing. Therefore the towed force on the trailer wheel is:

$$TF = 0,04 \cdot R \qquad \ldots (2)$$

Combining the horizontal forces:

$$P_4 = (M_1 + M_2) \cdot g \cdot \sin\beta + TF_1 + TF_2 \text{ (kN)} \qquad \ldots (3)$$

Combining the vertical forces:

$$P_4 = (M_1 + M_2) \cdot g \cdot \cos\beta - (R_1 + R_2) \text{ (kN)} \qquad \ldots (4)$$

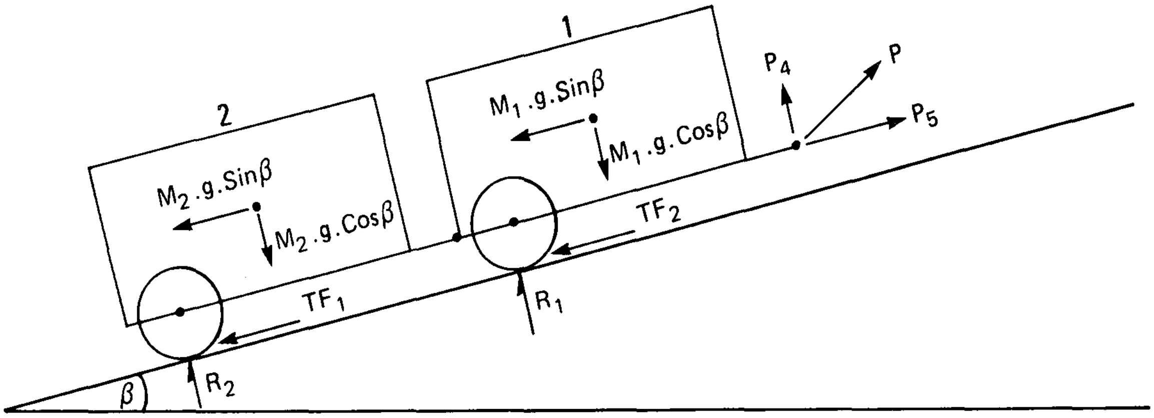

FIGURE 2 Diagramatic representation of the forces on tandem trailers.

where M_1 = mass of trailer one, tons
M_2 = mass of trailer two, tons
g = acceleration due to gravity, m s^{-2}
β = angle of slope
T_1 = towed force of Trailer 1 (kN)
T_2 = towed force of Trailer 2 (kN)
P_5 = horizontal component of drawbar pull, kN
P_4 = vertical component of drawbar pull, kN

To obtain the drawbar pull, $P = \sqrt{P_4^2 + P_5^2}$ (kN) . (5)

Once the required drawbar pull is known the forces acting on the tractor can be analysed. Using the notation in Figure 3, the load on the front wheel is determined by:

$$R_f = (W_t \cdot L_2 - P \cdot y_r)/L_1 \quad \ldots\ldots (6)$$

With R_f (reactive force at front wheel) now known the following equation is used to solve R_r (reactive force at rear wheel):

$$R_r = W_t \cdot \cos\beta + P \cdot \sin\alpha - R_f \quad \ldots\ldots (7)$$

Although there is no physical shifting of weight the changes in the forces R_r and R_f as a result of the drawbar force P are commonly known as weight transfer.

With the forces R_r and R_f known the towed forces TF_r and TF_f can be determined using equation (2) with respect to the rear and front tractor wheels. To determine the gross tractive force required by the tractor to move the tractor-trailer unit the sum of the forces in the horizontal plane are calculated:

$$F_r = W_t \cdot \sin\beta + TF_f + TF_r + P \cdot \cos\alpha \quad \ldots\ldots (8)$$

where F_r = gross tractive force
W_t = weight of tractor
β = angle of slope
TF_f = front wheel towed force
TF_r = rear wheel towed force
P = drawbar pull
α = angle drawbar pull inclined to slope

An equation has been developed to account for variations in the gross tractive force, caused by changes in soil strength and wheelslip, and including the effect of wheel load and tyre size (Wismer and Luth[3]). This equation is used in the model to determine the amount of wheelslip produced:

$$\mu g = \frac{F}{R_r} = 0,75 \cdot (1 - e^{-0,3 \cdot Cn \cdot S}) \quad \ldots\ldots (9)$$

where μg = gross tractive coefficient
S = wheelslip
e = base of natural logrithims

The maximum achieveable drawbar force may also be limited by the tractive conditions of the surface on which the tractor is operating. The gross tractive coefficient is a function of both drive wheel slippage and tyre and soil parameters. The exponential nature of equation (9) indicates

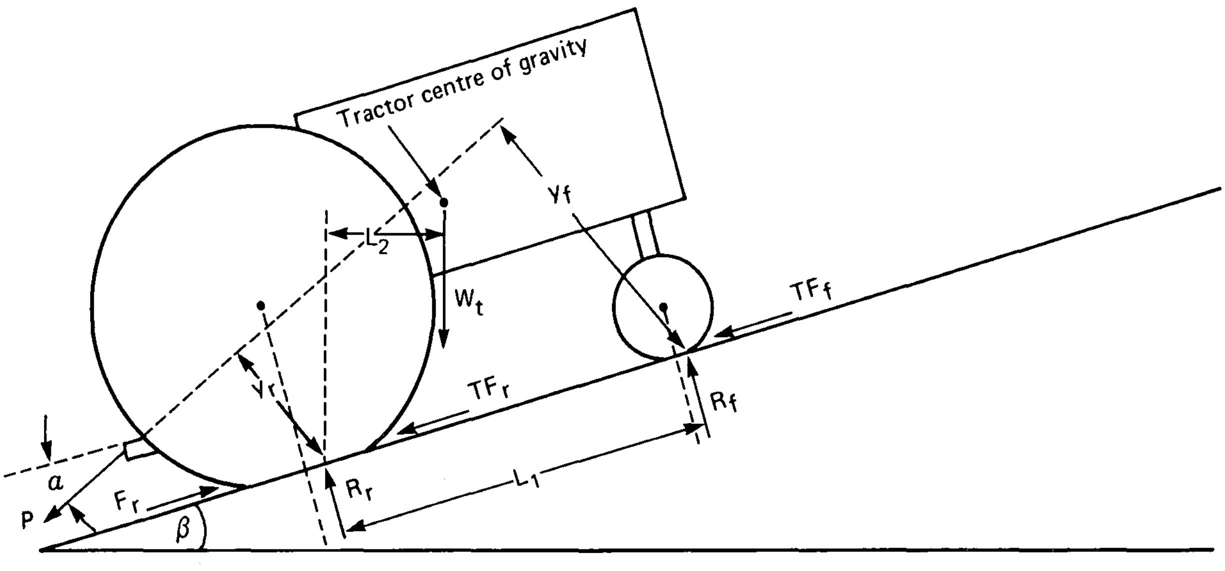

FIGURE 3 Free body diagram illustrating the forces acting on the tractor.

that the maximum value of μg that can be obtained is 0,75. Therefore to ensure that adequate traction is available μg must not exceed 0,75.

Once it is known that there is sufficient traction available the axle torque T_r can be calculated from the gross tractive force F_r and rear wheel radius r_r, using the following equation:

$$T_r = F_r \cdot r_r.$$

The required engine torque T_e may then be calculated from the equation: $T_e = T_r/(n \cdot G)$ where n is the efficiency of power transmission and G is the gear ratio between the engine and rear axle. If T_e is less than the maximum torque that the engine can produce the engine has sufficient power for the tractor to pull the given load. The torque-speed equations of the engine are then used to estimate the steady state engine speed $\emptyset$ at which the torque T_e is produced.

Fuel consumption and engine speed determination submodel

The fuel prediction model used in the program was developed by Jahns[2]. The model describes engine performance from an equation which was derived from nine points under the engine torque-speed curve. The equation covers the normal operating range from approximately 30% or more of the rated engine speed. The fuel consumption can be calculated for any torque, power and engine speed over this range of engine speeds.

It is assumed that the performance of the engine is continuous in the area under the torque-speed curve and that it can be approximated by a polynomial. The fuel consumptions can be calculated by using the following general equation:

$$B = C_1 + C_2 \cdot T + C_3 \cdot T^2 \quad \ldots\ldots (10)$$

where B = fuel consumption, $1\ h^{-1}$
$C_1 = (C_{11} \cdot N + C_{12} \cdot N^2 + C_{13} \cdot N^3)$
$C_2 = (C_{21} \cdot N + C_{22} \cdot N^2 + C_{23} \cdot N^3)$
$C_3 = (C_{31} \cdot N + C_{32} \cdot N^2 + C_{33} \cdot N^3)$
T = percentage of rated torque
N = percentage of rated speed
C_{ij} = equation coefficients

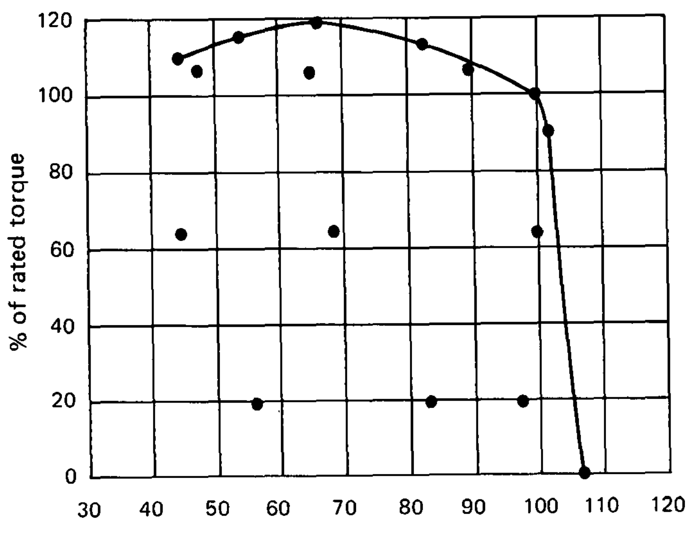

FIGURE 4 Engine torque-speed curve with the dots indicating the points used to determine the coefficients for the fuel and engine speed equations.

The equation is assumed to be universal for all engines, but the coefficients of the equation are specific for a particular type of engine. To calculate these coefficients the fuel consumption (B_i), engine speed (N_i), and torque (T_i) need to be recorded from nine points on the torque-speed curve. These points should be distributed as equally as possible over the area of the map. Figure 4 shows the positions of the nine points, under the boundary curves, which are used to calculate the coefficients. Using the values of B_i, N_i and T_i for these nine points and using the general equation 10, nine independent equations for the nine unknown coefficients C_{ij} can be written and solved using the Gauss-Jordan method. These coefficients are then entered into the program and used with equation 10 to predict the fuel consumption for the required engine speed and torque.

To determine the engine speed from a given torque an equation describing the torque-speed boundary curves is required. These curves are determined in a similar way to that of the fuel equation. The governed boundary line is established by recording the torque and speed for three points along the governed curve. The overload curve equation is established from five points along the overload curve. An example of the points used is illustrated in Figure 4. In both cases a simple polynomial is used and the coefficients are calculated in the same way as those for equation 10.

For the governed line, where N > 100% of rated speed:

$$T = d_1 + d_2 \cdot N + d_3 \cdot N^2 \quad \ldots\ldots (11)$$

where d_1, d_2, d_3 are coefficients
N = percent of rated speed
T = percent of rated torque

For the overload line, where N 100% of rated speed:

$$T = U_1 + U_2 \cdot N + U_3 \cdot N^2 + U_4 \cdot N^3 + U_5 \cdot N^4 \quad \ldots (12)$$

Where $U_1 \cdot U_5$ are coefficients

Using these two equations any speed along the torque-speed curve can be predicted from the calculated torque load. This predicted engine speed is then used to determine the tractor's forward ground speed.

Determination of tractor ground speed

The estimated steady state engine speed $\dot{\emptyset}_e$ results in a rear axle rotational speed of:

$$\dot{\emptyset}_w = \dot{\emptyset}_e \cdot G$$

Since the wheelslip of the drive wheels has already been determined the forward velocity of the tractor can be calculated by the equation:

$$\dot{x}_w = r_r \cdot \dot{\emptyset}_w \cdot (1 - S)$$

These calculations are repeated for each successive gear and the maximum possible forward speed for the required drawbar pull is determined. For this speed the fuel consumption in $1\ h^{-1}$ is calculated using equation 10.

Output

Once the speed and fuel consumption of each section of the test route has been determined the results are averaged over the route for each successive load. The values that are obtained for each load are time taken in minutes, average speed in $km\ h^{-1}$, average fuel consumption $1\ t^{-1}\ km^{-1}$ and haulage capacity in $t\ h^{-1}$.

From these predicted results regression equations are obtained and a graph can be plotted from these equations. These haulage performance curves were the final result of the modelling exercise.

Results and Discussion

Four tractors ranging in specified power from 39 to 55 kW were tested along the test route to compare the test results with the predicted results obtained from the computer model. All four tractors were equipped with the ADE 4.236 engine, each with different power rates and one with an altitude compensator. Each tractor was initially tested on an M&W P2000 pto dynamometer to check the power specifications and to obtain the torque-speed characteristics. Following the dynamometer test the tractors were road-tested along the specified route.

Specifications	Tractor 1	Tractor 2	Tractor 3	Tractor 4
Engine	ADE 236 AC	ADE 236	ADE 236	ADE 236
Rated engine speed (rpm)	2 300	2 200	2 000	2 250
Rated engine power (kW)	55,5	51,0	49,5	39,0
Measured pto power (kW) at rated engine speed	42,8	44,2	43,8	35,0

The results were then compared with the predicted results as seen in Table 1 for Tractor 2.

Table 1

Test and predicted road haulage results for Tractor 2

	Gross imposed load (t)	Time (min)	Speed (km h^{-1})	Fuel (l h^{-1})	SFC (l t^{-1} km^{-1})	Haulage capacity (t h^{-1})
Test	4,42	35,58	30,38	10,34	0,077	7,46
Predicted		33,94	31,83	11,75	0,084	7,88
Test	7,70	39,23	27,66	10,89	0,052	11,83
Predicted		37,80	28,57	12,43	0,057	12,22
Test	9,68	41,25	26,40	11,10	0,044	14,20
Predicted		39,89	27,07	12,43	0,047	14,56
Test	12,18	46,68	23,55	11,24	0,040	15,94
Predicted		44,11	24,48	12,76	0,043	16,57

Initially, the model was used to obtain predicted results using the same gross imposed loads that were used for the road tests. A comparison of these results showed that the largest variation in speed was 10 %, with the mean variation being 4 %. This indicated that the predicted results were a reasonable estimate of the test results. The largest variation in the fuel consumption values (l h^{-1}) was 24 %, with a mean variation of 11 % so the predicted results were considered to be acceptably reliable. The possibility of experimental error in the test results, due to the coarse recording methods used, should not be ignored. It was not possible to ascertain the magnitude of any errors.

The model was then used to predict results for a range of different loads to obtain regression equations that were used to plot the haulage performance curves. These predicted curves were then compared with the curves obtained from the test results. The curves for Tractor 2 are shown in Figure 5. The predicted and test curves correspond fairly closely although the speed curve could possibly be reduced to a linear regression. The specific fuel consumption (SFC) curve is not correct at the higher loads as the curve should not turn and increase at that point, but it should continue to decrease at a decreasing rate and then, theoretically, would start increasing. The curve fitting techniques that were used need to be improved to produce a more exact curve.

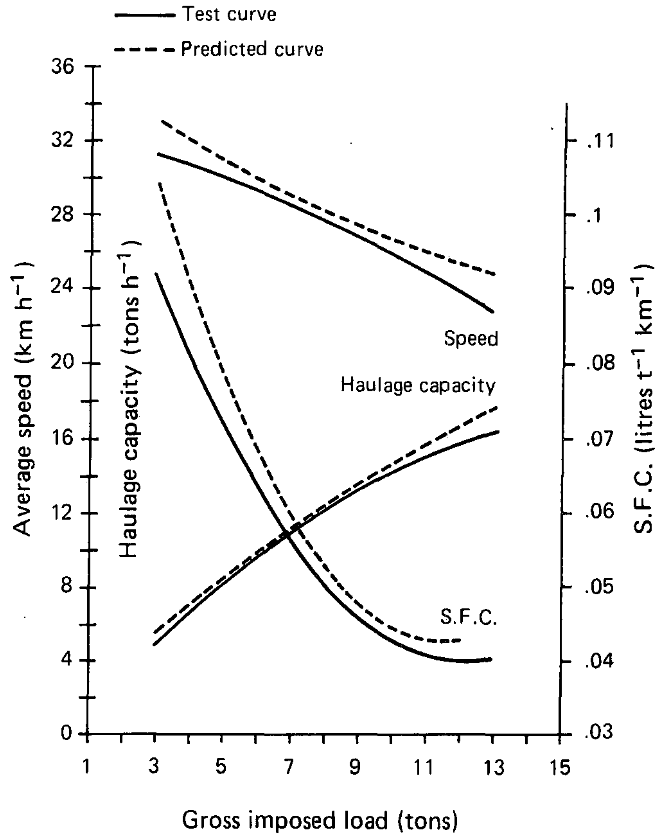

FIGURE 5 Comparison of test curves with predicted curves for Tractor 2.

Conclusion

The results obtained from the model so far appear to be reasonable estimates of the actual field tests. The one remaining problem is to determine a better method of fitting a smooth curve to the specific fuel consumption data.

Although the inputs to the program are numerous and complex the time saved in not performing the field tests far outweighs the problems associated with the model inputs. the model will be developed further by changing the soil strength index to predict haulage tractor performance on infield roads and other different soil surface conditions. The effect of different wheel sizes and gear ratios may also be analysed for possible design purposes.

The reason for developing this model was to reduce the amount of field testing necessary for determining tractor performance. The results from the model are considered to be an accurate enough estimate to be used as the alternative method in determining haulage tractor performance.

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