DEVELOPMENT OF A VEHICLE PERFORMANCE SIMULATOR: SENSITIVITY ANALYSIS

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Abstract

The performance of a haulage vehicle is affected by many factors such as frontal area, coefficient of drag, rolling resistance, road slope, weight, engine and transmission characteristics. The purpose of this study was to assess, with the aid of a computer based simulator, the relative contribution of each factor to the performance of a vehicle in terms of fuel consumption and average speed during a haulage cycle. The results obtained by varying each factor within an expected range indicated that the vehicle's performance was most sensitive to road slope, payload and rolling resistance. It was less sensitive to coefficient of drag and frontal area, and least sensitive to transmission losses, time to change gears and wheel rolling radius.

Introduction

A system was developed to facilitate the selection of vehicles and routes to enable one to optimise transport resources in the agricultural sector. The system, in the form of a vehicle simulation programme, is known as SimTrans (Lyne *et al.*, 1996). Although SimTrans is undergoing continuing development, it is a useful tool to analyse transport systems and was used to carry out a sensitivity analysis of the factors affecting vehicle performance.

Many factors such as frontal area, coefficient of drag, rolling resistance, road slope, weight, engine and transmission characteristics affect the performance of a haulage vehicle. Each parameter describing these factors was analysed to quantify its affect on overall performance in terms of average vehicle speed and fuel consumption.

Sensitivity analysis

These sensitivity analyses were carried out by simulating a Mercedes Benz 1414-48 operating on a 12 km route between La Mercy and Mount Edgecombe and formed part of an MScEng project (Clark, 1996). The factors which were considered included rolling resistance, slope of the road (grade), gross vehicle mass (GVM), engine torque, frontal area, coefficient of drag, transmission losses, rolling radius of the wheels, inertial mass factor and the time taken to change gears. Sensitivity to road slope was investigated using hypothetical road sections of uniform grade. Where appropriate, the sensitivity of variables was investigated for two GVMs; firstly with no payload, secondly with a maximum payload resulting in a GVM of 14,84 tons.

When considering the results of the sensitivity analyses presented below, it should be borne in mind that the interactions and feedbacks between the driver, the vehicle and the road, form a complex system. Different vehicles and routes may result in the model being more or less sensitive to different variables. The results are presented in descending order of effect on the performance of the vehicle.

Road rolling resistance

When evaluating the cost of repairing, resurfacing or upgrading a road it is important to consider the effect of rolling resistance. The sensitivity of vehicle performance to rolling resistance as the surface varies from smooth and hard to soft or rough is illustrated in Figure 1. A coefficient of rolling resistance of 1% is typical for a tar road in fair condition, while a coefficient of 3% is applicable to a soft or a very rough dirt road. Figure 1 shows that fuel consumption is more sensitive than average speed. As expected, sensitivity to the coefficient of rolling resistance increases with increasing load due to the linear relationship between rolling resistance and load. The sharp drop in average speed and increase in fuel consumption for a soft or rough surface is largely due to the vehicle being unable to change from first to second gear over the initial uphill part of the route as a result of the high resistance to motion experienced on the poor surface.

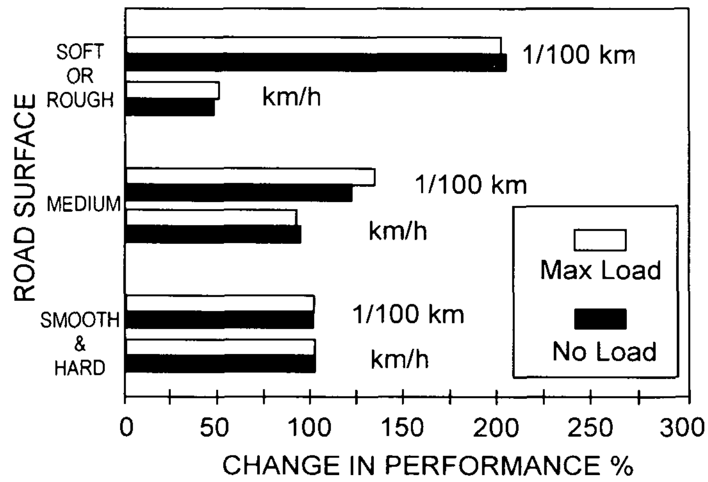

Figure 1. Sensitivity of speed and fuel consumption to rolling resistance as the road surface varies from smooth and hard to soft or rough dirt (after Clark, 1996).

Slope of the road

The slope leads to what is referred to as grade resistance and the sensitivity to grade resistance was investigated on hypothetical sections of road of uniform grade and with a coefficient of rolling resistance of 1%. The grades ranged from positive 1% to negative 1% and the results of the sensitivity analysis for grades are illustrated in Figure 2.

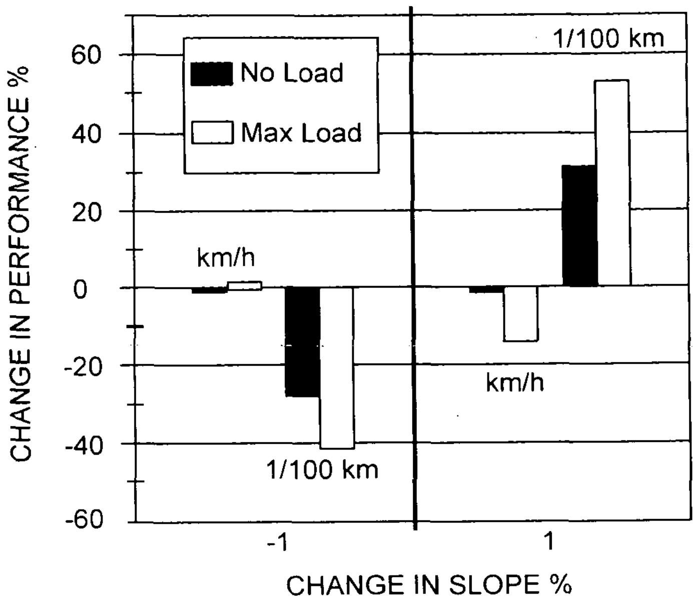

Figure 2. Sensitivity of speed and fuel consumption to changes in grade (after Clark, 1996).

Fuel consumption is very sensitive to grade as more or less power is required to travel along the road. The average speed is less sensitive to grade, with sensitivity increasing rapidly with increasing grade as the torque required to overcome motion resistance approaches maximum torque. As expected, sensitivity to grade increases with increasing payload.

Gross vehicle mass

One of the major factors affecting vehicle performance is payload, and thus GVM. To show the sensitivity of performance to a difference in GVM and therefore payload, the analysis illustrated in Figure 3 was performed. Acceptable excess above the specified GVM of 14,20 tons was assumed to be 5%, therefore GVMs of 5% above and below this value were analysed. From Figure 3 it may be seen that the performance is sensitive to changes in payload.

Engine torque

The SimTrans model requires the user to input the engine characteristics for the vehicle of interest. The engine characteristics required are the maximum torque envelope and six regression coefficients describing the specific fuel consumption surface. These engine characteristics are readily obtained from the engine maps published by engine manufacturers. However, there is some variability in the performance of each engine manufactured. Also, published engine maps usually include fan losses only and not other power losses due to such accessories as compressors, hydraulics and power steering. Engine performance also changes with wear and tear. For these reasons the sensitivity analysis illustrated in Figure 4 was performed.

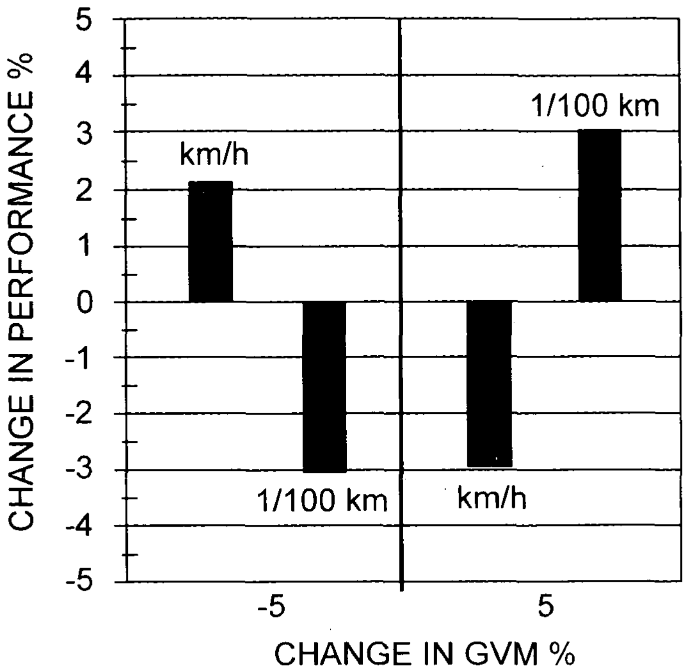

Figure 3. Sensitivity of speed and fuel consumption to a 5% change in GVM (after Clark, 1996).

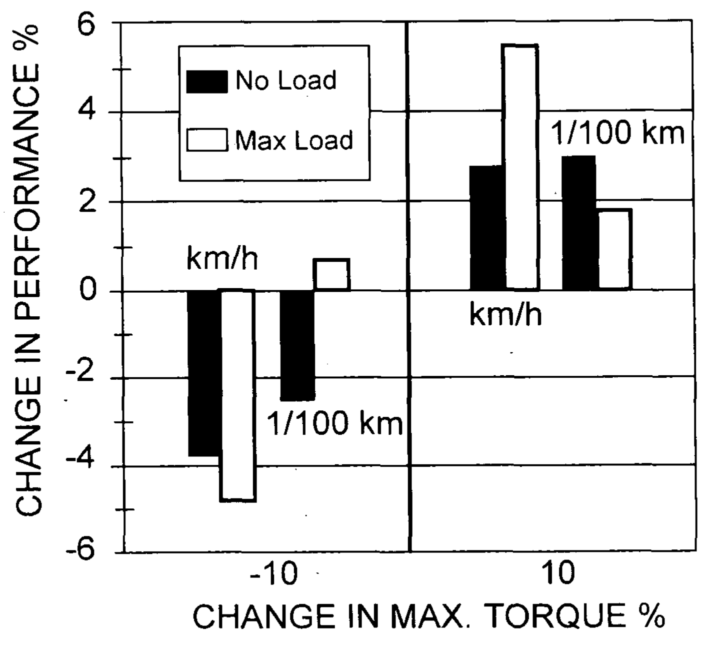

Figure 4. Sensitivity of speed and fuel consumption to 10% changes in the torque envelope (after Clark, 1996).

The specific fuel consumption surface was assumed to remain unchanged. The maximum torque curve was moved up and down by 10% of the maximum torque at rated speed, relative to the published maximum torque curve obtained from the manufacturers. Both average speed and fuel consumption showed considerable sensitivity to the changes in the maximum torque curve, but particularly the average speed. Average speed changes occurred due to changes in the torque available for acceleration. Fuel consumption was less sensitive, as changes in fuel consumption are smallest in the region around the maximum torque line, which is close to the locus of minimum specific fuel consumption. Sensitivity of the average speed increased with increasing GVM. For a GVM of 14,84 tons, the lowest fuel consumption occurred when using the manufacturer's maximum torque curve, this is due to the engine operating close to minimum specific fuel consumption over a large proportion of the route.

The remaining factors are discussed, although they showed very little effect on the performance of the vehicle. Individual results are not given. However, Figure 5 shows the combined effect of some of these variables.

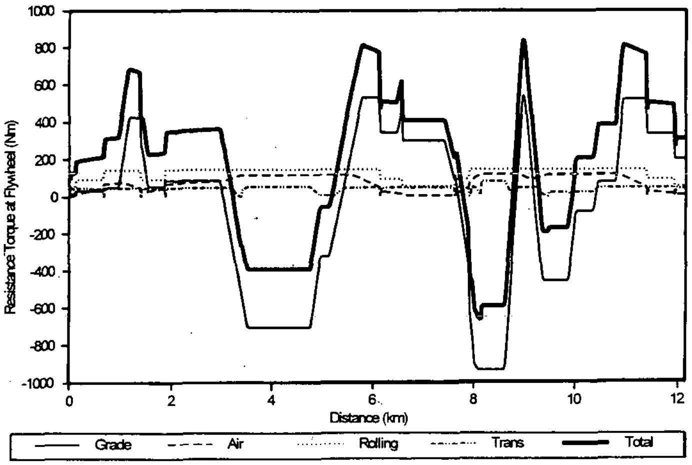

Figure 5. Simulated output illustrating the relative importance of some of the motion resistance components (after Clark, 1996).

Frontal area and coefficient of drag

Frontal area was used in the calculation of air resistance, and was varied by 10%. The results show that fuel consumption is more sensitive to changes in frontal area than to average speed, indicating that sufficient engine power was available to overcome the increase in drag. In both cases the sensitivity to frontal area decreases with increasing payload, due to air resistance forming a smaller proportion of motion resistance. Increasing frontal area reduces average speed and increases fuel consumption in all cases in this analysis.

The coefficient of drag is one of the more difficult variables to estimate, and can only be accurately determined in a wind tunnel. For vehicles with unenclosed load areas the coefficient of drag will vary for each load carried. Hence, it was estimated that a 20% error in the value of the coefficient of drag was possible. Results of the sensitivity analysis show that fuel consumption shows greater sensitivity than average speed, with the sensitivity decreasing with increasing GVM. An increase in drag coefficient reduces average speed and increases fuel consumption in all cases in this analysis. However, due to the relatively low speeds encountered with this type of vehicle, not greater than 80 km/h, the overall effect of these two variables was insignificant.

Transmission losses

Transmission losses are currently estimated in the model using a constant factor by which the input torque to the transmission is multiplied. In practice the transmission efficiency varies with the level of the torque being transmitted, the gear ratio and the engine speed. The sensitivity analysis was performed to investigate the sensitivity of performance to a 10% increase or decrease from the recommended constant value of 12% transmission losses for the Mercedes Benz 1414-48. The performance did show some sensitivity to these changes in transmission efficiency, but less so than for the other factors already discussed.

Rolling radius of wheels

The rolling radius of the driven wheels of a vehicle varies with GVM and inflation pressure. The analysis was performed to determine the effect of a 10% change in rolling radius from that measured for the Mercedes Benz 1414-48. The rolling radius was measured for five different GVMs. It was noted that, as for transmission losses, fuel consumption was not always more sensitive than average speed, and there was no trend in the sensitivity of fuel consumption with increasing GVM. Average speed decreased with increased rolling radius.

Inertial mass factor

A mass factor is included in the SimTrans model to account for the rotational inertia of a vehicle's wheels and transmission. A sensitivity analysis was carried out to determine the importance of this in the simulation of vehicle performance. A mass factor of 1,0 makes the rotational inertia equal to zero. SAE (1990) suggests a general value of 3% of a vehicle's tare, giving a mass factor of 1,03. An extreme value of 1,10 was also chosen for the analysis. The simulated vehicle performance showed little sensitivity to the inertia mass factor.

Time taken to change gear

A vehicle operation factor, dependent on the driver and type of gearbox, is the time taken to change gear. The time taken to change gear can influence the point on a route at which a gear change takes place, and whether a gear change is possible at all. An analysis was carried out for the following gear change times: a hypothetical value of zero, the value of 1,5 seconds measured while recording the observed performance data, and a value of 3,0 seconds. This variable had little effect on the performance of the vehicle.

Finally, the relative contributions of rolling resistance, air resistance, grade resistance and transmission losses to the total motion resistance are illustrated to show the relative effects. The Mercedes Benz 1414-48 with a GVM of 14,84 tons was simulated over the La Mercy to Mount Edgecombe route. Motion resistance components are plotted in Figure 5, expressed as equivalent torques at the flywheel for the purpose of easy comparison. Note the dominant effect which grade resistance has on the total motion resistance. The horizontal parts of the grade resistance curve occur on road sections of uniform grade. Rolling resistance is next most important and is constant for a particular gear ratio. Air resistance is less important and, as expected, is strongly influenced by vehicle ground speed. Only at high speeds does air resistance become greater than rolling resistance. Transmission losses mirror the changes in motion resistance and at times exceed the air resistance.

Conclusions

From the sensitivity analyses discussed above it may be concluded that it is important that accurate values of GVM, grade and coefficient of rolling resistance be determined. It is also important to use an engine map with characteristics as close as possible to those of the engine of interest. The coefficient of drag plays a minor role, and slightly less so the frontal area. Transmission losses, rolling radius and time taken to change gear have a small influence on performance, and for this vehicle and route do not require accurate estimation. For this vehicle the inertia mass factor is not important, but may be important for tractors and heavier trucks. These conclusions support the decision that it is necessary to accurately determine grade and coefficients of rolling resistance.

Acknowledgements

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