Simulating Truck Performance in Mining and Earthmoving

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Abstract The recent advances in real time GPS vehicle tracking have created a number of new possible applications for a windows based vehicle performance and fuel consumption simulator for use in earthmoving and open cut mining. This paper describes the development of a multi-purpose computer program, written in Delphi Pascal, to predict the performance and fuel consumption of diesel heavy haul vehicles, operating under various road and load conditions. The model input data includes, among other factors, vehicle rimpull-speed-rotating mass characteristic, road segment grade, speed limit, rolling resistance, radius of turn and coefficient of side friction. The model takes a novel approach to simulate the way braking is anticipated and cascaded over an arbitrary number of segments by first calculating the maximum final speed for every segment for both haul and return journeys. It then returns the simulated segment travel time, fuel consumed, speed profile and the actual simulated final speed which becomes the initial speed for the following road segment. In this way, any number of segments are cascaded forming a representation of a road, which may be a part of any road network. The flexibility of the operating system enables this model to become a component of a full-scale simulation model of a truck road network for specific applications to the transport of bulk commodities in earthmoving and open cut mining.

1. Introduction

Earthmoving vehicles are used extensively worldwide for haulage in both construction and open cut mining. Before any such operation commences, decisions need to be made on the optimum selection of vehicles for the job and the site layout. Furthermore, it is usually important to determine the project cost, particularly where tendering is involved. A high tender price can mean the contract is lost while a low tender price means less profit or even a loss.

Decision-makers need ever more powerful tools and increasingly demand these tools to be set in the familiar, easy to use environment of the microsoft windows operating system.

The development of new geographic positioning hardware for tracking of remote vehicles in real-time has led to the development of new information technology products to convey and record vehicle position and operating state. The current availability and increasing use of these systems in conjunction with earthmoving equipment (Macmahon 1996, Mincom 1997) allows new applications for real time vehicle modelling for incident detection, prevention, and for optimum site operation.

The aim of the computer model is to provide a prediction of a truck's earthmoving performance and fuel consumption. This then provides necessary inputs to the dynamic simulation modelling and evaluation of the economics of whole mine operation.

This paper describes the workings of a computer model of a heavy dump truck and briefly discusses the application of a vehicle simulator to real-time performance monitoring, incident detection, discrete simulation and tendering estimation.

2. Earthmoving applications of vehicle simulation

There are a number of vehicle simulators currently in use by the earthmoving industry. These include *VEHSIM* and *FPC* by Caterpillar, and *TALPAC* by Runge. Although these programs provide a good prediction of earthmoving performance (Philippou 1995), they have limited versatility and are not modern and user friendly by virtue of their DOS-based operating environment. The stand-alone nature and the fixed user interface mainly limits the applicability of these programs to fleet selection and estimator tendering.

The development of a vehicle simulator in a multi-tasking environment, not only enables the automation of the software's traditional uses, but also enables object, dynamic library linking and data exchange with other software-hardware systems for novel new applications.

The vehicle simulator described in this paper is intended for Macmahon "Earth Track". This system combines real time vehicle and load tracking using truck mobile geographic positioning system (GPS) with comprehensive vehicle state and load data provided by the truck payload management system (TPMS). Mobile data is sent by radio modem to a base server running geographic information systems (GIS), analysis and simulation.

2.1 Incident detection and guaranteed ore delivery

Every year millions of dollars are lost because high-grade ore gets mistakenly dumped, or low-grade ore gets inadvertently processed. Vehicle tracking systems offer new ways to address these problems.

While ore grade can be determined from the region on a GIS site map and a sufficiently accurate positioning of the excavator arm, it is a different matter ensuring that the given ore gets hauled to the correct destination.

Regular vehicle polling is one way of determining the ore's destination. The main limitation with this method is the required vehicle radio polling rate and the communications load it places on the limited bandwidth allocated for a mobile radio channel shared by all vehicles on site. By polling only at the critical times, more bandwidth-time is reserved for all other communication on site.

The vehicle simulator provides the ability to determine when the vehicle should have passed a given intersection in the road network, enabling the system to operate as an automated monitoring system using only available bandwidth. This can be achieved by only polling the vehicle when needed to confirm correct destination.

2.2 Road design and maintenance

Mine operational efficiency benefits from small improvements in road surface quality and road layout and cumulatively can result in considerable productivity, fuel and tyre savings. However, the construction of a high quality well banked and drained road and its maintenance can also be expensive. The design cost tradeoff between road construction and maintenance, and the long term operating efficiency, has been difficult to quantify and has remained a neglected area.

This model makes a step towards calculating a tradeoff by including as many road variables as possible, and their effects on vehicle motion and hence vehicle productivity and fuel consumption. By comparing the financial benefits of an improved road, to the costs of improving that road, informed decisions on initial construction plans, and timely road maintenance become possible.

2.3 Tender Estimation

Tendering is based on estimating the overall costs involved in running equipment to move the contracted volume of rock in the required time, from simulated vehicle performance. The main tool used by estimators is the vehicle simulator of which Caterpillar's *VEHSIM* appears to be the most popular.

A typical estimation, however, has to take into account the site changes and the effects of moving vast quantities of earth on the site topography over the life of the tendered contract. The ever changing site topography may require a very large number of simulation runs for every small incremental change. This requires a large amount of manual data entry when using the currently available DOS-based software packages. The Windows-based nature of our vehicle simulator, however, provides for the automation of this and other repetitive tasks, thereby saving time and reducing possibility for user errors.

3. Site and plant data for simulation

3.1 Truck Data

Vehicle manufacturers provide the vehicle performance curves in digital format by means of a look-up table that relates speed; rimpull and rotating mass (Morgan 1991). Furthermore, altitude correction, weight constants as well as idling and full throttle fuel consumption rates are also provided (Anon 1992) and entered into the model. Figure 1 is a rimpull characteristic for one of the vehicles available in our simulator. The curve approximates a constant power output, taking into consideration engine power variations over each gear's speed range, the chassis losses and loses due to all other systems deriving power directly or indirectly from the engine.

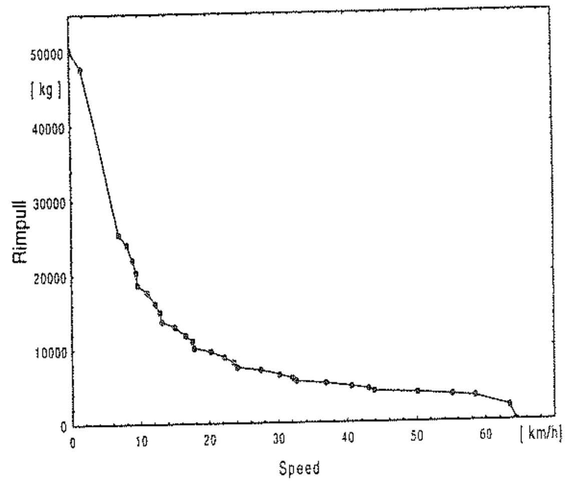

Figure 1 Truck rimpull vs. **speed for Cat. 777C truck**

3.2 Road Data

The road profile is generated from an actual site survey and is digitally stored as a sequence of road segments that comprise the links in the whole road network. The definition of a segment is based on the principle that all road conditions within a segment can be considered constant without significantly affecting the accuracy of the simulation. While segments can be of any length, the constant road conditions must include grade, road surface properties and maximum operating speed or speed limit, as shown in Figure 2.

This figure is a picture of the haul designer form from the current version of the simulator showing a part of its user interface. It shows input road variables used to obtain the results described later in Figures 3 and 4.

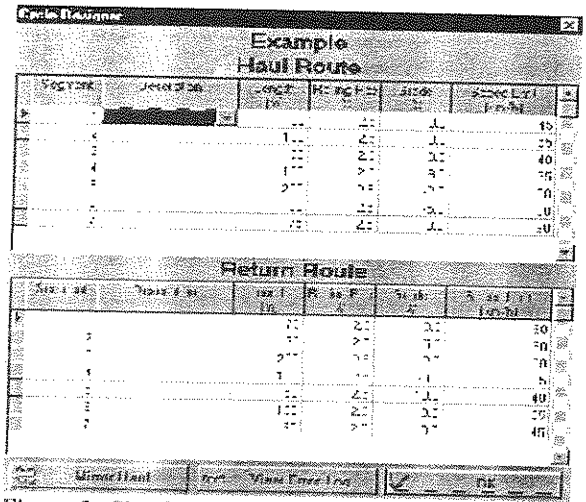

Figure 2 Simulator haul design with input variables

4. Truck and road interaction

At any point in time during the simulation, the vehicle can be described by one of three possible states of motion:

1. Accelerating or decelerating (up-hill) under full throttle.
2. Cruising (at constant speed) by using full or part throttle, or by braking without decelerating.
3. Braking deceleration.

By breaking the journey up into segments with fixed driving conditions and specified initial and final motion limit, we are limiting the vehicle operation to 7 different modes or sequences of operating states within each segment. These have been classified in Table 1.

Table 1 Vehicle operation modes

A	Brake for the entire segment
B	Cruise for the entire segment
C	Initially cruise then brake for the rest of the segment
D	Accelerate (or decelerate) under power for the entire segment
E	Accelerate (or decelerate) under power then cruise for the rest of the segment
F	Accelerate (or decelerate) under power then brake for the rest of the segment
G	Accelerate (or decelerate) under power, then cruise and then brake for the rest of the segment.

For the purposes of this model, acceleration and deceleration are classed together as in Table 1. Deceleration under power is an externally imposed loss of speed due to road alignment and gravity. It occurs when the vehicle starts an up-hill segment initially travelling faster than the sustainable equilibrium speed. Unlike braking, it is not a deliberate choice by the driver.

Cruising is achieved whenever the vehicle is travelling at constant speed, regardless of brake or throttle position.

5. Vehicle motion simulator

5.1 Retarding forces

Retarding forces, like the propulsive force, change with vehicle speed during the simulation. This effects the net force available for accelerating the vehicle during full throttle, and the fuel consumption during cruising.

The retarding (R_{req}) force is orthogonally resolved from the road grade angle (θ) using the rolling resistance (R_R) and gravity (g). Since the grade angle (θ) is negative on a down-hill slope, this force can act in the same direction as propulsion.

$$R_{req} = M * g * (\mathrm{Sin}(\theta) + R_R * \mathrm{Cos}(\theta)) + F_{cc} \quad \{1\}$$

The forces acting on the vehicle are calculated using (M), which comprises the vehicle empty mass plus payload. Calculation of acceleration, however, requires a correction for rotating mass, discussed later.

For the purposes of validation against *VEHSIM*, we have used the assumptions that actual rolling resistance is related to the nominal rolling resistance using equation {2}. It represents a linear increase of 1% rolling resistance for a vehicle *speed* increase of 60 km/h.

$$R_R = (1.075 * R_{Rn} - 0.9 + (speed/60))/100 \quad \{2\}$$

The linear assumption ignores the second order air resistance term and is reasonable at the slow speed of earthmoving vehicles.

The cornering drag (F_{cc}) used in equation {1} can be a major contributor on turns. It is calculated thus:

$$F_{cc} = \pi(MV^2/R_v)^2/(180nC_s) \quad \{3\}$$

Where vehicle speed (V) in m/s, radius of curve (R_v) m, the total number of tyres (n) and the average cornering stiffness of each tyre (C_s) Newton/degree (Smith 1970).

5.3 Rotary mass

While the vehicle is accelerating under power, part of the torque being transmitted through the drive system is exerted on rotary acceleration. The model therefore needs to account for parts that have mass but need to be accelerated linearly with the truck, as well as accelerated rotationally. The equivalent available torque at a given speed is therefore always lower when the vehicle is accelerating under power, than while cruising at constant speed.

The easiest way to account for this rotary inertia is to add an equivalent additional rotating mass to M (Anon 1991). The rotating mass can be represented as the product of a specified fixed mass constant (L_m) and a mass correction factor (mcf) which changes with each gearbox ratio with automatic transmission vehicles. The equivalent mass (M_u) is thus:

$$M_u = M + L_m * mcf \quad \{4\}$$

The vehicle manufacturer provides this data as a lookup table relating vehicle gear shifting speeds to ***mcf*** values (Morgan 1991) which makes M_u a speed dependant variable.

5.4 Full throttle acceleration and deceleration:

Unlike road vehicles, the high weight to power ratio of vehicles used in heavy earthmoving, means that they are operated at full throttle until speed becomes constant (ie.: cruising) or braking commences (Boulton 1980, Anon 1991). Full throttle operation corresponds to the characteristic in Figure I.

For simulation of full throttle operation, the vehicle's motion is broken down into even shorter units of distance called subsegments (Runge 1993, Anon 1993) where the acceleration can be assumed constant. The simulator calculates the distance travelled (ΔS) and the time required (ΔT) as the vehicle of total equivalent mass (M_u) travels at constant acceleration between two consecutive speeds (U_1, U_2) from subsegment start to end. Assuming that the most appropriate resistive and propulsive forces in this interval are those in the middle of the subsegment's speed range, $(U_1+U_2)/2$, Newton's laws of motion can be shown to produce the following relationships for subsegment distance (ΔS) and time (ΔT):

$$\Delta S = \frac{Mu(U_2^2 - U_1^2)}{F_1 + F_2} \qquad (5)$$

$$\Delta T = \frac{2Mu(U_2 - U_1)}{F_1 + F_2} \qquad (6)$$

Where F_1 and F_2 is the total net force, propulsive and resistive, acting on the vehicle at speeds U_1 and U_2 at the subsegment start and end respectively. The retarding force is calculated using equations (1) to (3) while the propulsive force at the given speed is obtained by linear interpolation from a speed–rimpull lookup table illustrated in Figure 1.

As the vehicle accelerates or decelerates under full throttle, progressing through consecutive points in the rimpull table, it sums time, distance and fuel for each subsegment. At some point, one or more of the following four contingencies will be detected at the end of the last calculated subsegment:

1. Total Segment distance exceeded
2. Required Braking distance infringed
3. Speed limit exceeded (acceleration only)
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The simulator calculates the position along the subsegment for all of the above conditions and finds the one that occurs first. Depending on the condition which was found to occur first in the subsegment, the simulator respectively either:

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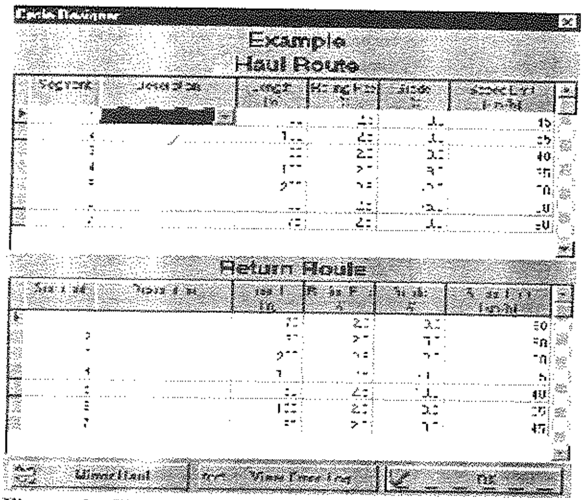
2. Calculates position where braking must commence by determining the remaining segment braking distance and braking time. It returns total travel time and fuel consisting of throttling and braking modes of operation such that final speed restriction is satisfied.
3. Calculates the position along the segment where speed limit is first reached, then calculates braking distance (if any) and then calculates the distance over which the vehicle is cruising (if any). The simulator returns the sum of acceleration, cruising and braking time and fuel, with the final speed restriction being met at the end of the segment.
4. Same as procedure 3, except in this case there must be some cruising time. In addition, the effective speed limit is imposed by the equilibrium of propulsive and retarding forces.

The accuracy of this simulator is maintained by using actual solutions to second order polynomials describing vehicle motion, braking and distance remaining in the segment to determine the point at which the vehicle changes from one operating state (eg: full throttle acceleration) to another (eg: cruising) within a subsegment. This differs to other vehicle simulators such as Talpac (Runge 1993) that approximate using the end of the subsegment. Maintaining mathematical accuracy independent of segment length, enables the simulator to work with a large number of vanishingly small segments, and immediately use high resolution digitally acquired road profile data for simulation, where processing speed is not a limiting factor.

5.5 Cruising

When the vehicle either reaches the imposed speed limit, and it is lower than the equilibrium speed dictated by vehicle power and retarding forces, it maintains constant speed using part throttle or braking. The speed limit is a very important parameter for accurate simulation.

The Vehicle speed limit represents the maximum safe speed and hence the expected driving behaviour. It is determined from a number of inputs; The user can specify the speed limit in the haul designer; a speed limit can be calculated automatically from other road properties; or a speed limit can be imposed from a larger simulation model. In any case, the model should always choose the lowest speed limit.



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5.6 Braking simulation

In order to simulate the way driving behaviour anticipates braking over any road distance, the simulator needs to look ahead to determine where braking needs to commence. Whereas *VEHSIM* only looks 2 segments ahead of the vehicle's current position (Anon 1991), this simulator can span braking over any number of segments by using an entirely different mechanism using the segment's *maximum final speed*.

Whereas the *segment speed limit* determines the maximum cruising speed, the *maximum final speed* determines the maximum speed at the point where the segment terminates and the next segment begins. This not only initiates braking at some point along the segment, but by pre-calculating all the segment *maximum final speeds* for the entire road link before vehicle forward motion simulation begins, allows braking to span any number of segments.

Consider, for example, the last segment of a haul road where the *maximum final speed* is zero (to simulate the vehicle coming to rest). Given the vehicle's braking characteristics and the length of the segment, it is possible to calculate the maximum speed at the start of this segment, which is equal to the *maximum final speed* of the previous road segment. Furthermore, the vehicle must not be permitted to enter last haul segment travelling faster than the *segment speed limit*. By choosing the lower of the two speed limits and setting the previous segment's *final speed limit* to this value, enables braking to commence in the previous segment and continue for the entire last segment of road. By considering the *segment speed limits*, we are also simulating the way the vehicle slows before reaching a tight turn or a hazardous stretch of road.

This procedure is repeated for the second last segment to determine the *final speed limit* of the segment before, and so on, until the *final speed limit* for the first segment of the road link has been calculated.

Since *maximum final speeds* usually need to be different for the same segments for the haul and return journeys, this procedure is repeated for the reverse direction of travel along the same road link.

5.7 Limited braking and tractive force with road condition

The model also considers the limitations placed on braking and accelerating due to wheel slip. Mannering and Kilareski (1990) provide a set of formulas that also take into account vehicle geometry. This allows testing the effects of road surface characteristics on vehicle performance.

6. Fuel Consumption model

The fuel consumption model is based on two fuel parameters, idling fuel rate α, and the full-throttle fuel rate β (litres/hour). By making the assumption that the actual rate of fuel consumption is proportional to the percentage throttle determined by the ratio R_{req}/R_{avl}, this method avoids the need for detailed engine fuel map data which is not available.

$$dC/dT = \alpha(1-R_{req}/R_{avl})+\beta(R_{req}/R_{avl}) \qquad \{7\}$$

The formula (Runge 1993) for the instantaneous truck fuel consumption rate (dC/dT) in litres/hour returns values between α for idling when R_{req} is zero, and β for full throttle operation when R_{req} is equal to R_{avl} and all available rimpull is utilised.

This formula is only evaluated when the vehicle is cruising at part throttle, since during full throttle operation, dC/dT is equal to β while during braking the engine is assumed to be idling resulting in the rate of fuel consumption equal to α.

7. Altitude and Tyre Correction

A vehicle model needs the flexibility to account for the effects of using non-standard tyres, as well as the effect of reduced engine power at high altitude. Both of these factors are taken into consideration by appropriately modifying the speed-rimpull characteristic of the vehicle.

8. Simulation results

The continuous operation of a vehicle along the same haul and return routes with the simulated travel time and the given fixed loading and dumping time, allows us to calculate the mass of material moved per hour. Furthermore, the volume of earth removed is calculated using the bench cubic metre (BCM) factor that depends on how the rock is blasted (swell factor) and material density. Non continuous operation of a vehicle that is taking regular break intervals is simulated with the *Operating (min/h)* field that can be set to less than 60 minutes per hour of actual vehicle operation.

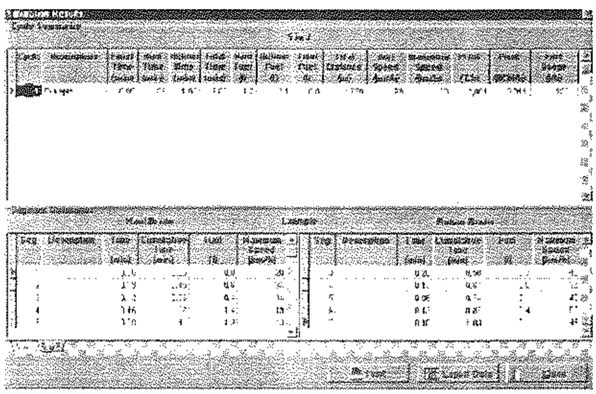

Figure 3 Simulator results window

Figure 4 is a graphical representation of the numerical results in Figure 3. Here it illustrates segments (large points) as well as subsegments (small points) as generated by the simulator. Segments in Figure 4 have been classified according to the operation modes described in Table 1.

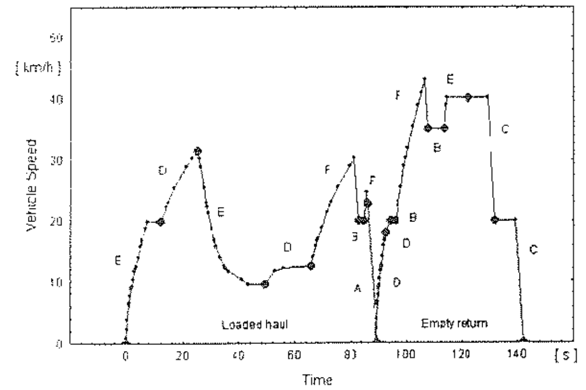

Figure 4 **Haul and return speed profile**

The road segment data used for this example is intended primarily to demonstrate the various aspects of the model's operation by generating results that illustrate many possible sequences of segment operating modes with only a few segments. The classification system in table 1 can be used to follow the operation of the vehicle for the journey.

8.1 Result validation

Since many of the physical assumptions used in the basic core of this model are based on the industry accepted Caterpillar program, *VEHSIM* has been used extensively to validate our model at this stage. Fuel consumption and cornering drag cannot be compared as *VEHSIM* lacks these features.

The maximum discrepancy over any single segment has never been observed to exceed 2% of travel time. With 43 comparisons, a standard deviation of 0.3% was observed. Over any given haul consisting of many segments, the discrepancy is usually even less.

9. Conclusion

The computer based heavy vehicle modelling program is being developed to simulate vehicle performance and determine operating costs for the transport of bulk commodities in earthmoving and open cut mining. Determining vehicle performance and fuel consumption allows the calculation of productivity and facilitates costing of the operation under various road and load conditions. The model facilitates the optimisation of the earthmoving operation as well as predicting the cost of running the equipment for future tendering. Furthermore, the flexibility of the model's programming environment, facilitates it to be integrated into a discrete transaction based simulation model of an entire earthmoving operation. This enables the evaluation of various strategies for optimum operation by maximising productivity while minimising operating costs for an entire earthmoving operation. These models permit the application of 'fine tuning' that can increase the productivity of mining operations and enhance the planning of mining and earthmoving.

10. Acknowledgments

This research is supported by an Australian Postgraduate Award (Industry) scholarship. The paper has been made possible with the help and resources of the Transport Systems Centre, Cameron Blanks and all the other Earth Track/MPMS team members at Macmahon P/L. Special thanks to David Campbell for writing the excellent "front end" user interface for the vehicle model and for the object oriented program framework. Parts of the user-interface have been digitally captured and used in this paper.

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