**Haulage Truck Performance and Fuel Consumption Model**

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Abstract:

This paper describes the design and application of a computer model representing a real world system that can be a powerful tool to predict, analyse and optimise a dynamic real world process. A model can be used to conduct experiments for the purpose of understanding the behaviour of the system, or for evaluating various strategies for optimum operation. A truck performance simulator is being developed in Delphi Pascal consisting of an analytical model to simulate haulage truck vehicle kinematics. The vehicle model uses the road segment length and road surface parameters, as well as the truck's engine rimpull characteristics, rotating mass, braking limitations, together with initial and required maximum final speed and operating speed limit within a road segment. Since the model provides travel time and fuel consumption, it can become a component of a full-scale simulation model of a truck road network for specific applications to be transport of bulk commodities in earthmoving and open cut mining.

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## Introduction

With the recent developments in new information technology products by the earthmoving sector (Macmahon 1996, Mincom 1997), the traditional computer based tools and software used in earthmoving is being left behind. New windows based software coupled with mobile hardware is being used to create real time equipment and productivity monitoring tools. These tools include new applications for vehicle simulation, leading to day-by-day and long term planning tools.

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. 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 modeling and evaluation of the economics of whole mine operation.

## Earthmoving applications of vehicle software

There are a number of vehicle simulators in use by the earthmoving industry (VSM, FPC, Talpac, etc.). Although these programs provide a fairly good prediction of earthmoving performance (Philippou 1995), the applicability of these programs is mainly limited to fleet selection and estimator tendering due to the stand-alone nature and the fixed user interface of these DOS based packages. 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 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 the vehicle payload management system where the mobile data is sent by radio modem to a base server running geographic information systems (GIS), analysis and simulation.

Real time 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 ore gets hauled to the correct destination. Regular vehicle polling is one way of determining the ore's destination but a major limitation encountered with this type of system is the required vehicle radio polling rate and the load it places on the limited bandwidth allocated for mobile radio communication channels 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 operate as an automated monitoring system using only available bandwidth, by only polling the vehicle when needed to confirm correct destination, such as after an intersection. The time for polling being determined from the simulated travel time.

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 travel time and fuel.

Estimators have methods for determining operating costs for a vehicle given it's travel time and fuel consumed. Similarly, the costs of roadwork can also be determined. 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.

Tender Estimation

Accurate and reliable tendering is important for winning a bid for a mutually profitable contract. Tendering is based on estimating the overall costs involved in running equipment to move the contracted volume of rock in the required time. The main tool used by estimators is the vehicle simulator and contract earthmoving companies use vehicle simulation software for predicting earthmoving costs.

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 tender contract. This may require a very large number of simulation runs which requires a large amount of manual data entry when using the currently popular DOS-based software packages produced by Caterpillar and Runge mining.

The Windows-based nature of this vehicle simulator provides for the automation of any repetitive task, thereby saving time and increasing accuracy.

## Site and plant data for simulation

The real world characteristics of the vehicle and the 3 dimensional road contour, are both analog properties that need to be 'digitized' before a computer can be employed to perform any kind of calculation and simulation The acquisition of this data is an essential step towards simulation.

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). Figure I is a rimpull characteristic of one of the vehicles available in this simulator The curve approximates a constant power output and the data points are taken directly from the lookup table
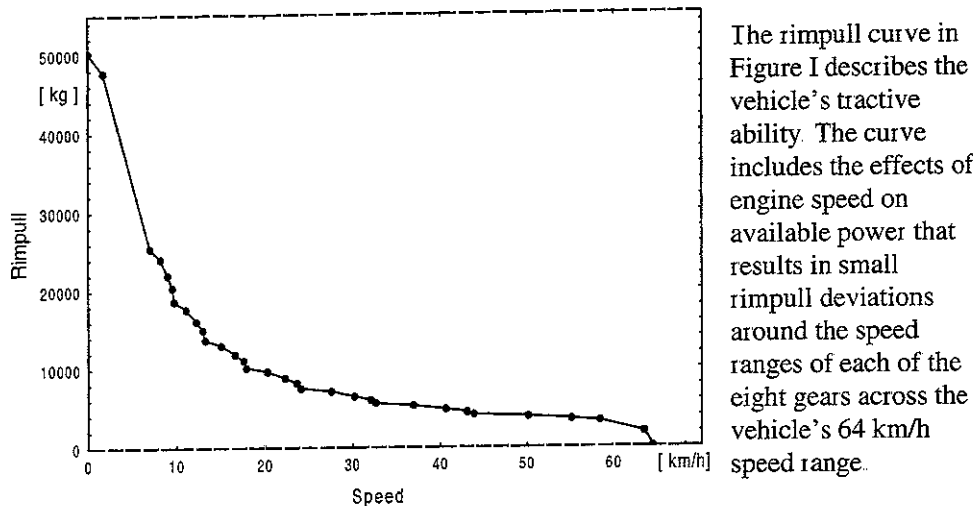


The rimpull curve in Figure I describes the vehicle's tractive ability The curve includes the effects of engine speed on available power that results in small rimpull deviations around the speed ranges of each of the eight gears across the vehicle's 64 km/h speed range.

**Figure I      Truck rimpull vs. speed for Caterpillar 777C truck**

Road Data:

The road profile is generated from an actual site survey The conversion of this data into road segments is an involved process that will be described in a future paper; however, it is based on the principle that all road conditions within a segment can be considered constant without significantly affecting the accuracy of the simulation. Segment road conditions include constant grade, road surface properties and maximum operating speed Road segments can be of any length, as they constitute the links in the overall road network

| Cycle Designer | | | | | |
|---|---|---|---|---|---|
| **Example Haul Route** | | | | | |
| Segment | Description | Length (m) | Rolling Res % | Grade % | Speed Limit (km/h) |
| 1 | | 50 | 2.5 | 0.0 | 20 |
| 2 | | 100 | 2.5 | 0.0 | 40 |
| 3 | | 95 | 2.5 | 11.5 | 40 |
| 4 | | 55 | 2.5 | 8.0 | 35 |
| 5 | | 110 | 2.5 | 0.0 | 55 |
| 6 | | 10 | 2.5 | 0.0 | 20 |
| 7 | | 10 | 2.5 | -10.0 | 45 |
| 8 | | 10 | 2.5 | 0.0 | 45 |

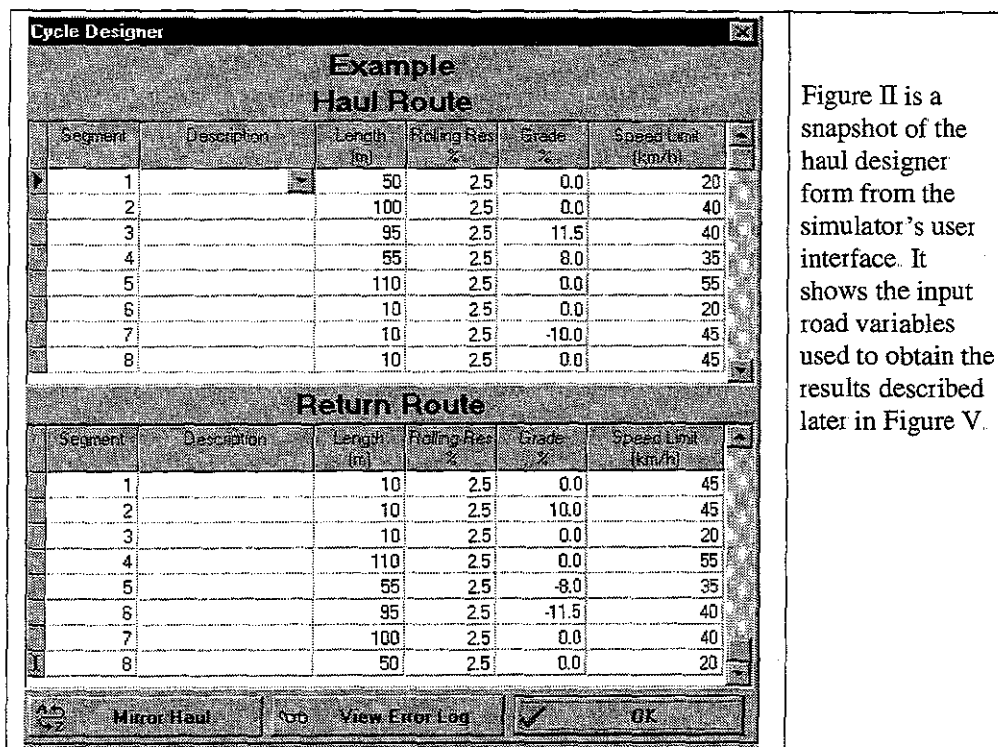| **Return Route** | | | | | |
|---|---|---|---|---|---|
| Segment | Description | Length (m) | Rolling Res % | Grade % | Speed Limit (km/h) |
| 1 | | 10 | 2.5 | 0.0 | 45 |
| 2 | | 10 | 2.5 | 10.0 | 45 |
| 3 | | 10 | 2.5 | 0.0 | 20 |
| 4 | | 110 | 2.5 | 0.0 | 55 |
| 5 | | 55 | 2.5 | -8.0 | 35 |
| 6 | | 95 | 2.5 | -11.5 | 40 |
| 7 | | 100 | 2.5 | 0.0 | 40 |
| 8 | | 50 | 2.5 | 0.0 | 20 |

Mirror Haul    View Error Log    OK

Figure II is a snapshot of the haul designer form from the simulator's user interface. It shows the input road variables used to obtain the results described later in Figure V.

**Figure II        Simulator haul design with input variables**

## Truck to road interaction

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

**Table I                              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 in Table I. Deceleration under power occurs when the vehicle starts an up-hill segment initially traveling faster than the sustainable equilibrium speed and cruising is achieved whenever the vehicle is traveling at constant speed, regardless of brake or throttle position.

## Vehicle motion

The simulator breaks the journey over each segment into shorter subsegments where the vehicle acceleration is considered constant (Morlok 1978)(Anon 1993).

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 under full throttle
2. Cruising (at constant speed) by either throttling or braking
3. Braking deceleration (at constant rate)

Full throttle acceleration and deceleration:

The very high weight to power ratio of vehicles used in heavy earthmoving leads most heavy vehicle (and train) simulators to make the assumption that it is operated at full throttle until speed becomes constant (i.e.: cruising) or braking commences (Boulton 1980). While the speed is changing, the vehicle's motion is broken down into even shorter units of distance called subsegments (Runge 1993) where the acceleration can be assumed constant. The simulator calculates the distance traveled ($\Delta S$) and the time required ($\Delta T$) 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 subsegments speed range, ($U_1+U_2$)/2, Newton's laws of motion can be shown to produce the following relationships for subsegment distance ($\Delta S$) and time ($\Delta T$):

$$\Delta S = \frac{Mu(U_2^2 - U_1^2)}{F_1 + F_2} \qquad \{1\}$$

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

Where $F_1$ and $F_2$ is the total net force, propulsive and resistive, acting on the vehicle at speeds $U_1$ and $U_2$ respectively and $M_u$ is the total equivalent mass (explained later).

Since the speed is changing with every consecutive subsegment, the available propulsive force ($R_{avl}$) and the retarding force ($R_{req}$) change. This effects the net force available for accelerating the vehicle.

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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)

4. Steady state (cruising) speed reached due to equilibrium of propulsive and retarding forces.

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 program respectively either:

1. Calculates the final time, speed and fuel at the distance corresponding to the actual end of the road segment.

2. Calculates position where braking must commence by determining the remaining braking distance and braking time. It returns total travel time and fuel consisting of throttling and braking modes of operation, with final speed restriction 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 condition 3, except in this case there must be some cruising time. Also, the speed limit is the speed for equilibrium of propulsive and retarding forces.

*Rotary mass:* While the vehicle is accelerating or decelerating under power, the vehicle empty mass plus payload (actual total mass, $M$) would not lead to the correct calculation for vehicle motion because $M$ also includes rotating parts that need to be accelerated rotationally as well as linearly. Since part of the torque being transmitted through the drive system is exerted on rotary acceleration, the equivalent available torque at a given speed is 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.

$$M_u = M + L_m * mcf \qquad \{3\}$$

The vehicle manufacturer provides this data as a lookup table relating vehicle gear shifting speeds to *mcf* values (Morgan 1991).
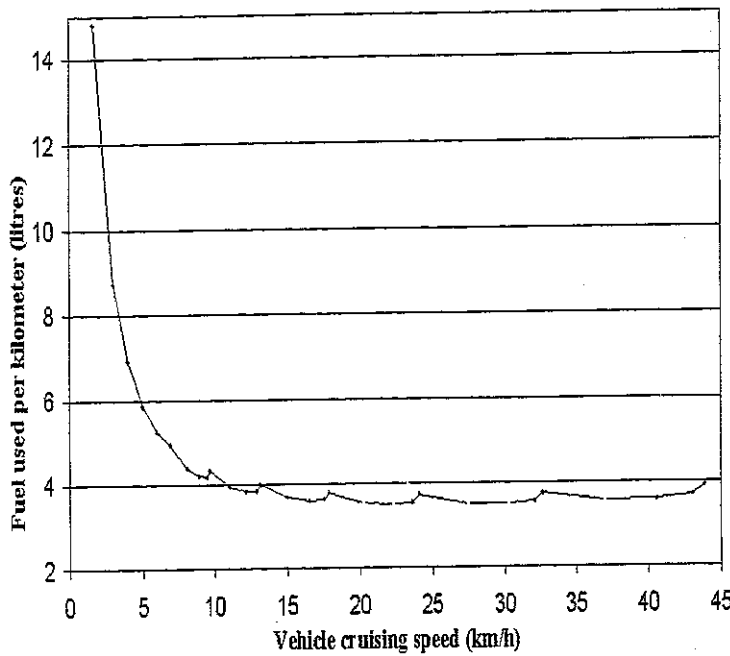
Cruising

A vehicle may be travelling at constant speed because it has reached a specified speed limit, or because all the forces are in equilibrium at full throttle. In either case, the calculation of travel time in this state is a straightforward function of the constant speed and distance

The calculation of fuel consumption uses two fuel parameters, idling fuel rate $\alpha$, and the full-throttle fuel rate $\beta$ (litres/hour). This model assumes that the actual rate of fuel consumption is proportional to the percentage throttle determined by the ratio $R_{req}/R_{avl}$. $R_{avl}$ is defined as the maximum available rimpull at the given speed and $R_{req}$ is the rimpull required for maintaining constant speed, or the sum of all retarding forces.

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

$$dC/dT = \alpha(1-R_{req}/R_{avl})+\beta(R_{req}/R_{avl}) \qquad \{4\}$$

Furthermore, when $R_{req}$ is less than zero such that cruising speed is maintained by braking on a negative grade, $R_{req}$ is set to zero to simulate engine idling fuel rate.



The cruising fuel economy graph in Figure III assumes the 777B truck is fully loaded and traveling at constant speed on a zero grade with a rolling resistance ($R_{Rn}$) of 2 5%. Fuel parameters for idling ($\alpha$) is 15 l/h and full throttle ($\beta$) 190 l/h.

**Figure III**    Simulated fuel consumption per km vs. cruising speed

Small fluctuations in fuel consumption are visible in Figure III in the relatively flat part of the curve above 10 km/h. These fluctuations correspond to the vehicle speed range of each gear and the small engine power variations over the speed range of each gear seen in figure I The fuel consumption calculation in this model therefore considers the engine-power variations with engine speed by virtue of the rimpull data in Figure 1. However, it also assumes that the engine fuel consumption can be determined from engine output power alone, without considering the individual effects of engine torque and speed on the engine's fuel energy efficiency.

A more accurate fuel model would use an engine fuel map Engine maps are commercially confidential and major truck manufacturers, including Caterpillar, do not make this data available to researchers

## Motion resistance

Motion resistance acts against propulsion and reduces the net force available to accelerate the vehicle, often limiting the vehicle speed. Whereas the propulsive rimpull force is calculated from a supplied lookup table (Figure I), the retarding force ($R_{req}$) is calculated from the vehicle's total mass ($M$), gravity, road grade angle ($\theta$) (Mannering 1990) and motion resistance ($R_R$) which includes a linear approximation for air resistance at the vehicle *speed* (anon 1987) in {7}.

$$R_{req} = M * g * (\text{Sin}(\theta) + R_R * \text{Cos}(\theta)) \qquad \{5\}$$

$$\theta = \text{Arctan}(grade\,\%/100) \qquad \{6\}$$

$$R_R = 1.075 * R_{Rn} - 0.9 + (speed/60)/100 \qquad \{7\}$$

## Braking simulation

The braking ability of heavy diesel trucks with automatic transmission leads to the use of a simple braking model that decelerates the vehicle at a constant rate dependant only on road grade (Anon 1993). The way that braking is cascaded across multiple segments, however, is another issue.

The commercial vehicle simulator VehSim meets braking requirement by looking 2 segments ahead as it sequentially processes segments in the direction of travel along the road link (Anon 1991) This vehicle simulator, however, employs a different approach where the segment maximum final speeds are firstly calculated for the entire road link by processing the segment data in reverse to the direction of vehicle travel (Dinovitser 1996) This is required before calculating consecutive segment travel times that use the maximum final speed as an input parameter. The advantage of this approach is that it can meet all braking requirements regardless of segment lengths, and can span braking over any number of consecutive segments. The method can be described by a 5-stage procedure for each segment, starting with the last road segment.

Braking procedure

1. The simulator firstly determines the braking rate $(B_r)$ in the segment In this case we are using the *VEHSIM* assumptions:

   $B_r = -1.8$ {8} in m/s$^2$ if grade is positive or zero

Else $B_r = -1.8(1+grade\%/30)$ {9} if grade negative.

Equation {9} reduces the braking rate linearly to zero up to a grade of -30%. Grades steeper than $-30\%$ are not supported by this method. Further reduction of $B_r$ by unfavorable road surface conditions will be described in equation {10}.

2. With the calculated braking rate $(B_r)$ and known segment length and maximum final $(V_{end})$ speed (which is zero for the last segment), we can calculate the segment's maximum initial speed $(V_{start})$ if braking is assumed for the entire length of the segment If the vehicle were to be moving faster than $V_{start}$, it would not be able to achieve $V_{end}$.

3. Now that the maximum allowable starting speed is known, we can compare this to the operating **SpeedLimit** to make sure that the vehicle doesn't start the segment exceeding the segment speed limit

   If $V_{start} > SpeedLimit$ then $V_{start}: = SpeedLimit$

Where speed limit is obtained from user input and from calculated speed restrictions described later.

4. The preceding segment in the haul database can now be updated for this direction:

   Maximum final speed of preceding segment: $= V_{start}$ as calculated

5. Make the preceding segment the current segment and go back to step 1, repeat until the first segment of the road link has been reached.

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

*Diesel electric vehicle braking*: This approach can also be used for more complex braking characteristics such as those in Diesel electric vehicles using more complex braking characteristics.

For example, instead of using a fixed figure of $-1.8$ for the braking rate to calculate $V_{start}$, $V_{start}$ may be determined from piecewise integration of the vehicle's retarding curve, supplied by the vehicle manufacturer. The retarding curve data would be stored in a lookup table, in the same way as the rimpull curve in Figure I

Limited braking and tractive effort with adverse road conditions

The condition of the road surface can be an important consideration for vehicle performance because wheel slip limits gradeability and braking (Anon 1996). On an unfavorable surface, the maximum available tractive effort in low gear and the maximum braking deceleration force could be limited by the maximum tractive force that the roadway surface-tyre contact can support (Mannering 1990). In order to check that the maximum forces are not being exceeded the absolute maximum acceleration ($A_{fmax}$) or deceleration ($A_{bmax}$) can be calculated using {10} and {11}.

During braking, more than half of the vehicle weight will be distributed towards the front tyres, while for acceleration, more than half of the vehicle weight will be distributed towards the back tyres according to vehicle geometry. For the purposes of this test, and to consider a worst case scenario to ensure a safety margin, and because information about vehicle geometry is not available, we might assume that the vehicle's weight is equally distributed for both cases. Using this assumption, the following formulas were derived (Mannering 1990):

$$A_{bmax} = g(0.5\mu + R_R\text{Cos}(\theta) + \text{Sin}(\theta)) \quad \{10\}$$

$$A_{fmax} = g(0.5\mu - R_R\text{Cos}(\theta) - \text{Sin}(\theta)) \quad \{11\}$$

These formulas use the coefficient of road adhesion ($\mu$), coefficient of rolling resistance ($R_R$) and angle ($\theta$) of road inclination or Arctan(grade%/100)

Turning and cornering speed limits

Vehicle manufacturers publish safe cornering speed graphs that the user can use to manually set the segment speed limit according to current practice (Anon 1996).

By automating the calculation of speed limits on turns, the model not only replaces the manual calculation, but also enables automatic comparison of a large number of alternative routes through the site topography and aid in the development of a tool for optimum site design.

This calculation is based on the centripetal force that acts between the tyre and the road surface and limits the maximum speed at which the vehicle can safely negotiate the turn. The speed limits can be calculated from the force exerted by the tyres at a normal to the direction of motion and the limiting force determined by the coefficient of side friction ($f_s$), road radius of curvature ($R_r$) and rate of superelevation ($\varepsilon$) or Tan($\alpha$)

The limiting speed ($V_{max}$) is calculated using the simplified formula (Mannering 1990):

$$V_{max} = (R_v g(f_s + \varepsilon))^{1/2} \quad \{12\}$$

The calculated speed limit is compared to the user input and the lower speed limit is used for simulation, allowing the user to override the calculation.

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Cornering drag

To account for all major forces acting on the vehicle, the simulator adds cornering drag to the other drag forces. In some cases, this drag can be greater than air and rolling resistance combined (Smith 1970). Cornering drag and cornering speed limit together provide for a more realistic model with the potential of providing more accurate results. Consideration of these factors can be important for decisions about road design and site layout, where even small improvements can cumulatively lead to considerable cost savings over the life of the operation.

A vehicle negotiating a turn is subject to centripetal force that acts over the distance of the turn. The deformation of the tyre transforms a part of the centripetal force to a force component parallel to the direction of motion. The resultant energy expended results in additional drag, which is in addition to all the other retarding forces

$$F_{cc} = \pi (MV^2/R_v)^2/(180nC_s) \quad \{12\}$$

The solution in {13} calculates the cornering drag force ($F_{cc}$) from vehicle speed ($V$) m/s, radius of curve ($R_v$) m, actual loaded vehicle mass ($M$) kg, the total number of tyres ($n$) and the average cornering stiffness of each tyre ($C_s$) Newton/degree.

This method has been used successfully with large vehicles (Smith 1970):

Tyre Correction

Vehicles fitted with standard tyres produce the specified speed-rimpull characteristic. When tyres with a different circumference are used, the speed rimpull characteristic needs to be modified. The tyre correction factor is simply the circumference ratio of the standard to replacement tyres. The speed is corrected by dividing by the tyre correction factor, while the rimpull is multiplied by the tyre correction factor (Anon 1992). The tyre correction factor significantly affects the vehicle top speed and low speed gradeability, but has a very small effect on travel time and fuel consumption because vehicle power remains the same. The simulation results use a standard tyre (tyre factor of 1.0), shown in Figure IV

Altitude performance correction

The altitude correction factor is a fractional coefficient representing the proportion of available engine power at a given altitude relative to power available at sea level (Anon 1992). Most truck manufacturers publish a table of altitude correction factors for their vehicles. Altitude is taken into account with the speed-rimpull characteristic by multiplying the rimpull by the altitude correction factor at every speed. Since engine power is proportionally reduced, travel time and fuel consumption is increased. The simulation results assume operation at sea level (altitude factor of 1.0), shown in Figure IV

**Cycle Viewer**

Simulation Details:
Last run on                by

| Cycle | Description | Operating (min/hr) | Fixed Time (min) | Plant Type | Empty Weight (T) | Payload (T) | Altitude Deration | BCM Factor | Tyre Factor |
|-------|-------------|--------------------|------------------|------------|------------------|-------------|-------------------|------------|-------------|
| 1 | ATRF example | 60 | 0.00 | 777b | 59.25 | 87.72 | 1.00 | 2.50 | 1.00 |

**Figure IV    Model input variables**

## 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 continuos operation of a vehicle that is taking regular break intervals is simulated with the *Operating (min/hr)* field that can be set to less than 60 minutes/hour of actual vehicle operation.

With the haul road data shown in Figure II, other variables in Figure IV and the fuel consumption parameters given with Figure III, Figure V presents the window with numerical results for each segment. More detailed results are available in Figure VI showing speed profile using simulated subsegments.

**Simulation Results**

Cycle Summaries                                Sim P4

| Cycle | Description | Fixed Time (min) | Haul Time (min) | Return Time (min) | Total Time (min) | Haul Fuel (l) | Return Fuel (l) | Total Fuel (l) | Total Distance (m) | Average Speed (km/h) | Maximum Speed (km/h) | Production (T/h) | Production (BCM/h) | Fuel Usage (l/h) |
|-------|-------------|------------------|-----------------|-------------------|------------------|---------------|-----------------|----------------|--------------------|----------------------|----------------------|------------------|--------------------|------------------|
| 1 | ATRF example | 0.00 | 1.49 | 0.88 | 2.37 | 4.3 | 1.2 | 5.5 | 880 | 22 | 43 | 2,221 | 733 | 138.4 |

Segment Summaries

Haul Route — ATRF example — Return Route

| Seg | Description | Time (min) | Cumulative Time (min) | Fuel (l) | Maximum Speed (km/h) | Seg | Description | Time (min) | Cumulative Time (min) | Fuel (l) | Maximum Speed (km/h) |
|-----|-------------|------------|-----------------------|----------|----------------------|-----|-------------|------------|-----------------------|----------|----------------------|
| 1 | E | 0.19 | 0.19 | 0.5 | 20 | 1 | D | 0.05 | 1.54 | 0.2 | 18 |
| 2 | D | 0.23 | 0.42 | 0.7 | 32 | 2 | D | 0.03 | 1.57 | 0.1 | 20 |
| 3 | E | 0.40 | 0.82 | 1.3 | 32 | 3 | E | 0.03 | 1.60 | 0.0 | 20 |
| 4 | D | 0.28 | 1.10 | 0.9 | 12 | 4 | F | 0.20 | 1.80 | 0.6 | 43 |
| 5 | F | 0.28 | 1.38 | 0.8 | 30 | 5 | B | 0.09 | 1.89 | 0.0 | 35 |
| 6 | B | 0.03 | 1.41 | 0.0 | 20 | 6 | E | 0.14 | 2.03 | 0.1 | 40 |
| 7 | F | 0.03 | 1.44 | 0.1 | 25 | 7 | C | 0.16 | 2.20 | 0.1 | 40 |
| 8 | A | 0.05 | 1.49 | 0.0 | 23 | 8 | C | 0.17 | 2.37 | 0.1 | 20 |

\Sim 1 /Sim4 /Sim 3 \Sim P4/

Print     Export Data     Close

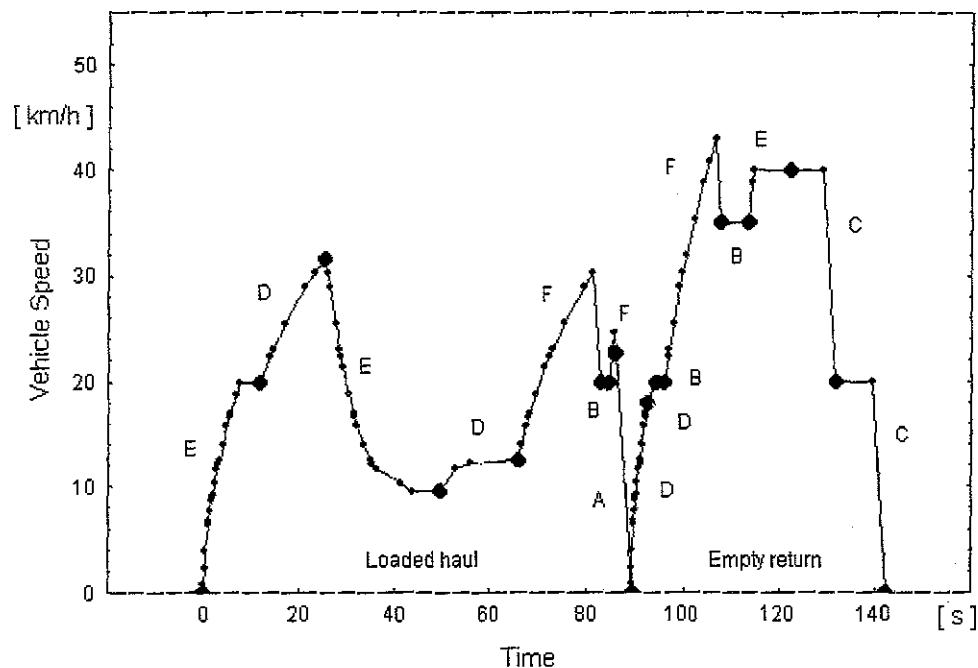**Figure V    Simulator results window**

**Figure VI     Haul and return speed profile**

Figure VI is a graphical representation of the numerical results in Figure V. Unlike Figure V, it presents segments (large points) as well as subsegments (small points) as generated by the simulator. Segments in Figure VI have been classified according to the operation modes described in Table I.

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. Cornering drag and cornering speed limits are disabled for the comparison with *VEHSIM* in Figure VII.

*Description of operating modes:* In the first segment (E) in Figure VI, the truck accelerates on zero grade and reaches the segment speed limit, continuing to cruise until the speed limit is eased in the next segment. (D) The vehicle can now continue accelerating at full throttle to the end of the segment. The vehicle continues traveling at full throttle in the next segment (E) but the vehicle is now decelerating because of the steep grade, reaching cruising speed at which all forces acting on the vehicle balance. In the next segment (D), the grade is only slightly eased, so the vehicle initially accelerates, but rapidly begins to approach a new cruising speed that is not quite reached before the segment ends. In the next segment (F), the vehicle accelerates on zero grade, but is rapidly approaching a tight turn and needs to start braking before the segment ends.

The classification system in table I can be used to follow the operation of the vehicle for the rest of the journey.

## Result validation

The Macmahon Earth-Track system will soon be able to record actual vehicle speed profiles by combining rapidly updated GPS position data with the truck's payload management system. This will be an ideal tool to not only provide hard data for model validation, but also show where and why model results deviate from actual driving behavior. This should lead to a better understanding of the factors involved and their relative importance, with the aim of producing a more accurate and realistic model

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 cannot be compared as *VEHSIM* lacks this feature

Using road and vehicle data from Figure II and IV, *VEHSIM* results are presented in figure VII for comparison with results in Figure V

| | | | |
|---|---|---|---|
| HAUL TIME = | 1.48 | PAYLOAD = | 87.7 MTON |
| | | PROD./60 MIN.HR. = | 2,223.2 MTON |
| RETURN TIME = | 0.89 | | |
| CYCLE TIME = | 2.37 | OPER. MIN/HOUR = | 60 MIN |
| TRIPS/HOUR = | 25.35 | PROD./60 MIN.HR. = | 2,223.2 MTON |
| CYCLE DIST. = | 880 | | |
| AVG.SPEED = | 22.3 | OPER. HR. REQ'D. = | 0 |

This is a part of the results generated by *VEHSIM* using the same road and vehicle data. Note the agreement with the described model and results in figure V.

**Figure VII    Comparative *VEHSIM* results**

## Conclusion

A 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 By costing operation under various conditions, the model facilitates the optimization of the earthmoving operation as well as predicting the cost of running the equipment for future tendering. Furthermore, the model could be integrated into a discrete transaction based simulation model of an entire earthmoving operation, facilitating the evaluation of various strategies for optimum operation for maximizing productivity while minimizing operating costs. These models permit the application of 'fine tuning' that will increase the productivity of mining operations and enhance the planning of mining and earthmoving operations.

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## References

Anonymous (1996) Surface vehicle recommended practice *Commercial truck and bus SAE recommended procedure for vehicle performance prediction and charting* J2188 USA: SAE

Anonymous (1993) Runge Mining Software *Talpac Reference Guide* Australia: Runge Mining

Anonymous (1992) *Caterpillar Performance Handbook* (24th Edition) Peoria USA: Caterpillar

Anonymous (1991) CAT FPC *Caterpillar Software manual*, appendix pages C1-X2 Peoria USA: Caterpillar

Anonymous (1987) CAT VehSim *Caterpillar Software manual*, appendix pages A1-K2 Peoria USA: Caterpillar

Boulton C B and Blair J R (1980) A performance simulator for heavy dump trucks *IFAC Mining, Mineral and Metal Processing*, Montreal Canada: IFAC

Dinovitser A (1996) Haulage truck simulation model *18th Conference of Australian Institutes of Transport Research (CAITR)*, Queensland University of Technology 2-4 December 1996: QUT

Macmahon (1996) *Earth Track* project brochure: Macmahon

Mannering, F L and Kilareski P W (1990) *Principles of Highway Engineering and Traffic Analysis*: Wiley

Mincom (1997) Press release Internet: *http://www.mincom.com/press/pr_caterpillar.html*

Morgan WC and Bremenkamp (1991) JR *VEHSIM vehicle simulation* version 2.21 Peoria USA: Caterpillar

Morlok E K (1978) Individual Vehicle Motion *Introduction to Transportation Engineering And Planning* chapter 4 pages 115-173: McGraw-Hill

Philippou M and Wingard B (1995) Quantifying the benefits of the Macmahon Productivity Management System *Investigation project final report*: University of South Australia

Smith G L (1970) Commercial vehicle performance and fuel economy *SAE transactions* 700194 USA: SAE