

Detailed Haul Unit Performance Model

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(Abstract)

In order to make a profit in any earthmoving operation it is important to plan the operation, select the appropriate equipment and use the haul units efficiently in order to obtain the maximum productivity. Maximizing productivity is one of construction project management personnel's primary objectives, but can also be one of their greatest challenges. The need for effective productivity planning is obvious since productivity ultimately translates into profit. In order to plan an earthmoving operation it is important to understand the travel times of the hauling equipment. Travel time is a variable that, in turn, depends upon other variables associated with the haul unit, and the haul road conditions. Presently there is no travel time model that appropriately considers these factors and simulates the interactions among them such that more detailed analysis could be performed. Such a model needs to be developed. The objective of this research is to develop a detailed model to simulate the travel time considering, in the amount of detail needed, the variables upon which travel time is dependent. The key in the development of the model is the calculation of acceleration. The simulation of how instantaneous acceleration varies may be a complex procedure because instantaneous acceleration is a function of numerous variables, many of which are in turn functions of the velocity and position, which are themselves integral functions of acceleration. The acceleration of a vehicle is dependent on the vehicle characteristics, road conditions, and operator. It is very difficult to consider changes in instantaneous acceleration by using analytical procedures. A numerical method should be used in order to analyze the complex system and determine the travel time or velocity profile of the vehicle. MATLAB™ software was used to analyze and solve the complex system numerically. A model that considers that the machine is working at full capacity was developed. It considers the variables that affect travel time in the amount of detail needed. The impact that the operator has in the machine performance can be highlighted after a comparison of the results obtained with actual field data, once the model is calibrated.

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Chapter 1: Introduction

Construction heavy equipment is of extreme importance in earthmoving operations. This equipment facilitates the transportation of soil from the point of cutting to the point where it will be used as fill or to the point where it will be wasted or stockpiled. These machines have been used since the earliest times to reshape the ground so that it can be used as intended by designers or owners. Over time, construction equipment has evolved to the modern and sophisticated equipment used today in earthmoving operations. Moving materials and leveling the ground to meet the needs of the owner are the primary functions of heavy equipment. The productivity of this modern equipment has increased with the increase in sophistication and modernization, thus allowing the cost of the operations to remain relatively stable. Inefficiencies and loss of productive time can result in increases in cost, because of the high cost associated with such equipment (Nunally, 1977).

The purpose of this chapter is to introduce the presented research. The concepts that are important for the development of the research are discussed. The statement of the problem and the purpose of this research are outlined. Along with the benefits of successfully completing the research, the basic premises of the research and its scope are explained.

1.1 HEAVY CONSTRUCTION EQUIPMENT

Heavy construction equipment is used to assist in moving material from the load area to the dump area. Hauling units (i.e. trucks and wagons) are used to haul materials. These hauling units operate at high speeds, when operating under suitable road conditions, therefore the unit hauling costs associated with them are low. Scrapers can load, haul, and dump loose material. Trucks have a better hauling capacity than scrapers, however scrapers can both load and haul, which gives them an advantage in hauls less than a mile (Peurifoy, 1996).

The cost of most of this heavy equipment can reach millions of dollars for very large units. The purchase of most of this heavy equipment requires the buyer to spend a considerably large amount of money. The goal of every contractor in every job is to make a profit (Mitchell, 1998). In order to make a profit in any earthmoving operation it is important to plan the operation, select the appropriate equipment and use the haul units efficiently to obtain the maximum productivity.

1.2 PRODUCTION PLANNING

Project managers should always try to maximize productivity. Maximization of productivity can present a big challenge to project managers. Productivity is generally defined as the ratio of useful work output to the time spent to complete that work. Adequate productivity translates into profit, therefore it is very important to plan productivity effectively (Perdomo et al., 1999). Effective planning and execution of a project is very important to survive in a highly competitive environment such as construction (Nunally, 1977). Projects that involve the movement of high volumes of soil require effective planning and execution because of the expensive equipment involved and the repetitive nature of the work. If the work is performed without inefficiencies and it is planned carefully, this could produce savings in cost and time. Many researchers had have studied earthmoving operations to improve productivity, thus decrease costs and maximize productivity (Martinez, 1998). The complexities, great variability, and numerous uncertainties associated with earthmoving operations can make productivity estimating and planning extremely difficult. In order to plan an earthmoving operation it is important to understand the times required for hauling equipment to travel over the various segments of the haul road. Travel time is a variable that depends on other variables associated with the haul unit, the operator, and haul road conditions.

Many civil engineering construction projects involve earthmoving operations. In highway projects as well as in building construction, earthmoving operations are used to level the surface. This leveling is accomplished by cutting or filling, thus preparing the ground to serve the needs of all parties involved. In some of the projects, earthmoving operations

are the major activity of the project. Adequate planning of activities, implementation of the plan and utilization of the appropriate tools are very important to complete a successful operation, thus finishing the project in time and within budget. Earthmoving operations have been planned using a combination of tools, as have many other activities in construction (Smith et al., 2000). In order to plan an earthmoving operation it is very important to understand the travel times associated with the haul unit. When calculating cycle times for a haul unit, the time taken to load, haul, dump and return need to be considered. The nature of these activities induces variability into the cycle time. The haul and return activities have a high variability, because of the factors upon which they are dependent. These travel times are variables that in turn are dependent upon other variables associated with the haul unit, and road conditions. In order to calculate accurate travel times it is important to consider the factors that affect the haul unit performance along the haul road. Traditionally, this travel time has been estimated by using manufacturer's charts. By using these charts an estimated travel time can be obtained. This estimated travel time does not consider changes in equipment performance (deterioration because of usage) and the variation of the characteristics of the haul road (rolling resistance) along the segment, among numerous other factors.

1.3 STATEMENT OF THE PROBLEM

Travel time is an essential component in the simulation model for the study of an earthmoving operation. Describing the travel time for hauling equipment is a time consuming activity. Assuming that the equipment can be observed on a specific haul road, data has to be collected and analyzed to determine the value that better describes the travel time of the observed equipment.

Discrete event simulation is a very useful tool for the design and analysis of earthmoving operations because it can consider most of the uncertainties and logic associated with them. Simulation tools exist that can model construction operations in detail (e.g. STROBOSCOPE). Among other things, for these simulation tools to generate accurate results, accurate descriptions of the duration of all the activities need to be input. The

inputs that describe the travel times for hauling units should consider equipment characteristics and haul road conditions in detail. The available models do not consider the equipment characteristics (i.e. efficiencies, reductions, power curves, etc.) in the amount of detail needed. Such a model needs to be developed in order to perform more sophisticated studies. This model should incorporate the amount of detail needed about the road conditions and equipment characteristics. Figure 1.1 illustrates the ideal conditions to develop a model, the available models and where the developed model fits.

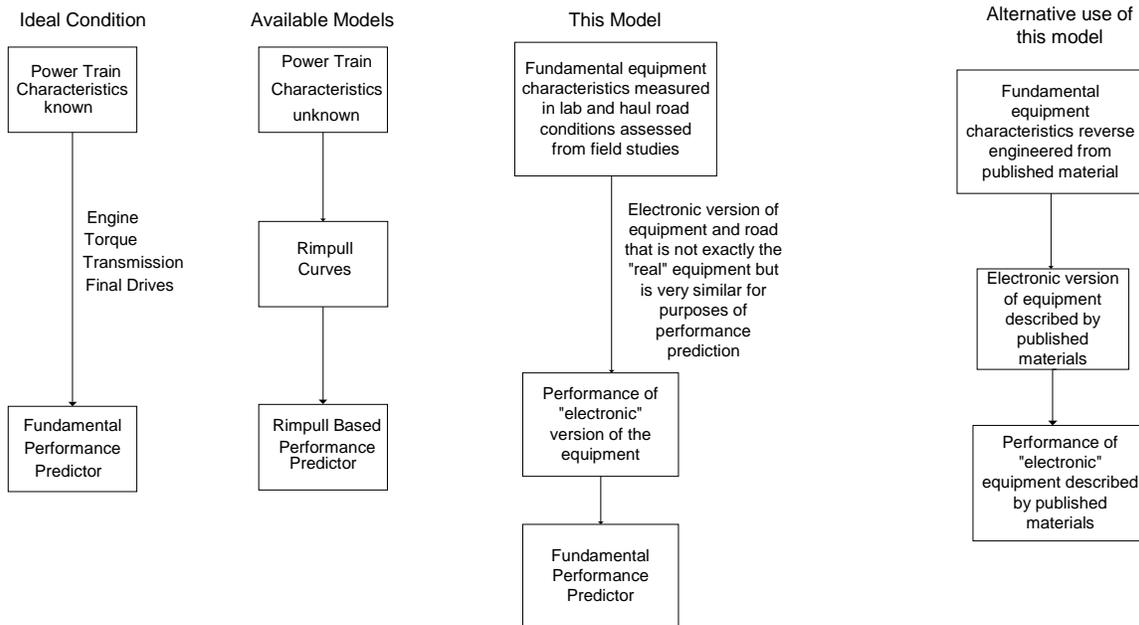


Figure 1.1: Ideal conditions, Available models and where the model fits

The ideal condition will be one in which the manufacturer discloses all the fundamental data about the machine, such as characteristics of the engine, transmission, and final drives. With this information a fundamental performance predictor could be developed. The available models start calculations from rimpull curves, since fundamental data are not available; therefore they are rimpull based performance predictors. Examples of such models include TALPAC and VehSim. In the model developed as part of this research, if the fundamental equipment characteristics are measured in a laboratory and the haul road conditions are assessed from field studies, an “electronic” version of the equipment can

be analyzed. This “electronic” version of the equipment is not exactly the “real” equipment but is very similar for purposes of performance prediction. An alternative use of this model is to obtain the fundamental equipment characteristics from published material using a reverse engineering process. An “electronic” version of the equipment, based on published material, can be analyzed. The model will predict the performance of the “electric” equipment described by the published material.

1.4 PURPOSE OF THE RESEARCH

The purpose of this research was to develop a model to calculate travel time from a fundamental level considering equipment characteristics such as efficiencies, and reductions, as well as other characteristics that have an effect on the haul unit performance. In order to develop the model, the parameters that have an impact on the performance of the equipment were identified. However, the measurement and description of these parameters in the field was not conducted. The purpose for the development of this model was two fold. First this model can be used, as it is, to calculate travel time in earthmoving operations and to monitor equipment performance along the haul road. Second and most important, this detailed model is the basis and foundation for the development of many other models in future research such as probabilistic travel time, fuel consumption, brake heat buildup and wear, etc. The amount of detail provided allows extensions such as these to be easily included.

1.5 OPPORTUNITY TO ACCOMPLISH THE RESEARCH

Many variables in science and engineering depend upon other variables. In order to solve these problems and get results for these variables, the values for other variables upon which they are dependent should be found first [Benjamin and Cornell, 1970]. Travel time is a variable that is a function of other variables such as rolling resistance, grade, and characteristics of the haul road, engine, transmission, and gross weight of the vehicle. Previously, the analysis of a variable that is dependent upon other variables, such as travel time, required a complicated and difficult analysis (i.e. the analytical solution of

several complex differential equations). Mathematical software now exists that is capable of solving complex differential systems numerically. MATLAB™, for example, is capable of solving complex differential systems. MATLAB™ was used to solve the complex differential relations between the involved variables, and also to incorporate the proper level of detail. It is possible to determine the speed and distance traveled at any time, by supplying a function that calculates acceleration given equipment characteristics and road conditions.

1.6 LIMITATIONS AND ASSUMPTIONS

Models, such as the one developed as part of this research, are representations with assumptions. Like many models, this model is an approximation that might not exactly represent what is taking place in the field, but it is a good approximation of the process being modeled. This section presents the limitations and assumptions considered while developing the model.

The limitations of the model and research are:

- The parameters that may affect equipment performance are described in Chapter 3. However, the relation between the value of the parameters and the actual performance metrics were not field validated.
- It is assumed that the operator will always operate the machine to maximize performance when the machine is accelerating and decelerating due to road characteristics not braking. In reality, however, the operator will not operate the machine at maximum performance throughout the haul segment and it might be possible that the operator never operates the machine at maximum performance in a certain segment.
- Multiplication of torque due to the effect of the torque converter, as well as electronic devices in the engine, was not considered explicitly. The details on how the torque converter works are complex and difficult to analyze analytically. A description on how the torque converter works is given in Chapter 3. In order to model the torque multiplication due to the effect of the torque converter, a

detailed study of the flow of the hydraulic fluids inside the torque converter needs to be done. This study of hydraulic flows is out of the scope of this research. No mathematical model that describes how the torque converter works was found. However, an analytical representation on how the torque converter works was done as part of this research. The details on this analytical approximation are given in Chapter 4. Electronics devices are used to adjust the power and torque curves; therefore if these curves are adjusted they should be measured in the field using a dynamometer to get an accurate description of the engine. The range of RPM for gear change can be programmed. Vehicle speeds can be limited by programming the engine (Brady, 1997).

- Hydraulic retarders are used to maintain a steady speed when the vehicle is traveling downhill. The retarder is not considered in the study. A description of how the retarder works is given in Chapter 3. Engine retardation is used to maintain a maximum speed. A distinction between engine retardation and hydraulic retarder is presented in Chapter 3.
- The way in which the braking system works and the heat builds up due to braking were not considered explicitly.
- The only characteristic that the vehicle carries from one segment to the next is the velocity. The vehicle does not carry the momentum from the previous segment.

The assumptions while developing the model are:

- The power curve is constant for all gears. Although the band may not be perfectly constant it is, according to Chuck Kroll of Carter Machinery Inc., a good approximation to assume that it is constant in all speeds and gears.
- It is assumed that the operator is capable and willing to obtain the maximum performance possible when the vehicle is not braking. In other words the operator is applying pressure to the throttle at 100% at all instances that the vehicle is not braking.
- A constant deceleration is used to simulate braking effect.

1.7 SCOPE OF THE RESEARCH

In order to develop the model, the parameters that may appear to have an effect on the equipment performance were identified and are described in Chapter 3. However the measurement and description of these parameters in the field was not conducted. The model considers road conditions and equipment characteristics, except braking system, and retarder, to calculate equipment performance. An analytical procedure is used to approximate the torque converter.

1.8 BENEFITS OF THE RESEARCH

The primary benefit of this research is to provide a tool that enables users to make better decisions while planning an earthmoving operation. The user is able to model equipment performance from basic fundamental principles for every haul unit in the conditional space defined by the haul road conditions and equipment characteristics. As a result, the user is able to plan earthmoving operations and estimate total project time in an accurate way. The user can simulate different scenarios with different equipment in order to find the best-case scenario, which will give the lowest project completion time and project cost by finding the configuration of equipment that gives the best productivity.

1.9 THESIS OUTLINE

This thesis describes the detailed equipment performance model developed. The chapters are written in a way that the reader can understand the process and parameters used while developing the system. The chapters should be read in order, so that the reader can follow the motivation and need behind the development of the model, and the parameters considered in the model and why these parameters are considered. Chapter 1 presented an introduction to this document and to the work performed. Chapter 2 presents a review of the previous work performed in the area of estimating travel time for hauling equipment in earthmoving operations. In addition, this chapter presents some computer programs used in planning earthmoving operations. Chapter 3 describes the parameters that affect

equipment performance, thus affecting the value of travel time. Chapter 4 describes the methodology to calculate efficiencies and reductions for construction equipment developed as part of the research and the analytical representation to approximate the torque converter. Chapter 5 explains the methodology used to develop the performance model and the model itself. A discussion of the process for power transfer from the engine through the transmission until it reaches the area of contact between the wheel and the surface is presented. Chapter 6 presents an analytical validation of the model. In addition, the chapter presents a comparison of the values obtained from the program with the output from two commercially available programs for planning earthmoving operations, Truck and Loaders Productivity and Costing (TALPAC) by Runge Mining Systems and VehSim by Caterpillar. Chapter 7 presents a brief summary of this research, the accomplishments, and directions for future research. The References are presented after the conclusions. Appendix A presents a User's Manual for the program and Appendix B presents the Source Code Listings. Appendix C presents the data used to compare the rimpull curves.

Chapter 2: Literature Review

This chapter presents a review of the previous work performed in the area of estimating travel time for hauling equipment in earthmoving operations. In addition, some computer programs used in planning earthmoving operations will be presented. The chapter will present manual methods followed by computer models that are commercially available and computer models developed as part of research studies. In addition, some practices recommended by the Society of Automotive Engineers (SAE) for vehicle performance prediction are presented.

2.1 TRAVEL TIME CALCULATION

The issue of estimating travel times for haul unit equipment has been studied before and some models have been developed. Different methods can be used to estimate productivity and to plan earthmoving operations. Both manual and computer-based methods have been developed. In both methods, the calculations are based on equipment performance specifications and the field conditions that are expected. The values obtained with either method are highly dependent on the accuracy of the information available and assumptions used to calculate the travel time values that are used in the estimation of productivity (Perdomo et al., 1999). Several models have been developed to estimate travel time. The most sophisticated models consider acceleration, rolling resistance, length and grade when calculating vehicle performance. Most documented models however, involve very little detail.

2.2 MANUAL METHODS

In order to use manual methods, the estimator has to collect information from company records such as equipment specifications and performance characteristics, manufacturer literature, and/or handbooks. In addition, expected project conditions need to be estimated. With the information available, then the estimator has to calculate equipment performance under those conditions. The amount of data collected can be huge and the estimation process becomes very tedious and is prone to error. When production records

are not available the estimator has to rely on manufacturer's literature to estimate the performance of the equipment. This information will allow the planning and scheduling of a project. In addition, this information can be used for bidding purposes. Manual methods can be time consuming, tedious, require intensive labor, and are prone to error. Because of the above and the high variability in the factors that affect travel time, manual methods fall short as production planning tools (Perdomo et al., 1999).

2.3 METHOD OF DISTANCE AND CONSTANT SPEED

This method is based on calculating the speed of the vehicle from rimpull curves or fundamental data. The problem with this method is that it disregards the acceleration and deceleration periods.

2.4 COMPUTER BASED METHODS

Computer programs to assist estimators in productivity planning have been developed in recent years. These programs have proven to be a valuable tool for estimators for productivity planning. These programs were intended to be used to aid in equipment sales and maintenance. Equipment manufacturers and independent software developers developed these programs. Some of these programs are commercially available (Perdomo et al., 1999). There are other systems that are also computer based, which have been developed as part of research studies. A general description of some of these systems follows.

2.4.1 PLANNING AND DESIGN SYSTEMS

Planning and Design Systems were developed to be used by equipment sales personnel. They include specifications and performance information in a database of construction equipment. This information is needed to perform the calculations. The user can specify the conditions under which he wants to calculate equipment performance and productivity. The advantage of having the equipment information in a database format is that the estimator does not have to search company records for the information and does not have to rely on his knowledge of a particular piece of equipment. In addition, since

they are computer based, comparison of performance for different types of equipment can be done relatively quickly (Perdomo et al., 1999).

Many contractors have recognized that these systems can be used for productivity planning and design. The calculations performed in these programs are the same calculations that an estimator will perform when using a manual method. Since these systems are computer based, the estimator can simulate different equipment configurations with the information that he has about the job site even before the project begins. Factors that cannot be considered when using manual methods can be considered while using computer based methods, because computers can handle complex calculations (Perdomo et al., 1999). A description of three Production Planning and Design software tools follows.

2.4.1.1 VEHSIM

VehSim was developed by Caterpillar. This DOS based program is designed to estimate haul unit performance by simulating the operation with the parameters given by the user. The inputs to this program include machine to be used (selected from a database), productive minutes per hour, haul road initial velocity, haul road final velocity, return road initial velocity, return road final velocity, material density, distance, rolling resistance, grade, speed, tire size, empty weight and fixed time. The outputs of the program are cycle time, trips per hour, average speed, operating minutes per hour, productivity, and haul and return times. This system is a black box, it is not extendable, and cannot interface with other tools. It is left to the belief of the user that this program does the right calculations and considers assumptions appropriately. Many are not comfortable with such systems.

2.4.1.2 THE FLEET PRODUCTION AND COST ANALYSIS (FPC)

The Fleet Production and Cost Analysis (FPC) was developed by Caterpillar Dealer Channel Systems Group (Caterpillar, FPC 1996). This DOS based program is designed to

assist with determining the most efficient equipment fleet for a project involving earthmoving or other material handling. FPC can estimate the productivity of the fleet, the cost of using the fleet, and the time required for the project. FPC allows the user to enter one or more courses over which the earthmoving operation will occur. The user describes the course by inputting various factors, including distance, rolling resistance, grade, speed, and any passing restrictions. Each course can also be divided into various segments with different properties. This program has the same limitations as VehSim, but it has some extra features.

2.4.1.3 TALPAC (TRUCK AND LOADER PRODUCTIVITY AND COSTING)

TALPAC is a truck and loader simulation system. The program has a database of trucks and loaders from manufacturers worldwide. The system uses a stochastic method of simulating the operation of trucks and loading equipment over a specific haul profile. TALPAC allows the study of most factors affecting productivity and the sensitivity of productivity to these factors. The user specifies the haul route in which the truck will operate, which truck or group of trucks is to be used, and what operating limitations are set (e.g. speed limits, final velocities, etc.). In addition, TALPAC can be used to analyze scraper productivity. TALPAC takes raw data in the form of truck and loader performance information, haulage profiles, and equipment costs to perform a number of functions at the user's request. These functions include Loading Analysis, Production Analysis and Optimization of Fleet Size, Motor Power, and Payload. The results include travel time, equipment productivity, and costs. Unlike Caterpillar products, TALPAC includes clear and concise explanations of how it determines equipment performance. There are several limitations. The simulation capability is very limited and lacks flexibility for operations planning purposes. It provides no facilities for modeling routing strategies or strategies to deal with constrained haul segments (e.g. narrow), interactions with traffic, and interactions with other dynamic and simultaneous operations such as compaction and material preparation. The travel time is based on the rimpull curve, which prevents extensions that are based on fundamental issues such as engine RPM

history. Examples may include fuel consumption, heat buildup in braking system, and a host of other analysis that might subsequently be based on the engine and transmission. The system cannot be integrated nor integrate other tools, therefore it has to be used only as intended by its designers.

2.5 OTHER COMPUTER-BASED METHODS

Bulton and Blair (1980) developed a simulator to predict performance of heavy diesel electric dump trucks. The purpose of this simulator was to provide a realistic prediction of speed and fuel consumption over a specific road, and as an aid for optimizing truck operations. A modular programming was used in order to model different types of trucks and operator's behavior. The truck and driver are presented separately in major modules. The driver module is divided into braking and accelerating conditions. The results obtained with the simulator were compared to instrumented trucks and supposedly these tests confirmed that the simulator produced realistic driver and operator behavior.

According to Karafiath (1988), the analysis of hauling alternatives requires the estimation of performance of haul vehicles under the various road conditions encountered along the route. Rolling resistance and grade are the main site characteristics that affect the performance of haul vehicles. He points out that the present methodologies used to estimate rolling resistance are not adequate and are uncertain. Karafiath suggests that RR is not constant and that it varies between driving and trailing wheels. In addition, he suggests that the estimation of haul unit performance can be done by using the values of RR and the Rimpull-Speed relationships supplied by the manufacturer.

Bang (1998) developed a model to estimate travel times for buses between stations. In this model he used simple dynamics equations to describe the movement of the buses. This model considered the position of the throttle as an independent variable because the other parameters such as grade, length, rolling resistance, demand, and traffic conditions could not be controlled. This bus simulation model yields profiles of speed, travel time, and fuel consumption as outputs. Factors such as maximum speed, wind drag

coefficients, vehicle acceleration, and deceleration are used as variables in the bus operation simulation model.

Kannan (1999) adapted Bang's model to calculate truck travel time. The engine power is considered as constant, and as a result a smooth curve for rimpull against speed is used.

Smith et al. (2000) proposed a methodology for estimating travel time for haul units. The most important factor considered in this methodology is the rolling resistance. This methodology proposes a back calculation of rolling resistance using established calculation tools such as VehSim (Caterpillar, 1987) and Accelerator (Accelerator, 1987). The estimation for travel time is performed using manufacturer's tables along with soil data taken from the field.

None of the models studied based their calculations on fundamental data. Previous models derive their parameters from rimpull curves. This approach is perhaps due to the fact that manufacturers do not disclose fundamental equipment characteristics. On the other hand, researchers possibly do not want to expend their time in developing a formal procedure to obtain these values. Moreover, the availability of rimpull curves discourages researchers from taking the additional effort of measuring the parameters in the field.

2.6 PROCEDURES OF THE SOCIETY OF AUTOMOTIVE ENGINEERS PRACTICES

The Society of Automotive Engineers (SAE) prepares some recommended practices for vehicle performance prediction. The practices that will be discussed here can be used to estimate vehicle performance and retarding performance. A brief description of these practices follows.

2.6.1 SAE J218 MAR96- SAE RECOMMENDED PROCEDURE FOR VEHICLE PERFORMANCE PREDICTION AND CHARTING

The procedure described by the SAE in this practice takes into account modern standardized methods for collecting and summarizing data that have an effect in vehicle's performance such as engine output, gross and net; transmission losses; drive train efficiencies; as well as road surfaces and air density variations resulting from altitude variations. The procedure does not address vehicle transient performance (acceleration, braking and cornering) nor does it address vehicles with torque converters or automatic transmissions. Vehicles equipped with modern electric engines can be analyzed using this procedure by adjusting the transmission ratios.

2.6.2 SAE J1489 JUN87 HEAVY TRUCK AND BUS RETARDER DOWNHILL PERFORMANCE MAPPING PROCEDURE

This procedure provides a uniform method for calculating and supporting the steady state control speed maintainable by engine, transmission or retarders employed by heavy trucks and buses operating in downgrades. It provides a method for predicting retarder performance in a specific vehicle using data describing retarder performance characteristics and vehicle design variables. It is intended to assist in the proper selection by watching stated performance capabilities against actual vehicle functional requirements.

These recommendations are consistent with the contents of the work done. Both sections include recommendations that were included in this work and that are not included in the systems studied as part of the research.

2.7 SUMMARY

This chapter presented a literature review that gave the background needed to understand this research and the chapters that follow. A review of previous research in the area of

estimating travel time for haul-units in earthmoving operations was presented. Most of the models presented here contributed to the development of the model developed as part of this research. It is very important to note that existing models start the calculations from rimpull curves. None of the existing models consider the efficiencies and reductions of the machine in the calculations.

Most of the previous models operate as black boxes, and are not extendable, therefore cannot interface with other tools, and must be used only as intended by its designers. Some of these models have very limited simulation capability and lack flexibility for operations planning purposes. They provide no facilities for modeling routing strategies or strategies to deal with constrained haul segments, interactions with traffic, and interactions with other dynamic and simultaneous operations such as compaction and material preparation. The travel time is based on the rimpull curve, which prevents extensions that are based on fundamental issues such as engine RPM history.

The next chapter will describe the parameters that affect equipment performance. This chapter provided the background needed to understand the model developed as part of the research.

Chapter 3: Parameters that affect Equipment Performance

As was mentioned in Chapter 1, travel time is a variable that in turn is dependent upon other variables associated with the haul unit and road conditions. The purpose of this chapter is to describe those parameters that affect equipment performance, thus affecting travel time. Parameters that might have an impact in the equipment performance such as engine, transmission, tire size; length of the segment, grade resistance, and rolling resistance among others will be discussed.

3.1 EQUIPMENT CHARACTERISTICS

Equipment characteristics play an important role in equipment performance under a specified set of road conditions. The Gross Vehicle Weight (GVW), size of the tires, available engine horsepower, reductions, and efficiencies will determine and contribute to vehicle performance. A brief description of the components that describe the characteristics of the haul equipment follows.

3.1.1 ENGINE

Most of the construction hauling equipment use diesel or gasoline engines. These engines burn a mix of air and fuel inside the same unit that turns the shaft. They are different from steam engines. Steam engines burn fuel to make steam; this steam is then passed to the engine that converts this steam to power (Nichols 1976). Diesel machines are commonly used in construction heavy equipment because diesel engines perform better than gasoline engines (Peurifoy, 1996). In addition, diesel engines consume less fuel than gasoline engines and have longer service lives. The fuel used in diesel engines has a higher heat value and acts with the heated air. Carburetors and ignition systems are not used in diesel engines since the fuel self-ignites when it is injected directly into the superheated air that has been compressed in the cylinder. The engine generates power by burning the mixture of air and fuel. This creates pressure against the piston that turns the

shaft (Nichols, 1976). In other words, the engine is used as the source that generates the power that the machine will use. Most of the modern heavy vehicles are equipped with electronically controlled diesel engines. These engines produce their best power at midrange rpm. Torque increases as the engine speed is reduced from its maximum rpm to the midrange rpm. The torque drops quickly when the rpm goes beyond the midrange rpm. The same is valid when the engine speed falls below the midrange rpm. Fine control of the torque and power curves can be achieved by programming the electronic devices in the engine. Electronic engines can develop higher horsepower and torque at lower engine speeds than mechanical engines (Brady, 1997). The way in which electronically controlled engines work was not considered in this study, however it can all be traced to changes in the power curve, which could be easily studied using this research as a basis. A brief description of the performance factors that describe an engine (e.g. Power, Torque) follows.

3.1.1.1 POWER

Power is used to describe the rate of work done during certain period of time. In other words the rate of work can be measured in terms of power or how many units of work have been done in a unit of time (Brady, 1997). In equation form this can be described as:

$$Power = \frac{work}{time}$$

The engine develops a piston force, which acts on a crankshaft of certain radius. This develops a crankshaft torque at a certain speed (Peurifoy, 1996). The output of an engine at certain revolutions per minute (RPM) can be expressed as horsepower.

The term power is commonly used to describe the output of internal combustion engines. Flywheel power is a standard rating typically used to describe a machine's power (Peurifoy, 1996). Power can be classified into two categories: Brake power and Indicated power. Brake power is the power developed by the flywheel. Indicated power is the

power developed within the cylinder based in the amount of heat released, but no frictional losses are taken into account (Brady, 1997).

Power rating can be classified into different categories (Nichols, 1976, Brady, 1997). The categories discussed by Nichols will be presented followed by the categories presented by Brady.

Nichols (1976) states that in order to understand an engine and its specifications, it is important to know the different kinds of power ratings. He classifies the power rating into seven categories. These categories are brake power, drawbar, net power, flywheel power, maximum power, intermittent power, and continuous power. Nichols' definitions for the different categories of power follow. *“Brake power measures the capacity of an engine to work in the range between maximum speed and maximum torque. Net power is brake power with drag accessories deducted. Flywheel power is engine power with or without accessories. Drawbar power is a tractor’s flywheel power less friction losses in the power train and track or tires. Maximum power is the most that an engine can develop for five consecutive minutes. Intermittent power is power that can be developed in changing load such as are provided by construction equipment. Continuous power is the rating for long life performance under steady loads such as deep well irrigation pumping.”*

Brady (1997) classifies the power ratings into seven categories. These categories are rated power, intermittent rated power, intermittent maximum, continuous power, intermittent continuous, shaft power, and road power. Brady's definitions for the different categories of power follow. *“Rated power refers to the net power available from the engine with a specified fuel injector fuel rate and engine speed according to SAE standard ambient conditions, elevation and air density. Intermittent rated is used for variable speed and load applications where full output is required for short intervals of time. Typical examples are shovels, cranes, scrapers and an off highway rear end dump truck. Intermittent maximum is used for applications that require maximum output. Long engine life between overhauls is of secondary importance or applications in which the*

load does not exceed 35% of the full load at average operating speed. Continuous power is used when an engine is running under a constant load for long periods of time without a reduction in speed or load. Intermittent continuous is used with operations that are primarily continuous, but have some variations in load, speed or both. Shaft power is the net power available at the output shaft of an application. Road power is the power available at the drive wheels, for example in a truck after losses due to the transmission, driveline and to other components.”

3.1.1.2 TORQUE

Brady (1997) states that the capacity of an engine to do work is defined as torque. Torque is defined as a turning force that is developed at the engine crankshaft. Nichols (1976) states that torque is the turning power of a shaft, which is not correct. Torque is the force of a turning shaft. Torque is defined by the following formula:

$$\text{Torque} = \text{Force} * \text{Distance (i.e. lever arm)}$$

The engine’s ability to overcome hills at low speeds depends on the torque and the transmission.

3.1.2 TRANSMISSION

Transmissions enable trade-offs between speed and force. They are designed to transmit the engine power to the rear axle differential, axle shafts, and then the road wheels through the propeller shaft (Brady, 1997). The number of revolutions of the axle is reduced, from those at the axle, the torque is multiplied, and in the process some power is lost due to non-perfect efficiencies. Efficiencies and reductions have two components, one dependent on the gear and one that is independent of the gear. The ratio of flywheel speed to axle speed is defined as reduction. The ratio of the power at the axle to the power at the flywheel is defined as efficiency (Martinez, 1997). The configuration of the

transmission places an important role in the transfer of power from the engine to the rear axles and subsequently to the area of contact between the wheel and the surface.

Modern heavy vehicles are equipped with torque converters in their transmission for automatic torque multiplication. This torque converter is used primarily when the equipment is operating in the first gear, for some equipment such as scrapers it is used in the second gear also, and it is not used in the other gears. The torque converter transmits the torque of the engine by using hydraulic fluid. The torque converter multiplies the twisting effort of the crankshaft by using this hydraulic fluid. The torque converter automatically engages and disengages power transfer from engine to the transmission with relation to the RPM. This is possible by using electronic devices connected to the flywheel. There is no power transfer when the vehicle is in neutral, because there is not sufficient fluid flow to drive the converter. The main components of the torque converter are the pump, the stator and the turbine. These components can be seen in Figure 3.1.

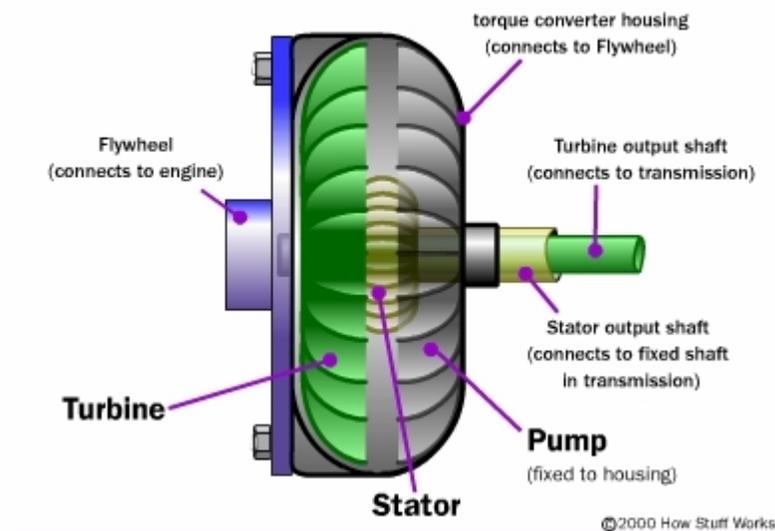


Figure 3.1: Parts of the torque converter (Source: howstuffworks.com)

The pump is used to direct pressurized oil against the turbine. The turbine is connected to the shaft to transfer power into the transmission. The stator is used to redirect the oil back to the pump after hitting the turbine. Torque multiplication can only take place when the

pump is turning faster than the turbine. The pump directs pressurized oil against the turbine. After hitting the turbine, this oil has more velocity due to resistance of the turbine, thus assisting the pump in the rotation, therefore multiplying torque. The greater the resistance of the turbine, the greater the torque multiplication. This is why the torque converter is mainly used in low gears (i.e. first and second), because the speed of the vehicle is low in these gears, therefore torque can be multiplied by the torque converter (Brady, 1997). Many torque converters are equipped with a hydraulic retarder. This retarder is located between the transmission and the torque converter. It has only one moving part called a rotor, which is part of the torque converter and the transmission (Brady, 1997). The retarder is a resistance mechanism that runs freely when it is empty, but slows the drive shaft when it is full with oil. This mechanism is used to slow down the machine or to maintain a steady speed. Travel times can be reduced when using a retarder because it is safe to travel in downhill grades at higher speeds (Road Star Online, 1999). The operator has to activate the retarder. When it is activated, oil flows into the rotor. This oil is pressurized and works against the vanes of the rotor, slowing it down and creating braking power to the rear wheels. Throttle has to be in idle position while the retarder is in operation (Brady, 1997). The effect of the hydraulic retarder is different from the engine retardation. When engine retardation is used, fuel is cut to the injector. The piston compresses the air. As the piston moves up compressing the air, an exhaust valve is opened to release the pressurized air. No explosion is created, because no fuel its been injected, therefore no power is created. This creates a loss in energy. The energy needed to move the piston down is taken from the engine, slowing it, therefore slowing the vehicle. This creates the braking effect. Although torque converter and retarders affect performance, they were not modeled from fundamental characteristics, instead, they were modeled by empirical approximations that mimic published performance data.

3.1.3 BRAKING SYSTEM

Brakes are used to slow, stop or hold a machine. The vehicle has a certain amount of kinetic energy and the brakes are used to remove the energy from the vehicle in order to slow it down or stop it. The primary function of the braking system is to turn the energy

of motion into heat by friction. The momentum of the machine is turned into heat when brakes are used. Metal bands are used to slow down the vehicle by applying them into a cylindrical drum. The drum converts the energy due to the movement of the vehicle into heat. The heat is generated faster when greater force is applied, thus creating greater stopping power. The brake drum has to have the capacity to store this heat and then dissipate it to the air (Brady, 1997). The force applied to the braking pedal varies depending on actual speed, road characteristics and operator's comfort. A detailed study is needed in order to model the amount of pressure that the operator applies to the pedal and the subsequent heat-build up in the drum.

Disc brakes work on the same basic principle of the drum brakes. The pads are pressed against a surface that is spinning to turn the kinetic energy into heat by friction. Disc brakes are similar to the brakes on a bicycle. In a bicycle, when the brakes are applied the pads are squeezed against the wheel. In a vehicle, when the disc brake is applied the brake pads squeeze the rotor instead of the wheel. The friction generated between the pads and the disc slows the disc down. Most disc brakes have a set of vanes that pump air into the disc to provide cooling (Nice, 2000). Figure 3.2 illustrates the parts of a drum brake system and of a disc brake system. The difference on how both system works can be seen from the figure. The way in which the braking system works and the heat builds up was empirically considered.

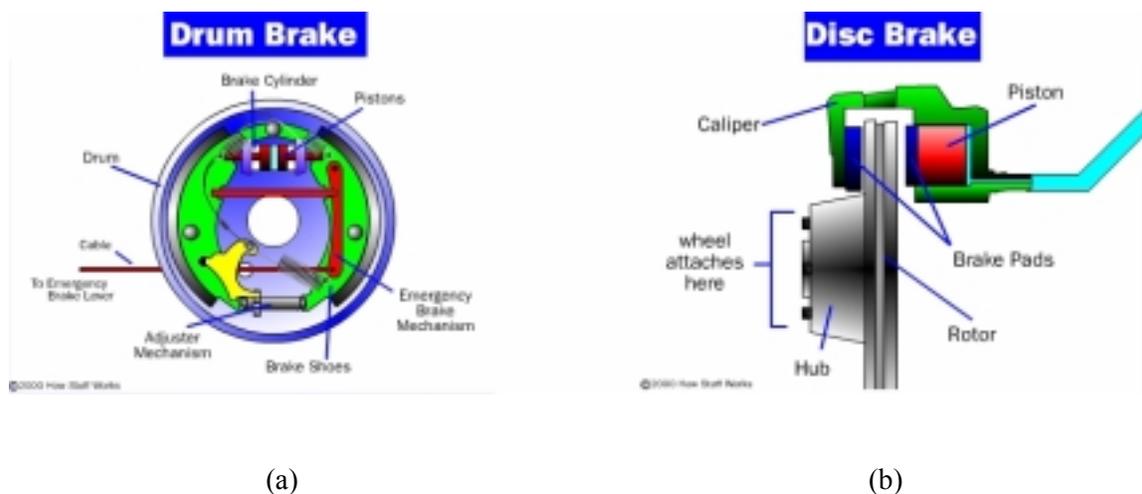


Figure 3.2 Parts of a drum brake system (a) and of a disc brake system (b)

(Source: howstuffworks.com)

3.2 HAUL ROAD CHARACTERISTICS

The characteristics of the haul road can affect the performance of the haul unit in various ways. The way in which a haul unit will operate in a haul road varies greatly with variations in the characteristics of the haul road (i.e. rolling resistance, grade, length). A brief description of these characteristics follows.

3.2.1 LENGTH

It is clearly seen from fundamental laws of Physics and Dynamics that length plays a very important role in travel time. The general formula is:

$$Time = length/velocity$$

It can be seen from the above equation that length is very important in the time taken by the haul unit to travel.

3.2.2 ROLLING RESISTANCE

Rolling resistance is the resistance to movement of a vehicle over a travel surface. There are some factors that affect the rolling resistance. Among these factors are internal friction, tire flexing, and penetration of the tire into the travel surface (Nunally, 1977). Nichols (1976) defines rolling resistance as the power consumed by the ground surface and tires as the vehicle moves. Some of the power absorbed is due to the flexing of the tire, and due to the interaction of the tire treads and haul road. TALPAC (1998) defines rolling resistance as the result of the frictional force that occurs between the truck tires and the ground, which is not true. In addition, they state that this force is perpendicular to the ground and acts opposite to the direction of motion of the truck and the greater the gross vehicle weight of the truck, the greater the rolling resistance. Karafiath (1988) states that RR is not constant and that it varies between driving and trailing wheels. The

type of soil and conditions of the haul road also determines the value of rolling resistance. Soft surfaces offer more resistance to travel than harder surfaces (Peurifoy, 1996). It is very important to keep a well maintain surface. A grader can be used to eliminate indentations in the ground and thus keep the value of rolling resistance as low as possible. The vehicle can move at higher speeds when traveling in a well-maintained surface, thus reducing the time taken to travel the segment. In addition, well-maintained surfaces reduce the cost of maintenance and repairs of the equipment.

3.2.3 GRADE RESISTANCE

A machine has to develop extra force to travel up an adverse grade. This force is referred as grade resistance. Grade resistance is the force opposing movement when the vehicle is moving on a slope. This is true for vehicles that are moving uphill. The force that a vehicle has to develop increases as the slope in which it is traveling increases. If the machine is traveling in a favorable grade (i.e. downhill) the rolling resistance should be able to coast down (Nichols, 1976). It is very important to consider the changes in slopes in highway projects. The slopes change with cut and fill operations. It is important to keep in mind these changes when selecting the layout of the haul road. The selected layout should maximize equipment productivity and performance. In addition, speed and fuel considerations should be considered when developing the layout. Vehicle speed and fuel economy are affected by adverse grades. In addition, adverse grades will increase tire wear, and maintenance costs (Nichols, 1976).

3.3 LOAD

Hauling load or payload is defined as the weight of the material that is being hauled. The payload capacity or load that the vehicle can carry is given by the manufacturer. It is important to know the capacity of the vehicle that is hauling to avoid overloading. Overloading causes accelerated wear of the machine and more frequent breakdowns (Nichols, 1976). The load of a hauling unit affects the value of rolling resistance. The

greater the load that the vehicle is carrying, the deeper the tire will sink under soft ground conditions. This will result in a higher rolling resistance (Nunally, 1977).

3.4 TIRE SIZE

The proper selection and maintenance of tires is one of the most important factors to consider in earthmoving operations. The productivity of haulers can depend greatly on the performance of its tires. The tires used in off road equipment should be able to operate under a variety of surface conditions. In addition, tires should operate under different weather conditions. Surface conditions, weather conditions, and maintenance schedule can have an effect in life of the tires.

The size of the tire is identified with the vehicle empty. The size is calculated as the width of a section of inflated tire and by the diameter of the rim where the tire bead rests (Nichols, 1976). The speed developed by a moving circular object varies proportionally with the radius of the wheel. This relationship can be seen in the following equation:

$$Speed = Circumference * RevolutionsPerTime$$

The rimpull developed in the area of contact between the tire and the surfaces varies inversely proportional to the radius of the wheel. The following equations describe this relationship:

$$Torque (axle) = Torque (flywheel) * efficiency * reduction$$

$$Rimpull = Torque (axle) / WheelRadius$$

Tire nomenclature is derived from an approximation of the cross section width and the rim diameter. For example a tire designated as 24R35, means that the approximate cross section is equal to 24 inches and the rim diameter is equal to 35 inches. The R denotes radial construction (Caterpillar, 1997). The radius of the wheel can be obtained by using the following procedure. Multiply the approximate cross section by the aspect ratio and

divide the rim diameter by 2. Add these numbers and that is the approximate wheel radius.

$$\text{Wheel radius} = \text{Approximate cross section} * \text{Aspect ratio} + \text{Rim diameter}/2$$

It is very important to select the proper tire size for the haul unit to achieve maximum speed possible, but keeping in mind the rimpull requirements.

3.5 SUMMARY

This chapter presented a description of the equipment characteristics, haul road characteristics, and other parameters (i.e. tire size, load), that affect equipment performance. The way in which each and every one of these parameters affects the performance of a haul unit was discussed. Reductions and efficiencies are very important to consider. Reductions reduce the number of revolutions and the power is reduced due to efficiency considerations. This reduction in power is due to non perfect efficiencies.

The concepts presented in this chapter presented the background needed to understand parameters considered in the model and the model itself. Chapter 4 presents the process developed to estimate efficiencies and reductions for haul units and the empirical approximation of the torque converter. This fundamental data is needed as input to the model. Chapter 5 will describe the process that takes place to transfer the power from the engine, through the transmission, until it gets converted into rimpull. This process is used as the basis to develop the model that considers the parameters described in this chapter.

Chapter 4: Methodology to Calculate Efficiencies and Reductions for Construction Equipment

Different types of machines can be used to transport materials, the haul traveling distance being very important for equipment selection. Existing roads, capacity of the ground, suitable courses, amount of material to be moved and the loading equipment available are factors, which are important to consider when selecting the machines to do the work in the most efficient and profitable way. Correct combination of loading and hauling equipment is important to obtain maximum profitability in the transport of materials. To adequately combine hauling and loading equipment it is necessary to consider the volume per unit of time and the total quantity of material to be transported (Volvo, 1995). The characteristics of the equipment play an important role when selecting the type of equipment to use in a specified earthmoving operation.

In order to perform accurate calculations the model requires fundamental data as input. This data can be measured in the field using mechanical procedures or in mechanical labs using dynamometers. Equipment manufacturers measure the values for these parameters, although they are not published. Instead, they use them to derive rimpull curves, which they may later adjust and do publish. Making some assumptions, the values of interest can be derived from rimpull curves published by the manufacturers using a process that will be described in detail. This chapter explains the methodology used to estimate the efficiencies and reductions for some of the Caterpillar trucks (i.e. rigid frames and articulated) and scrapers. Fabricators of heavy equipment expend a lot of time and money doing research about their equipment's components in order to produce the most efficient equipment. This information is confidential and is not given away by the fabricators because of the high competitive environment of their sector. In order to develop the model to simulate haul unit performance from a fundamental level this information is needed. The methodology used to estimate efficiencies and reductions is discussed in the next section.

4.1 METHODOLOGY

The process used to estimate efficiencies and reductions will be explained in this section. The calculation of the parameters was done for Caterpillar hauling equipment, however the approach and methodology used to determine the efficiencies and reductions can be applied to hauling equipment from any other manufacturer to determine the same parameters. The equipment manufacturer gives the maximum power that the engine can develop at a rated RPM. If a curve of maximum force that the machine can develop against speed is prepared and then this curve is superimposed to the rimpull curve of the equipment, the total efficiencies can be calculated. Figure 4.1 presents a rimpull curve and the theoretical horsepower curve given by the manufacturer. These curves are just for illustrative purposes and do not represent a particular equipment.

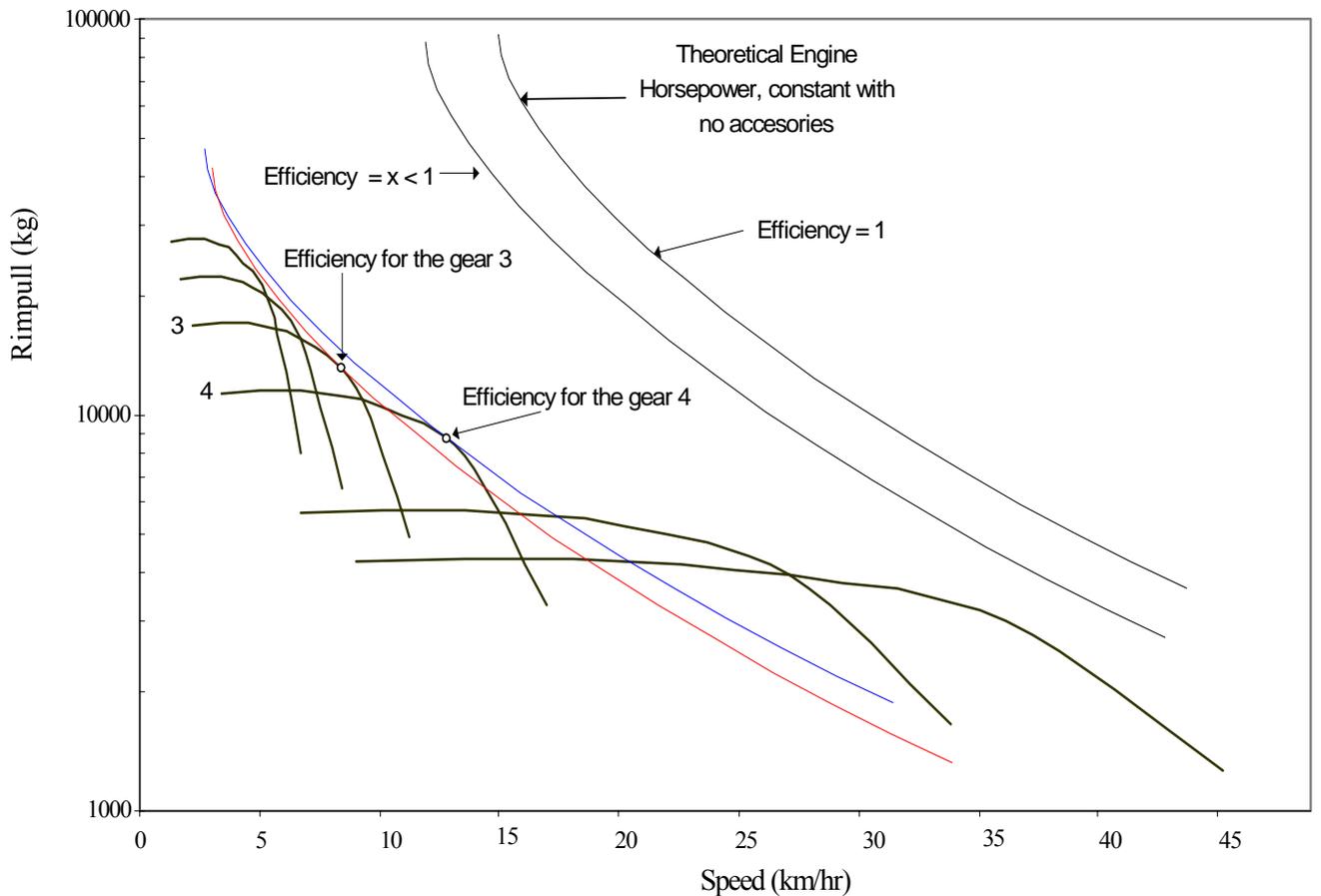


Figure 4.1: Rimpull Curve and Theoretical Engine Horsepower Curves

The power curve given by the manufacturer can be multiplied by a factor less than one. By multiplying this curve by a factor less than one, this curve will be lowered and will come closer to the rimpull curve. As it can be seen in Figure 4.1, the curve that was multiplied by a value of efficiency less than one is closer to the rimpull curve. The curve can be multiplied by various factors with magnitude less than one. When this curve touches the rimpull curve at a particular gear, the value of efficiency for that gear is found. The efficiencies for gears 3 and 4 are represented in the figure. At the points illustrated in the figure, for gears 3 and 4, the machine is working at peak torque at the current RPM. The power generated by the equipment is less than the maximum power that the machine can generate, the difference being the efficiency. This process has to be done in every gear in order to obtain all the efficiencies for the equipment. With the values of efficiencies known and with rated RPM of the machine known, then the reductions can be calculated. The following section will discuss an example for the calculations for efficiencies and reductions for a CAT350 Series II Articulated truck.

4.2 EFFICIENCIES AND REDUCTIONS FOR CAT350 SERIES II ARTICULATED TRUCK

This section will present an example of the calculation for the efficiencies and reductions for a CAT350 Series II Articulated Truck. The tools used and procedures will be presented and discussed. The calculation for the efficiencies will be first, followed by the discussion for the values of reductions.

4.2.1 EFFICIENCIES

The data needed for the calculation of efficiencies and reductions are the rimpull curves of the equipment, rated RPM and maximum power at rated RPM. For the CAT350 Series II Articulated the rated RPM is 2000 and the maximum flywheel power is 265 kW. This information is available in the CAT350 Series II equipment brochure. The rimpull curves were obtained from the Caterpillar Performance Handbook Edition 30. The first step in the process to calculate the efficiencies for the CAT350 Series II truck was to take data

directly from the rimpull curve. In order to get accurate data, these data were collected from a scanned rimpull curve using the program Datathief. This program allows getting points from a graph that is in digital format. This program proved to be very helpful as a data collection tool, because instead of reading the values from the performance handbook, they were collected directly from the rimpull curve, which increases the accuracy of the readings. In addition, the program allows to get more sample points from the rimpull curve, much more points than if it is done by inspection (i.e. using visual approximation), which eliminate gaps and allow for a better estimation of the value of efficiency. A sample data taken with Datathief is shown below. The left column shows values for speed in km/hr, while the right column shows values for rimpull in kg*1000.

Speed (km/hr)	Rimpull (kg*1000)
2.0	24
2.9	19
4.1	16
5.1	13
6.8	12
8.4	10
8.8	7.8

A screenshot of the program Datathief can be seen in Figure 4.2. The graph shown in the screenshot represents the rimpull curve for the CAT350 Series II articulated truck. Note that three points of data for the first gear are shown for illustrative purposes. The value for speed and its corresponding rimpull can be seen from the screenshot. Many data points such as those shown in the screenshot were taken to perform the analysis.

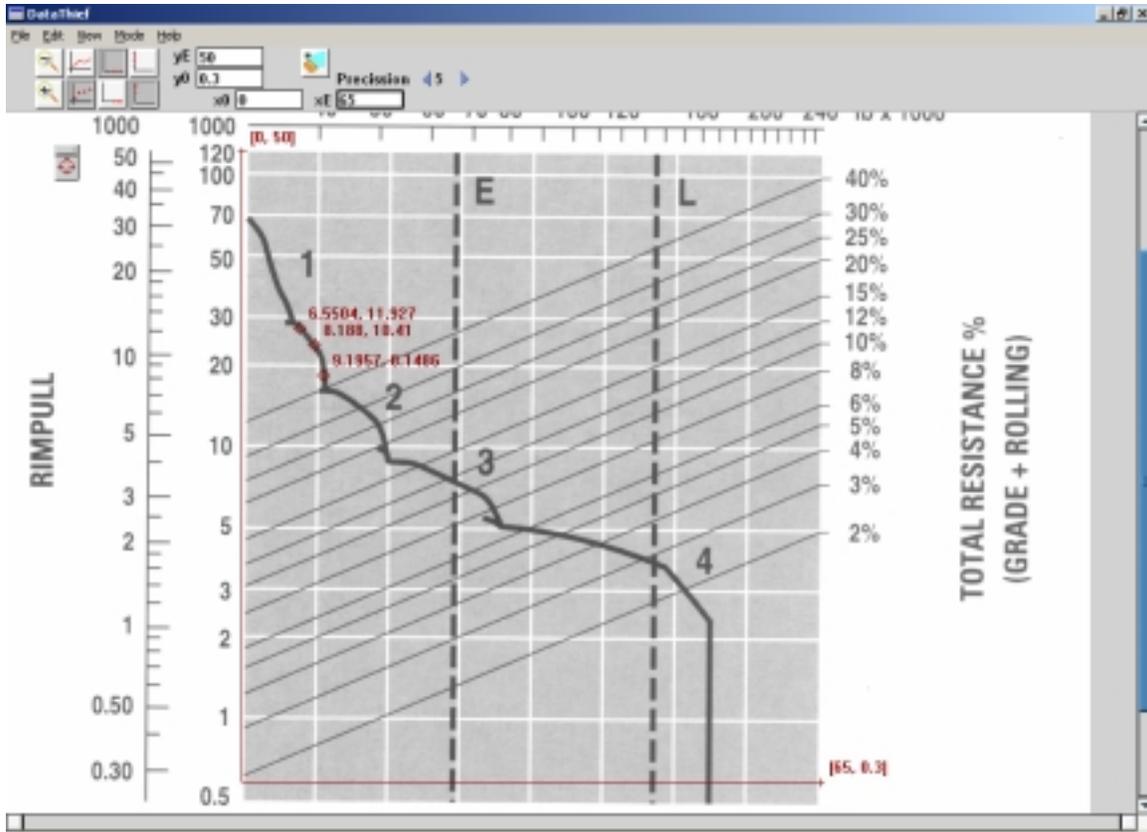


Figure 4.2: Screenshot of Datathief (Rimpull curve for a CAT350 Series II, Caterpillar)

Several values for speed and the corresponding rimpull were obtained for each gear. It is important to mention that the values where the torque converter was used were not considered while calculating the mechanical efficiencies and reductions for the gears for the trucks. The reductions of the equipment when the torque converter is used are hydraulic reductions instead of mechanical reductions. In the case of the scrapers, the torque converter is used always in the first and second gear, therefore the efficiencies and reductions calculated in those gears are hydraulic not mechanical. It was not possible to calculate mechanical efficiencies and reductions for the scrapers in those gears with the information available. The value of reductions in the torque converter area are greater than the values were mechanical gears are used. Once all the data was collected from the rimpull curves, an MS Excel[®] spreadsheet was developed for the calculations. The value of power that the vehicle can develop at current speed was calculated by using the following formula:

$$Power = speed * rimpull$$

Where the rimpull corresponds to the rimpull that the machine can develop at that value of speed. If we take the first value from the data shown above then the power will be:

$$Power = (1.999/3.6) * (24.32*1000) * 9.8/1000 = 132.42$$

With the value of power calculated, the next step is to determine the value of efficiency that will give a value of power (i.e. nominal power multiplied by an efficiency value that is less than one) equal to the power that the machine can develop at current speed. Since a lot of data was collected for every gear, the value of efficiency was calculated as follows:

$$Efficiency = speed (m/s) * rimpull (kg) / (Max Power that the machine can develop)$$

So for our example above the value of efficiency is:

$$Efficiency = 132.42 / 265 = 0.50$$

This does not mean that our value of efficiency for this gear is 0.50. This is because at the given speed and gear, the corresponding RPM may not be at the peak torque. All the data collected have to be analyzed in order to find the value of efficiency. The formulas shown above have to be applied to all data for any particular gear. The value of efficiency for the gear will be the highest value obtained after all the data collected has been analyzed. The value of efficiency obtained for this gear was 0.87, which is much more higher than 0.50. Table 4.1 presents the calculated values for all the data points captured for the first gear for a Caterpillar 350 Series II Articulated. The efficiency increases while the RPM of the vehicle is less than the RPM that provides peak torque. Once RPM of the vehicle is greater than the RPM that produces the peak torque, the efficiency decreases.

Gear	V		RP (kg)	Total Efficiency
	(km/hr)	(m/s)	By Curve	e
1.00	2.00	0.56	24320.00	0.50
1.00	2.92	0.81	19350.00	0.58
1.00	4.10	1.14	15950.00	0.67
1.00	5.14	1.43	13380.00	0.71
1.00	6.83	1.90	11830.00	0.83
1.00	8.38	2.33	10100.00	0.87
1.00	8.79	2.44	7756.00	0.70

Table 4.1: Calculation of efficiencies for the first gear CAT350 Series II

4.2.2 REDUCTIONS

After calculating the values for efficiency, the following step was to calculate the value of reduction for the gear. Since the values for rated RPM, speed and efficiency are known, the calculation of reductions were done using the following formula:

$$Reduction = Rated\ RPM * 2 * \pi * r / (60 * speed)$$

Where:

The constant value of $2 * \pi$ is used to convert angular speed to the horizontal vehicle speed, r is the radius of the wheel, and the constant value of 60 is used to convert the RPM to RPS.

If we calculate the value of reduction for the first gear for the CAT350 Series II using the equation presented previously, the rated RPM given, velocity from rimpull curve and the value calculated for efficiency we would get the following results:

$$Reduction = 2000 * 2 * 3.1428 * 0.8762 / (60 * 8.382/3.6) = 79$$

After the values of reduction and efficiencies were calculated, a power curve was developed in every gear, to see if the engine mapping (i.e. power and torque) is constant in every gear. First the RPM of the engine was calculated using the following formula

$$RPM = Reduction * speed * 60 / (2*\pi*r)$$

Then the value of Power was calculated using the following formula

$$Power (kW) = Rimpull * speed / (Efficiency)$$

The values obtained for the data taken for the first gear of the CAT350 Series II are shown below: The left column represents the RPM and the right column represents the Power in kW.

RPM	Power (kW)
477	152
697	177
978	204
1227	215
1628	253
2000	265
2098	214

In order for the calculations to be correct, we should get 265 kW at 2000 RPM. As it can be seen from the data 265 kW were obtained at 2000 RPM, which proves that the method used is appropriate. The results obtained for efficiencies and reductions for the CAT350 Series II are presented in Table 4.2.

Gear	Efficiency	Reduction
1	0.87	79
2	0.92	44
3	0.93	25
4	0.96	15

Table 4.2 Efficiencies and reduction for CAT350 Series II Articulated Truck

Figure 4.3 shows the power curve obtained for every gear using the method mentioned above. From the graph it can be seen that curves behave in a similar way. The only major difference is after passing the maximum power value that first and second gear separate from the third and fourth gears. In order to corroborate the values calculated for efficiencies and reductions, a rimpull curve was prepared with these calculated values.

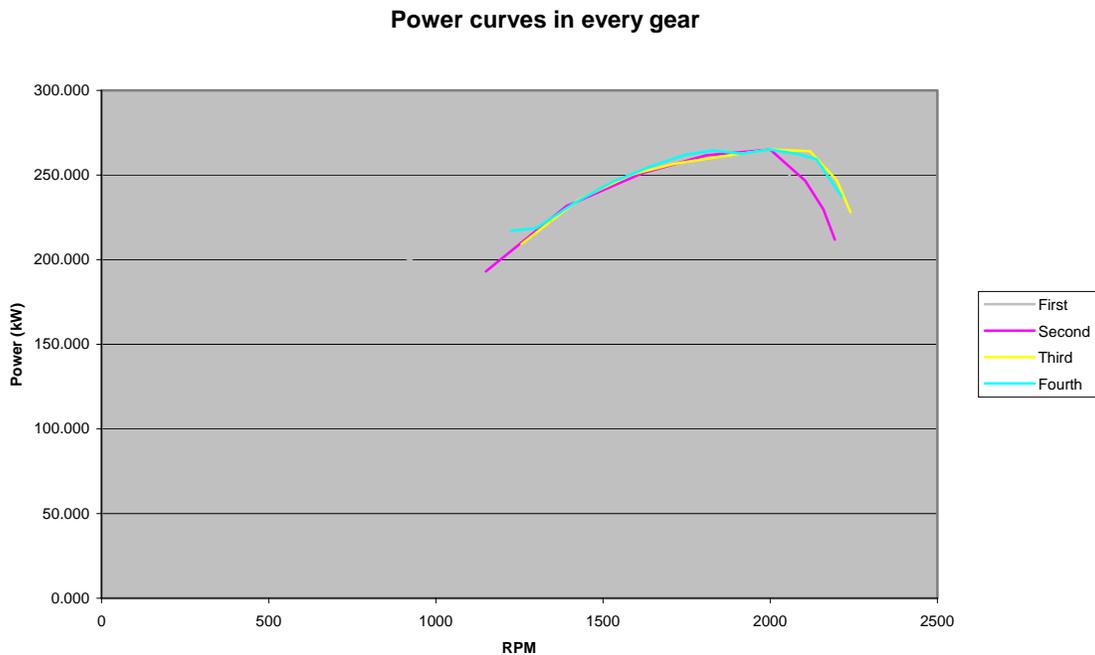


Figure 4.3: Power Curves in Every Gear for CAT350 Series II

This rimpull curve was then superimposed with the rimpull curve given in the Caterpillar Performance Handbook to compare how good the calculated rimpull curve fits with the curve given in the handbook. Figure 4.4 presents a graph of the calculated rimpull against the curve given by the performance handbook. It can be seen from the graph that the calculated curve matches the curve given by Caterpillar, therefore proving that the process used is accurate and that the efficiencies and reductions used are close approximations to the real values, which are unknown and were unknown to us while performing the study.

4.3 ANALYSIS OF RESULTS

The process explained in the preceding section was used to calculate efficiencies and reductions for the hauling equipment available in the Caterpillar Performance Handbook. The equipment analyzed includes standard scrapers, articulated trucks and rigid frame trucks. It is important to mention that since the rated RPM of the equipment was not available at the time of the study, a rated RPM equal to the value provided by Caterpillar

Rimpull Curve

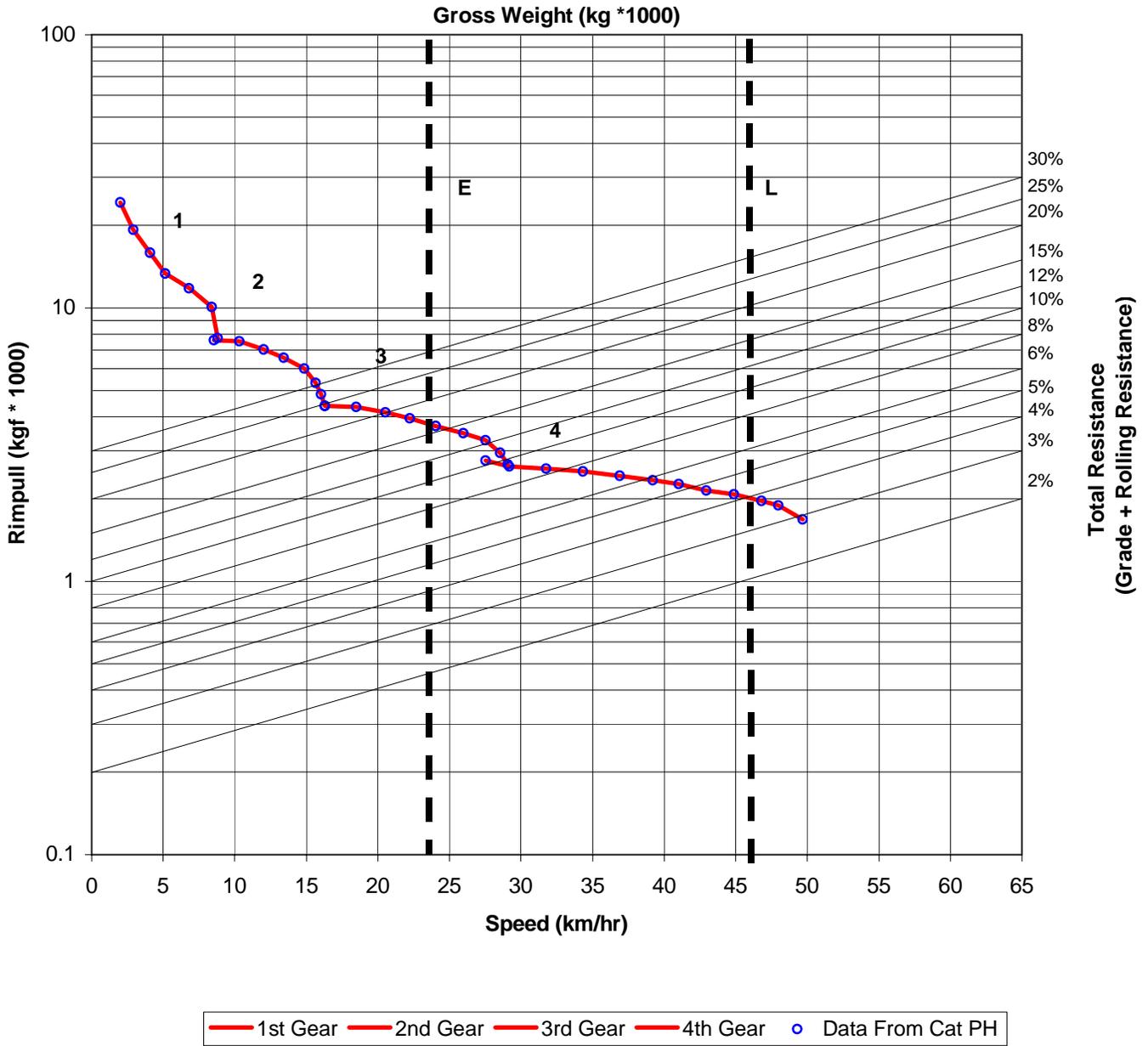


Figure 4.4: Comparison of calculated Rimpull Curve against given Rimpull Curve in the Caterpillar Performance Handbook

for the CAT350 Series II and the CAT400 Series II Articulated trucks was used to perform the analysis. The value assumed for the analysis can create a variation in the results obtained for the reduction.

If the rated RPM for the equipment is smaller than the value assumed, the value for reduction is overestimated. Similarly if the value for the rated RPM is greater than the value assumed the RPM is underestimated. In addition, if the value for rated RPM differs from the value used, there will be a translation of the power curve.

In other words if the rated RPM of the machine is smaller than the assumed value, the power curve will be translated to the left. The opposite (i.e. power curve translated to the right) is true if the rated RPM is greater than the value used for the analysis. However, the rimpull curve generated from these reductions and efficiencies matches the source rimpull curves as it can be seen in Figure 4.3. In other words, the reverse engineering process is adequate.

4.3.1 SCRAPERS

Scrapers play an important role in earthmoving operations. They can load, haul and dump in a single cycle (Nichols, 1999). Scrapers are designed to load or haul. Trucks may be a better option to use as hauler, especially if there is a long distance. In haul distances that are relatively small, they have an advantage over haulers because they can both load and haul (Peurifoy, 1996). In various models, its economical haul distance ranges from less than 1,000 feet to nearly a mile. They could be more cost effective than other type of haulers if the conditions are adequate (Nichols, 1999). Scrapers can be more profitable where the ground is dry, has a high bearing capacity but is easy to excavate and free from stones and boulders (Volvo, 1995). The calculations for efficiencies and reductions were done for standard scrapers only. Standard auger and tandem powered auger scrapers were not considered in the study. Standard auger scrapers are specialized equipment and the rimpull curves are not available. The model cannot handle equipment with two engines,

therefore the study was not done for tandem powered scrapers. Table 4.3 gives the values for efficiencies obtained for standard scrapers.

Efficiencies								
	1	2	3	4	5	6	7	8
Standard Scrapers								
621F	0.66	0.69	0.81	0.81	0.81	0.82	0.83	0.83
631E Series II	0.67	0.70	0.82	0.83	0.82	0.82	0.82	0.81
651E	0.70	0.70	0.80	0.81	0.81	0.82	0.82	0.83

Table 4.3 Efficiencies for standard scrapers

The efficiencies calculated for the first and second gears are hydraulic because the torque converter is used in these gears. The values for the first and second gears are close to 0.70. These values are similar to the values obtained for torque converter efficiency for trucks, both articulated and rigid frame. The torque converter is less efficient than mechanical gears, however the torque converter is used because it allows working at low speeds by providing big reductions and torque multiplication using hydraulics. Nichols (1999) points out that the torque converter usually has lower mechanical efficiency due to slippage and that an average efficiency can be taken as 75 percent. The efficiencies are between 0.80 and 0.83 from the third through the eighth gears. The values for the standard scrapers are very similar in all gears. If the user does not know the model of the standard scraper that he will use, he can select values for any model because they are very similar.

Table 4.4 presents the values of reductions for the scrapers described above. There is no definite pattern for the values of reduction. The reductions in the first and second gear are hydraulic, because the torque converter is used in these gears. The big reductions in the first and second gear are due to the effect of the torque converter that allows working at low speeds by providing big reductions and torque multiplication using hydraulics. The torque converter is always used in these two gears; therefore it was not possible to calculate mechanical efficiencies and reductions for these gears. For the first gear the reductions range from 220 to 317. For the second gear the reductions are between 120 and 142. For the third gear the value is between 83 and 92. For the fourth gear the value

is between 58 and 69. For the fifth gear the value is between 45 and 50. For the sixth gear the value is between 30 and 40. For the seventh gear the value of reduction is between 20 and 30. For the eighth gear the value of reduction is between 17 and 21. In order to get accurate results, the user should have the specific model of scraper that he will be using to select the most appropriate set of values of reductions.

Reductions								
	1	2	3	4	5	6	7	8
Standard Scrapers								
621F	317.06	140.91	83.16	58.31	44.11	31.91	24.16	17.49
631E Series II	284.29	142.04	89.78	64.98	49.77	37.59	27.11	20.80
651E	220.55	120.29	91.70	69.43	49.15	38.93	26.82	20.84

Table 4.4: Reductions for scrapers

4.3.2 ARTICULATED TRUCKS

Articulated haulers are to be used when the haul road is good, but the conditions in the dump and load areas are constrained or the soil conditions are slippery and other type of haulers could sink and have difficulties traveling. In narrow roads, they offer an advantage over rigid frame trucks since articulated trucks could pass each other anywhere by using the side of the road while rigid frame trucks could pass each other only at special points (Volvo, 1995). This section will present the results obtained for efficiencies and reductions for the Caterpillar articulated trucks series. Table 4.5 presents the efficiencies obtained for this equipment.

Efficiencies							
	1	2	3	4	5	6	7
D25D	0.92	0.91	0.93	0.93	0.94		
D30D	0.97	0.94	0.95	0.96	0.98		
250	0.84	0.86	0.87	0.89	0.90		
350 II	0.87	0.92	0.93	0.96			
400 II	0.70	0.83	0.83	0.84	0.85	0.85	0.86

Table 4.5: Efficiencies for Articulated Trucks

A pattern cannot be defined for the values of efficiencies as they depend on the model of articulated truck. From the table it can be seen that for five gear units the most efficient truck is the D30D, but other than that no pattern can be developed since the values vary from model to model. The efficiencies increase as the gear increases, which mean that these trucks work better in high gears. This is consistent with published literature that says that efficiencies increase as the speed of the vehicle increases. In addition, this is consistent with the way they are used, since trucks are used to haul materials for relatively long distances as opposed to dozers that are used mainly in the first gears, therefore it is expected that the efficiency of the truck increases with an increase in gear.

Table 4.6 shows the values of reductions for the articulated trucks. The values for the five gear trucks are close from the third gear until the fifth gear, but they are not the same. In the first two gears the difference among the values is larger. No definite pattern can be associated with the articulated trucks.

	Reductions						
	1	2	3	4	5	6	7
D25D	129.21	76.54	45.15	24.99	15.03		
D30D	119.11	70.25	45.10	25.01	16.23		
250	113.03	68.50	43.09	24.97	14.00		
350 II	78.81	44.46	25.45	14.72			
400 II	116.57	62.33	48.67	34.66	25.23	18.40	13.84

Table 4.6: Reductions for the Articulated Trucks

4.3.3 RIGID FRAME TRUCKS

Rigid frame trucks can travel at high speed under adequate road conditions and they offer relatively high capacity. These trucks could do a better job than other type of haulers, when the distance is big, the amount of soil to move is considerable and the road conditions are adequate for them to travel. They have less maneuverability than articulated trucks, therefore precautions should be taken when dealing with constraint areas (Volvo, 1995). Table 4.7 shows the calculated efficiencies for the rigid frame trucks. For all the models the values of efficiencies are close to 0.80 and above in every gear except for the 773D and 775D models. The highest value for the 775 models is 0.78.

All efficiency values for this model fall between 0.74 and 0.78. As in the case for the scrapers and articulated trucks, in order to get accurate values for efficiencies the user should know the model of the equipment to be used. Similar to articulated trucks, these trucks are used to haul material when the distance is relatively long.

Rigid Frame	Efficiencies						
	1	2	3	4	5	6	7
769D	0.84	0.86	0.83	0.84	0.83	0.83	0.83
771D	0.82	0.81	0.80	0.80	0.81	0.81	
773D	0.75	0.80	0.80	0.78	0.78	0.81	0.80
775D	0.74	0.75	0.75	0.78	0.76	0.78	0.78
777D	0.86	0.81	0.84	0.85	0.81	0.79	0.78
785B	0.90	0.87	0.87	0.86	0.87	0.88	
789B	0.90	0.89	0.90	0.89	0.90	0.90	
793C	0.90	0.89	0.90	0.90	0.91	0.91	

Table 4.7: Efficiencies for Rigid Frame Trucks

Table 4.8 shows the values of reductions for the rigid frame trucks. There is similarity for the values of reductions for some of the gears. The range for the first gear is the biggest one. The values in this gear range from 57 to 119. For the second gear the values range from 43 to 90. For the third gear the values are between 32 and 63. For the fourth gear the values are between 23 and 47. The values for the fifth gear range from around 17 to around 36. The values for the sixth gear range from around 12 to around 28. For the seventh gear the values range from around 9 to around 16. A pattern cannot be established. It was mentioned previously that in order to get accurate results, the user should know the model. This statement also applies in this case, since there is a variation in the values for all the models.

Rigid Frame	Reductions						
	1	2	3	4	5	6	7
769D	57.05	43.71	32.12	24.05	17.22	12.95	9.42
771D	60.58	43.28	33.13	23.86	17.84	12.62	
773D	82.29	56.45	41.15	32.15	22.58	16.86	12.42
775D	82.13	57.82	43.81	31.41	23.42	17.41	12.44
777D	95.10	77.04	55.33	40.85	30.13	22.13	16.02
785B	85.26	63.07	49.51	36.83	25.72	20.11	
789B	107.98	84.81	58.17	43.60	33.03	24.38	
793C	119.46	90.25	63.67	46.97	36.14	28.18	

Table 4.8: Reductions for Rigid Frame Trucks

For most of the hauling equipment analyzed it was found that the value of efficiency increased as the gear increased. This is consistent with the fact that these hauling units are designed for relatively long hauls, therefore they should have high efficiency in high gears. If the same study is done for dozers, it is expected to have high efficiencies in the lower gears since it is in these gears that this equipment mostly operates. The value of the reduction should decrease as the vehicle is gaining speed. This is due to the fact that the velocity at the axle is increasing and getting “closer” to the speed at the flywheel. On the other hand the efficiency should increase as the vehicle gains speed and as the reduction decreases.

4.4 MODELING THE TORQUE CONVERTER

The torque converter transmits the torque of the engine by using hydraulic fluid. The torque converter works as a fluid coupling and it multiplies the twisting effort of the crankshaft by using this hydraulic fluid. The flow of the oil is used to generate extra force on the turbine (Nichols, 1999). The torque converter is used to provide big reductions and multiplication of torque to generate the torque required to get the vehicle moving or to keep the vehicle moving at low speeds. In order to model the interaction and flow of fluids inside the torque converter and how this flow is used to create the extra force, a detailed and complex study of the kinematics and viscosity involved is needed. This detailed study is out of the scope of this research. However, an empirical study is used to approximate the torque converter operation. This approximation will be explained in this section.

The methodology used to model the torque converter uses the same principles explained in Section 4.1. DataThief was used to collect rimpull and speed data in the torque converter area from the rimpull curve provided by the manufacturer. These data were collected at small intervals of speed. With the mechanical efficiencies and reductions for the gears already calculated, with the process discussed in Section 4.1, the corresponding reductions and efficiencies at current speed in the torque converter zone can be calculated using the procedure that will be explained in the following sections.

With the value of speed and corresponding rimpull at that speed, the power developed can be calculated using the following equation:

$$Power = rimpull * speed$$

This power is then compared with the maximum nominal power that the machine can develop given by the manufacturer. This comparison will give the total efficiency (i.e. mechanical efficiency of the gear plus constant efficiency plus efficiency of the torque converter). The mechanical efficiency of the gear is known; therefore the efficiency of the torque converter at that speed can be calculated using the following equation:

$$Torque\ Converter\ Efficiency = Power\ at\ current\ speed / (Maximum\ Nominal\ Power * total\ efficiency\ in\ current\ gear)$$

The reductions can be calculated with the values of speed, the rated RPM and the wheel radius already known. This calculated reduction is the total reduction (i.e. reduction of the gear plus constant reduction plus reduction of the torque converter). The equation used to calculate torque converter reduction is the following:

$$Torque\ converter\ reduction = ratedRPM * 2 * pi * wheel\ radius / (60 * speed * total\ gear\ reduction)$$

With the values of efficiency and reductions calculated for different speeds in the torque converter zone, then the next step was to find a relationship between the efficiencies and the reductions in the torque converter area. A regression was used to find an equation that better represents the relation between efficiencies to reductions in the torque converter area. By doing an approximation using MS Excel[®] it was found that the relation between efficiencies and reductions in torque converter area is represented by a power equation (i.e. $y = x ^ \text{exponent}$). The data was analyzed in order to get the equation. The least square approach was used to get the equation that best fits the data. For our case the equation that relates the torque converter efficiencies to the torque converter reductions is the following:

$$\text{Torque Converter efficiency} = \text{Constant} * \text{Torque Converter reduction} ^{-\text{Total Gear Efficiency}}$$

The constant can be calculated following the least square approach using the following procedure. As it was discussed previously, the torque converter efficiencies and the torque converter reductions can be calculated once the data is collected. The values for torque converter reductions are raised to an exponent equal to the negative of the total efficiency of the gear. These values are then multiplied by a constant. The constant should be a variable and the same value for all values of reductions raised to the exponent. This is a fairly easy process using MS Excel[®]. These values (i.e. the constant multiplied by the reductions raised to the exponent) are then subtracted from the torque converter efficiencies calculated from speed and rimpull obtained from the rimpull curves. These differences are then squared. By using the solver in MS Excel[®] the value of the constant that minimizes the differences between the points can be calculated. This value is the constant of the equation. An example of these calculations for a CAT250 Articulated can be seen in Table 4.9.

Cat250 Articulated Torque Converter Modeling

Speed		RP (kg)	Power (kW)	Eff.Total	Eff.TC	Total Red.	TC Red	x ^{eff}	C*x ^{eff}	Differences	
km/hr	m/s										
0.01	0.00	24300.00	0.86	0.00	0.01	47148.66	339.09	0.01	0.01	0.00	
0.01	0.00	24300.00	0.93	0.00	0.01	43780.89	314.87	0.01	0.01	0.00	
0.02	0.00	24300.00	1.13	0.01	0.01	36054.85	259.30	0.01	0.01	0.00	
0.02	0.01	24300.00	1.26	0.01	0.01	32259.61	232.01	0.01	0.01	0.00	
0.02	0.01	24300.00	1.39	0.01	0.01	29187.26	209.91	0.01	0.01	0.00	
0.03	0.01	24300.00	1.66	0.01	0.01	24517.30	176.33	0.01	0.01	0.00	
0.04	0.01	24300.00	2.85	0.01	0.02	14254.24	102.52	0.02	0.02	0.00	
0.05	0.02	24300.00	3.59	0.02	0.02	11310.80	81.35	0.02	0.03	0.00	
0.08	0.02	24100.00	5.14	0.03	0.03	7828.00	56.30	0.03	0.04	0.00	
0.08	0.02	24300.00	5.25	0.03	0.03	7729.29	55.59	0.03	0.04	0.00	
0.17	0.05	24100.00	11.10	0.06	0.07	3626.82	26.08	0.06	0.07	0.00	
0.19	0.05	24000.00	12.43	0.06	0.07	3225.96	23.20	0.07	0.08	0.00	
0.37	0.10	23000.00	23.19	0.12	0.14	1656.57	11.91	0.12	0.14	0.00	
0.55	0.15	23000.00	34.47	0.17	0.20	1114.42	8.01	0.17	0.20	0.00	
0.82	0.23	22000.00	49.16	0.24	0.29	747.48	5.38	0.24	0.28	0.00	
1.10	0.31	22000.00	65.95	0.33	0.39	557.21	4.01	0.31	0.35	0.00	
1.30	0.36	21000.00	74.39	0.37	0.44	471.49	3.39	0.36	0.41	0.00	
1.50	0.42	20000.00	81.75	0.41	0.48	408.62	2.94	0.40	0.46	0.00	
1.80	0.50	20000.00	98.10	0.49	0.58	340.52	2.45	0.47	0.53	0.00	
2.00	0.56	19000.00	103.55	0.52	0.61	306.47	2.20	0.51	0.58	0.00	
2.20	0.61	19000.00	113.91	0.57	0.67	278.61	2.00	0.56	0.63	0.00	
2.30	0.64	18000.00	112.82	0.56	0.67	266.49	1.92	0.58	0.66	0.00	
2.50	0.69	18000.00	122.63	0.61	0.73	245.17	1.76	0.62	0.71	0.00	
2.80	0.78	17000.00	129.71	0.65	0.77	218.90	1.57	0.68	0.78	0.00	
3.00	0.83	16000.00	130.80	0.65	0.77	204.31	1.47	0.72	0.82	0.00	
3.20	0.89	15000.00	130.80	0.65	0.77	191.54	1.38	0.76	0.87	0.01	
										difference	0.02
										SQRT(difference)	0.14

Table 4.9: Least Square Calculations Example for a CAT250 Articulated

Figures 4.5, 4.6 and 4.7 present graphs of the regressions for a CAT250 Articulated truck, a CATD30D Articulated and a CAT773 Rigid Frame truck respectively. The R^2 value for the regression in Figure 4.5 is equal to 0.9982. The R^2 value for the regression in Figure 4.6 is equal to 0.9932. The R^2 value for the regression in Figure 4.7 is equal to 0.9759. From these graphs and by looking at the R^2 values, it can be seen that the regressions adjust fairly well to the data calculated from rimpull curves. The pattern observed is consistent with published literature in the sense that reductions decrease with an increase in speed and efficiencies increase with an increase in speed and a decrease in reductions. Nichols (1999) states that the losses in power are greater in the first gears because the greatest reductions are used in these gears and greater pressures in the gear tooth increase friction. Therefore, it is expected that the analytical approximation is useful to approximate the torque converter operation.

**Torque Converter
Efficiencies vs. Reductions
CAT250 Articulated**

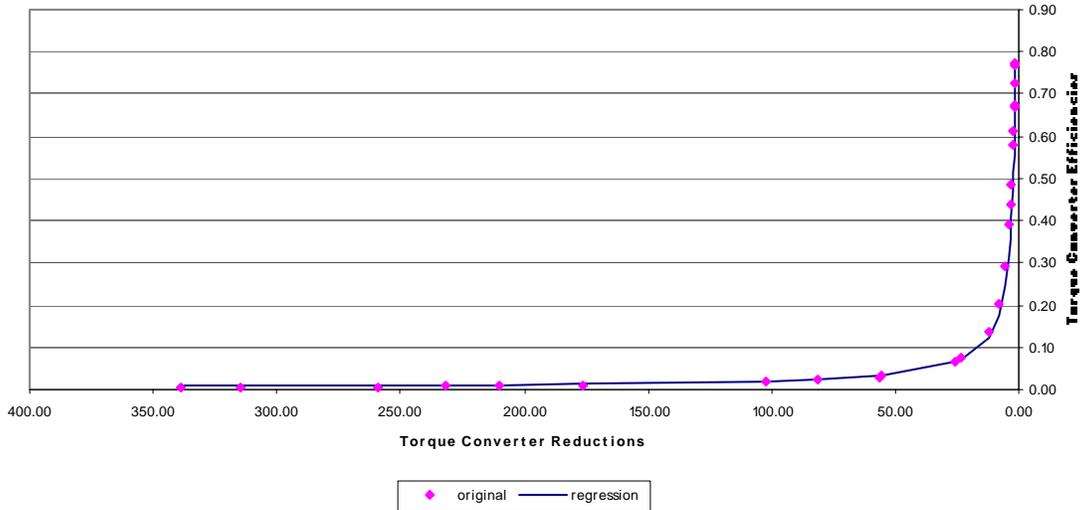


Figure 4.5: Regression for Efficiencies and Reductions in the Torque Converter area for a CAT250

**Torque Converter
Efficiencies vs. Reductions
CATD30D Articulated**

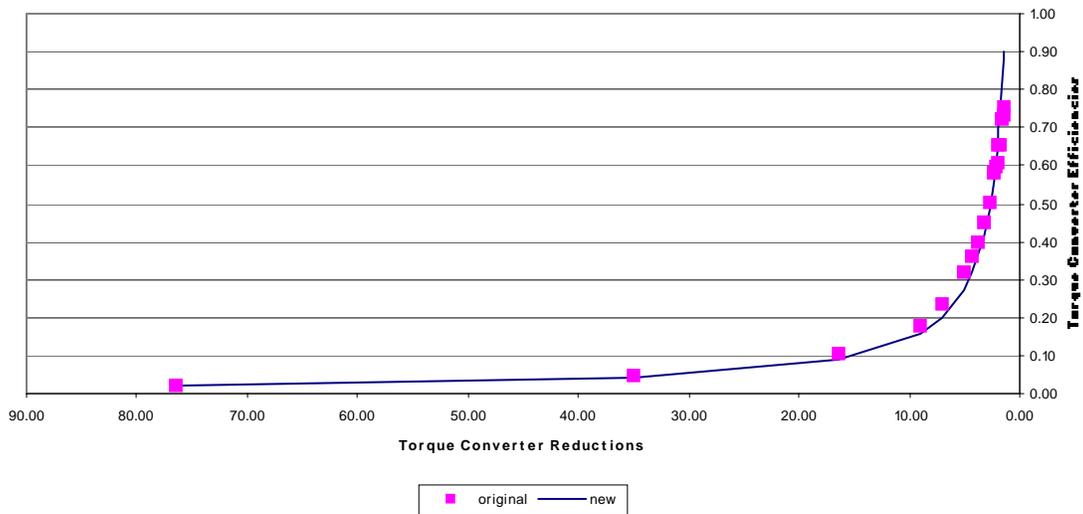


Figure 4.6: Regression for Efficiencies and Reductions in the Torque Converter area for a CATD30D

**Torque Converter
Efficiencies vs. Reductions
CAT773**

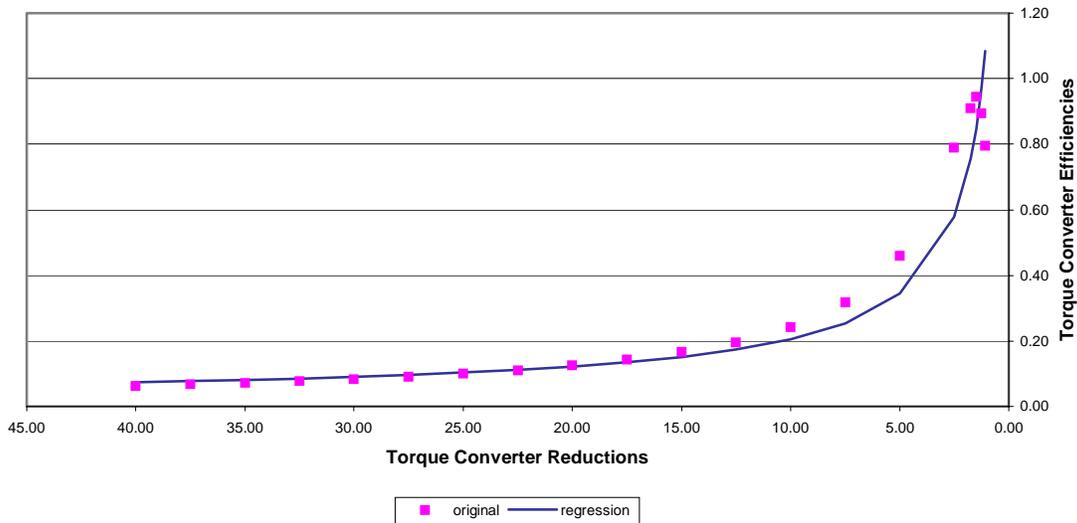


Figure 4.7: Regression for Efficiencies and Reductions in the Torque Converter area for a CAT773

The torque converter reduction can be calculated if the current speed of the vehicle and the total reduction of the gear are known. The torque converter efficiency can be derived from the torque converter reduction by using the regression for the particular equipment. One of the drawbacks of the methodology is that the user needs to know the rated RPM of the machine. The formula used to calculate the reduction requires speed as an input. When the input velocity is equal to zero, an infinite reduction is obtained. In order to use the approximation, the user has to specify the stall ratio. Martel (1999) states, “*The stall torque ratio is the amount of engine torque that the torque converter can multiply at a particular rpm level. By definition, stall torque ratio is when the turbine is at 0 RPMs and the converter is at maximum designed stall.*” Yank Performance Converters published in their web page the following definition for stall speed: “*Stall speed is the amount of engine R.P.M. that can be attained at full throttle with the brakes locked and the transmission in gear before the drive wheels turn.*” Nichols (1999) states that the maximum reduction of the torque converter is given by multiplying the stall ratio by the total mechanical reduction of the gear. He adds that the reduction will decrease

automatically as the vehicle gains speed up to a minimum equal to the mechanical reduction. In that case the reduction of the torque converter is equal to one. When the reduction of torque converter is equal to 1, the vehicle is operating in direct drive. In direct drive model, the power is passed directly through the transmission in a 1:1 ratio with no torque multiplication. With the stall ratio and mechanical reduction of the gear known, the reduction at stall speed can be obtained. With this reduction, the acceleration can be calculated and the approximation can be used to get the torque converter efficiency. Lastly, it was not possible to derive the mechanical efficiencies and reductions for scrapers with the available information. The torque converter is always used in the first and second gears. In order to use this approximation with scrapers, a value for mechanical efficiency and reduction similar to the values for trucks was assumed. The error incurred by doing this assumption is compensated when the regression is used to calculate the torque converter efficiency. Figure 4.8 illustrates the regression for efficiencies and reductions in the torque converter area for the first gear for a standard scraper 621F. The regression adjusts fairly well to the data calculated from rimpull curves. The R^2 value for the regression is 0.912.

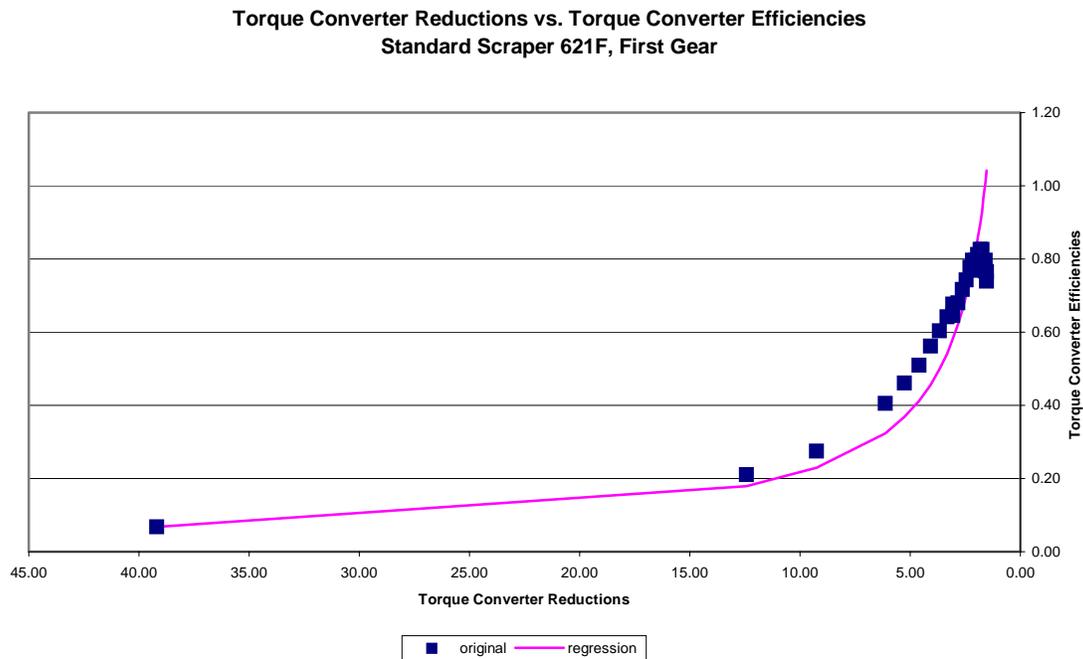


Figure 4.8: Regression for Efficiencies and Reductions in the Torque Converter area for the first gear for a Standard Scraper 621F

4.5 SUMMARY

This chapter focused primarily in the determination of efficiencies and reduction values for a haul unit. The methodology used to calculate the values of interest (i.e. efficiencies and reductions) was explained in detail. An example of calculating efficiencies and reduction for a CAT350 Series II articulated trucks was presented and explained. Although the calculations were done for a data point in the first gear, the procedure is the same for all gears and all points. The user should get high quality data from the rimpull results in order to get fairly accurate results. For these purposes the program Datathief was mentioned. The details on how to use this program can be obtained from the user's manual. Corroboration of the accuracy of the method was obtained while calculating the power curve and the rimpull curve for the equipment. The rimpull curve prepared for checking the methodology matched the rimpull curve given by the performance handbook for all the equipment analyzed. The values for the CAT350 Series II were given, for the benefit of any person that could be using one of those trucks. The power curves in every gear for the CAT350 Series II articulated as well as the comparison of calculated rimpull curve and given rimpull curve were shown with the purpose to try to demonstrate that the power curves remain constant in every gear for the equipment and to verify the accuracy of the calculated values. The results obtained for scrapers, articulated trucks and rigid frame trucks were presented and discussed. Finally, the methodology used to approximate the torque converter operation was presented and discussed. This empirical study was used to model the torque converter operation. However, to model the hydraulic flows inside the torque converter a more detailed study is needed to consider the kinematics and viscosity involved. This study is out of the scope of this research. Limitations of the analytical approximation were presented.

Chapter 5: Methodology for Estimating Equipment Performance

Chapter 2 provided the background needed to understand the development and need for the model. Chapter 3 presented the factors that affect the performance of heavy equipment and why these factors should be considered. Chapter 4 presented the methodology needed to estimate fundamental equipment data needed as input to the model. This chapter explains the methodology used to develop the performance model and the model itself. A discussion of the process for power transfer from the engine through the transmission until it reaches the area of contact between the wheel and the surface is presented. This process was used as the basis to develop the model.

5.1 DESCRIPTION OF THE PROCESS FOR POWER TRANSFER

This section describes the process that takes place to transfer the power from the engine until it reaches the area of contact between the wheel and surface. It was mentioned earlier in Chapter 3, that the engine is the source that generates the power needed by the machine. The power generated needs to be transferred to the wheels in order to develop the rimpull needed. The description that follows will be as general as possible, but including the amount of detail needed to make sure that the reader understands the process easily.

Figure 5.1 shows the components used for power transfer. The engine is the source that generates power. There is a ring gear in the flywheel that drives the torque converter. The torque converter has a lockup switch that allows the machine to work in torque converter mode or direct drive mode. When the machine is working in torque converter mode (lock up switch not engaged), oil enters the torque converter and flows through the internal passages to the impeller. The impeller drives the oil direct to the turbine. After the oil passes through the turbine, it is redirected to the impeller to assist in torque multiplication. When the torque converter is engaged the impeller is turning at the same speed of the engine, but the turbine is turning relatively slowly. When the lock up switch

is engaged, the impeller, turbine and assembly rotate as a unit. Drive is transmitted from the engine flywheel through the rotating housing, lock up clutch and converter output shaft (Caterpillar 1999).

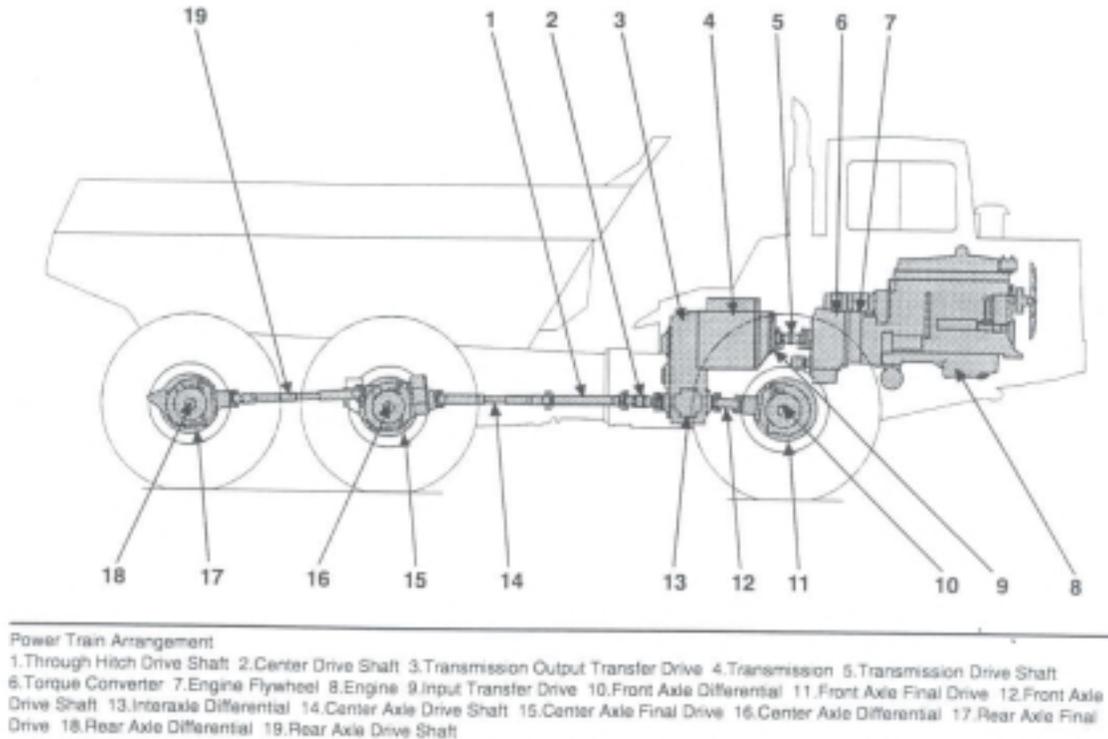


Figure 5.1: Power Train Arrangement for a 350 Series II Articulated Truck (Caterpillar 1999)

Drive is transmitted to the transmission. Transmissions reduce the number of revolutions per time unit and in the process reduce power due to efficiency considerations (Martinez, 1997). The transmission output shaft transmits drive to differential input gear. The differential input gear is connected to the axle differential housing. The axle differential divides torque between front and rear axles. This differential axle is a primary gear unit. When the machine is moving straight with equal resistance at each wheel, the housing, spiders and wheel rotate as a unit. If resistance at the wheels changes due to ground conditions, drive to each axle will be different and this is primarily due to the operation of the differential axle (Caterpillar 1999). Drives will operate with the same amount of

torque but at different speeds. The power is then transferred to the final drives. Final drives are planetary gear reduction units.

The rotational speed (reduction), torque (increase), and power (loss due to efficiency) are further changed from the output of the gearbox before delivery to the driving axle(s). These additional conversions are determined by an efficiency and reduction that is constant and independent of gear. The torque is converted into rimpull at the area of contact between the wheel and the surface. The conversion of this torque into rimpull depends on the wheel radius. Rimpull is the value of interest when analyzing equipment performance. It is defined as the usable force developed at the point of contact between the ground and the tire for a wheel machine. Nichols (1976) states that rimpull is the torque that a machine is capable of exerting at the point of contact of its drive wheels with the ground. The next section will explain the concepts considered to develop the model followed by a description of the model. Table 5.1 gives a summary of the process that takes place in power transfer as explained above.

5.2 METHODOLOGY

The key in the development of the model is the calculation of acceleration and deceleration when the vehicle is not braking. The acceleration of a body during an interval of time is the change in velocity divided by the time interval or, in equation form, $a = \Delta V / \Delta t$. As Δt becomes smaller and approaches zero in the limit, the average acceleration approaches the instantaneous acceleration (Meriam, 1992). This acceleration is described by the following formula $a = \delta V / \delta t = \delta^2 s / \delta t^2$. The velocity and acceleration can be obtained if the position at any value of time is known, by using successive differentiation with respect to time. In many problems the functional relationship between position and time is unknown, and it has to be determined by successive integration from acceleration (Meriam, 1992). In our case, the latter method is the most appropriate and it is the method used. The determination of instantaneous acceleration may be a complex procedure because it is a function of numerous variables, many of which are in turn

Gear	Engine	Torque Converter	Gear Box	Final Drive	Wheels
1a	The engine has a characteristic Power curve that is dependent on RPM. It will be assumed that this curve is the same for all gears	In newer equipment a Torque converter is used to automatically multiply (increase) the torque. Mostly used in the first gear only, although in some equipment it is also used in the second gear	The gearbox reduces rotational speed and increases torque. In doing this, a certain amount of power is lost due to efficiency issues. The amount of rotational speed reduction, torque increase, and power loss due to efficiency are determined by a reduction and an efficiency that depend on the current gear.	The rotational speed (reduction), torque (increase), and power (loss due to efficiency) are further changed from the output of the gearbox before delivery to the driving axle(s). These additional conversions are determined by an efficiency and reduction that is constant and independent of gear.	The torque is converted into rimpull at the area of contact between the wheel and the surface. The conversion of this torque into rimpull depends on the wheel radius.
1b					
2		The torque converter is not used in these gears for torque multiplication			
3					
4					
5					
6					
7					

Table 5.1: Flow of Power from the engine until it reaches the wheels

functions of velocity and position, which are themselves integral functions of acceleration. For example, the excess force that can be provided by the engine and transmission are dependent on the current speed and several other factors. Acceleration changes constantly as it changes the variables upon which it depends. In order to obtain velocity, a differential function involving acceleration has to be solved. This acceleration, however, depends on the actual velocity. The result is a very complicated differential system. If there is a constant velocity, a value of zero for acceleration will be obtained. In addition, acceleration of a vehicle is dependent on the vehicle characteristics and road conditions. The variables (i.e. equipment characteristics, road characteristics) have a direct impact in the value of acceleration. However, these variables are related, because a

change in one of the variables causes changes in one or more of the other variables. For example, the performance of the equipment is dependent on the road conditions as well as on current speed. Figure 5.2 shows an influence diagram of the variables that affect the value of acceleration.

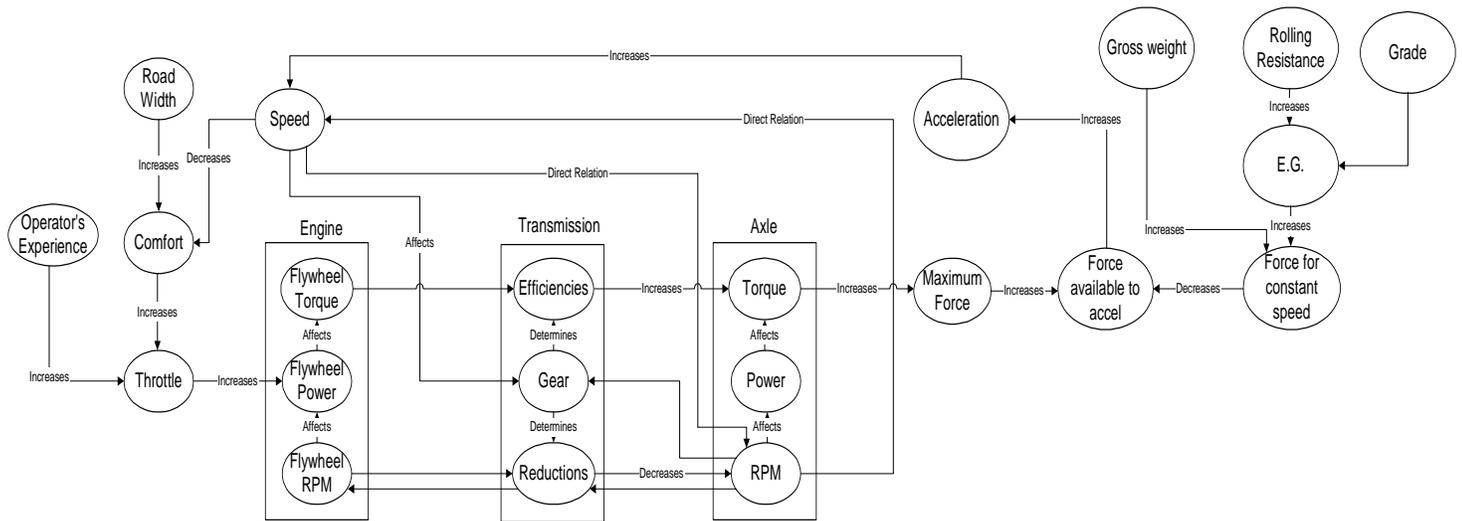


Figure 5.2: Influence diagram for the variables that describe acceleration

These changes in power with changes in speed need to be considered in detail, because the power is not constant. Moreover, power is changing constantly as speed and rpm change. Figure 5.3 shows the variables in the machine that have an effect in the value of acceleration.

The model requires fundamental data as input. Making some assumptions, the values of interest were derived from rimpull curves published by the manufacturers using a process that was described in detail earlier in Chapter 4. Any user can use the methodology explained in Chapter 4 to derive the values needed as inputs to the model. Moreover, if the equipment is available, the user can measure the inputs in the field.

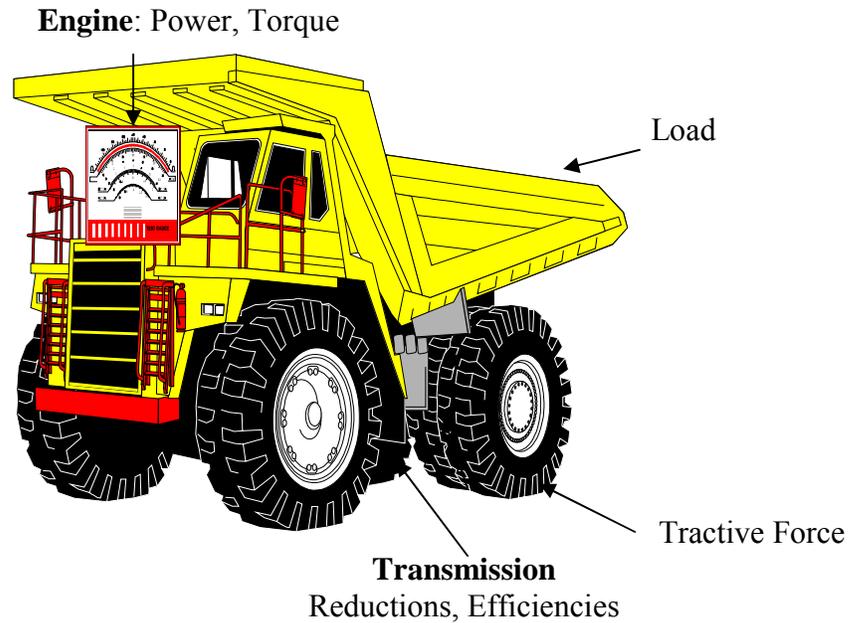


Figure 5.3: Factors in the machine that affect acceleration (Image courtesy of Govi Kannan)

5.3 DESCRIPTION OF THE MODEL

This section will describe the model developed as part of this research. The objective of the model is to apply the process described in Section 5.1 to estimate equipment performance and therefore travel time. The model uses the methodology explained in Section 5.2 to calculate acceleration and by successive integration calculates velocity and position. In addition, profiles of speed and distance versus time can be obtained.

The development of the MATLAB™ model started in the summer of 1999. A preliminary model was developed to calculate travel times. The model was able to calculate travel time for one segment. The primary inputs for that model were equipment characteristics (e.g. engine power, torque, retarding curves, reductions and efficiencies of the transmission), road characteristics (e.g. length, equivalent grade), current velocity and current gear. The output generated by the model consisted of graphical representations of the rimpull curve, retarding curve, power and torque curves, and a velocity profile. The user had to input the values for road characteristics every time that a new segment will be analyzed. The model calculated acceleration at small intervals of time. By successive

integration using differential equations, velocity and position were also calculated. The model was able to calculate the travel time of a haul unit in a specified segment, while the vehicle was traveling at maximum speed. The model calculated travel time for one segment at a time, if the user wanted to analyze a series of segments the user had to remember the last values output by the model with respect to speed and gear. No provisions for stopping or torque converter were considered. When the vehicle was traveling in a negative slope the model calculated the travel time by simulating equipment performance while the vehicle was traveling at maximum speed. If the vehicle was trying to slow down the model used engine retardation power to slow the vehicle. This model was refined and aspects that were not considered previously, such as braking effect and the ability to model more than one segment etc., were included to have a more complete performance predictor. The remaining sections of this chapter describe the model. The travel times are obtained by simulating equipment performance assuming that the equipment is working at full capacity (i.e. the operator is not a limiting factor) when the model is not simulating braking. A user's guide is available in Appendix A for the model developed as part of this research. Once the user tries to run the program, a textbox with a disclaimer appears. In order for the program to perform any calculations, the user has to agree with the disclaimer. If the user selects "OK" from the textbox the program asks for the inputs, otherwise it exits.

5.3.1 INPUTS

In order for the model to estimate accurate travel times for the haul unit, the user has to describe the parameters that will affect the performance of the equipment. These are the inputs to the model. The model simulates equipment performance starting from rest. The primary inputs of the model are equipment characteristics and road characteristics. Other additional inputs needed for the calculations are Speed Limit, Target Speed, and Load (payload). These inputs and the format that should be used in order for the program to read them accurately are discussed in the following sections.

The user has to create a text file to describe equipment characteristics. This file is used as an input to the model. This file should include the following information in the following sequence in order for the program to read and use the information accurately. The power curve should be represented by a series of points that describe the power at a specific RPM. This number of points that describe the power curve should be included as well the values for power and RPM. This also applies for the retarding power curve. The torque and retarding torque curves are obtained from the power and retarding power curves. The other parameters that should be included in the file are: vehicle empty weight, efficiencies (both constant and gear dependent), reductions (both constant and gear dependent), radius of the wheel, and number of gears. In order to model the torque converter operation, the user has to specify the torque converter as another gear and assign the mechanical efficiencies and reductions of the torque converter equal to those of the first gear. It is assumed that the torque converter is used in the first gear. An example file that describes the order in which the equipment characteristics should be entered follows. Letters in italics are used only to demonstrate the order. An example input file will be presented afterwards

Vehicle Empty Weight in kilograms

Number of RPM points that describe the power curve

RPM that describes power curve

Power in Watts at the corresponding RPM

Number of RPM points that describe the retarding power curve

RPM that describes retarding power at the corresponding RPM

Retarding power in Watts

Wheel radius in meters

Constant reduction

Constant efficiency

Number of gears

Reductions

Efficiencies

Rated RPM

Constant To Model Torque Converter

Exponent to Model Torque Converter

Stall Ratio

An example of a file that describes the characteristics and expected sequence for a Cat350 Series II Articulated follows.

```
30190
8
477 978 1583 1712 2000 2119 2200 2240
152178.47 204551.89 250104.36 260854.05 265000.00 264061.71
246614.89 227945.91
6
1200 1350 1500 1750 1950 2100
93310 111972 149296 223944 298592 354577
0.88
1
1
5
79 79 44 25 15
0.87 0.87 0.92 0.93 0.96
2000
1.47
-0.87
3
```

The user has to create a text file with the haul road characteristics. Inputs that describe haul road characteristics include rolling resistance, grade, speed limit of the segment, target speed and length of the segment. The values for rolling resistance and grade should be entered as a percent (%) not as a decimal. Speed Limit refers to the maximum speed at which the vehicle can travel along the segment. This value can be used to limit the maximum speed in cases where there are some factors that don't allow the vehicle to

travel at the maximum speed that it can develop. Target speed refers to the desirable speed at the end of the segment. If the vehicle has to come to a stop at the end of the segment, then this value should be set to zero. If the vehicle can go as fast as possible then this value should be set equal or greater to the value of speed limit. Both values should be entered in km/hr. The length of the segment should be input in meters.

The text file is used as an input to the model. The data for all the segments should be input. The values should be separated by a space. This file should include the following information in the following sequence in order for the program to read and use the information accurately. The headings below illustrate the order in which the data should be input.

RR (%) Grade (%) Speed Limit (km/hr) Target Speed (km/hr) Distance (mts) Coefficient of Traction

These headings are shown to illustrate the order in which the parameters should be input and they should not be included in the file. An example of an input file that describes haul road characteristics follows. The model assumes that the vehicle starts from rest.

```
3 -5 45 500 120 0.36
2 8 500 500 150 0.36
3 1 45 500 200 0.36
3 -4 50 50 175 0.36
4 -2 25 0 500 0.36
```

The user has to input the load that the vehicle is carrying. It is important to specify the load of the truck. If the truck is traveling empty, a value of zero should be entered. If the truck is traveling fully loaded, enter the payload. If the vehicle is not traveling fully loaded, the load that it is carrying can be specified here. The value of the load should be input in kilograms. After the user enters this value the program starts the calculations. It is very important that user input the parameters that describe the piece of equipment and specific haul road in order to get accurate results. The last input is the load distribution for that particular equipment.

5.3.2 CALCULATIONS

This section describes the formulas used in the program in order to calculate the performance of the equipment and estimate the travel time. Most of the formulas used to develop the model are taken from the Means and Methods Class Notes given by Dr. Julio Martinez. After all the parameters needed for the calculations are input, the program reads this data and calculates the engine and retarding torque by using the following formulas:

$$\begin{aligned} \text{EngineTorque} &= \text{EnginePower} ./ (\text{RPM}/60 * 2 * \pi) \\ \text{RetardingTorque} &= \text{RetardingPower} ./ (\text{retardingRPM}/60 * 2 * \pi) \end{aligned}$$

This is a vector member-by-member operation and the dot in front of the division symbol tells MATLAB™ that this operation is taking place. The inputs for power should be arrays or the program read them as arrays, since a power curve needs to be described by more than one point.

Following this calculation the model enters into a loop to do the calculations until all the segments specified by the user are analyzed. Inside that loop, another loop follows. This loop calculates acceleration, speed and distance traveled as function of time for one segment at a time. This loop takes place until the total length of the segment has been reached. A differential system is used to calculate speed and position with the value of acceleration calculated previously. In order to perform the calculation of acceleration, the model uses the current gear and current speed of the vehicle. The piece of code shown below is used to call the differential equation solver in order to calculate speed and distance as a function of time.

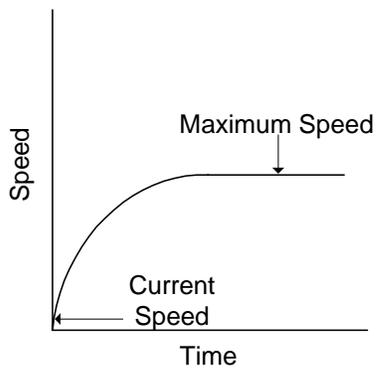
```
[tg,DandVg,TE,YE,IE]=ode45('AcelMode',[CurTm:TimeDelta:TimeLimit],  
[CurD; CurV],odeset('Events','on'), CurGear, Distance);
```

In the piece of code shown above *ode45* is a solver function for the differential system that uses a fifth order Runge-Kutta solution algorithm. *AcelMode* is the string that contains the ode file name. *CurTm:TimeDelta:TimeLimit* represents the time span that

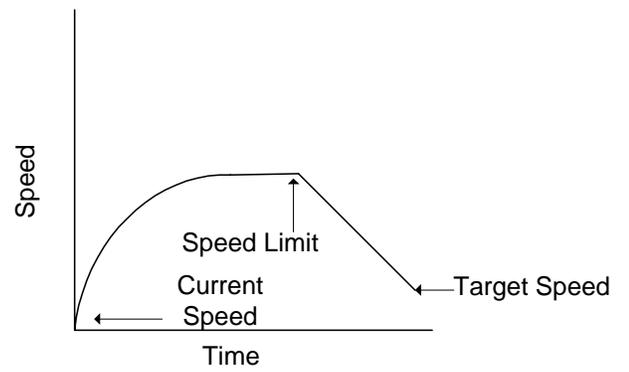
tells the solver to integrate between *CurTime* and *TimeLimit* with increments equal to *TimeDelta*. *CurD* and *CurV* represent the initial conditions for the integration. The command *odeset* creates an options structure that can be supplied to the ode solver. In this case the *odeset* command tells the ode solver that it handles events. When the *events* parameter is on, this tells the solver that the ode file is coded so that it returns appropriate event function information. In this case the function's event handler will stop the integration when the rimpull that can be provided by the next gear is higher than the one that can be provided by the current gear. The value *tg* corresponds to time. *DandVg* are results for speed and distance that correspond to *tg*. *TE* represents a column vector of times at which the events occur, *YE* are solutions corresponding to times in *TE*. *IE* specify which event occurred at the time in *TE*.

The program considers the following cases. First, the vehicle starts with the current speed and gear and tries to go as fast as possible. Second, the vehicle starts with the current speed and gear and the maximum speed is limited by road conditions or the maximum speed at the end of the segment is limited by the maximum speed on the next segment. Third, the vehicle starts with the current speed and gear and final velocity at the end of the segment equals zero. The program will consider these cases for both positive and negative equivalent grades. Figures 5.4a, 5.4b, and 5.4c present graphical representations of the cases mentioned above.

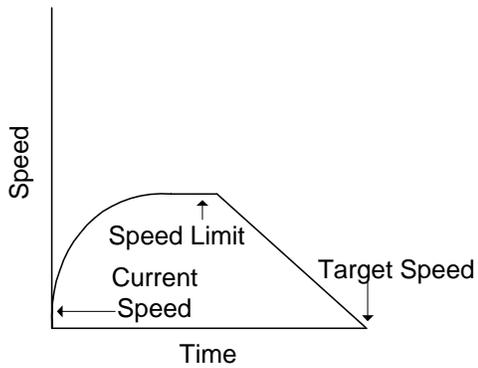
Depending on the value of the initial speed and the value of target speed the vehicle can try to go as fast as possible or try to slow down to Target Speed. The program initially checks if the current speed of the haul unit is greater than the maximum permissible speed of the segment. If this is the case, the model will simulate the braking effect to slow the vehicle down to the speed limit. Figures 5.4d, 5.4e, and 5.4f present a graphical representation of these cases. A constant deceleration equal to 0.83 m/s^2 is assumed in order to reduce speed. This value of 0.83 m/s^2 is the average of a set of field data collected using Global Positioning Systems. The objective of the research is to develop the model not to calibrate it. A value of 0.83 m/s^2 is adequate for developing purposes. If the user wants to change this parameter, data collection is required since this value



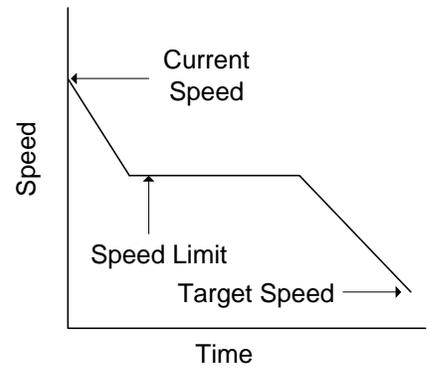
(a)



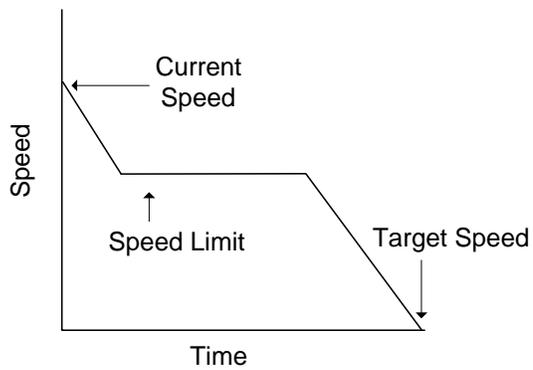
(b)



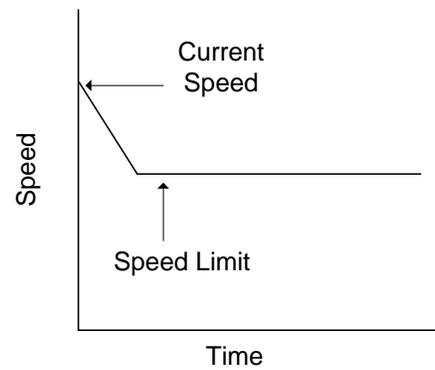
(c)



(d)



(e)



(f)

Figure 5.4: Graphical representation of cases considered

depends on a variety of factors such as grade, road width, etc. This constant deceleration can be changed as an option to the program. For more details see the User's Manual in Appendix A of this document. When the program performs the calculations for braking, it will calculate the time needed to reach zero velocity at the end of the segment, from the current speed at which the vehicle is traveling. If the distance required for braking is greater than the available distance for all cases the program will exit.

If the vehicle is trying to go as fast as possible the following formula is used to calculate acceleration.

$$Acceleration = (RimpullFromSpeedAndGear(DandV(2), Gear) - GVW * EG * 9.81) / GVW$$

RimpullFromSpeedAndGear is a function called by *Acceleration* in order to calculate the rimpull in that gear and at the speed in which the vehicle is traveling. This function calculates the rimpull that the vehicle can develop at a particular speed and particular gear. This function takes into consideration the cases in which no rimpull is being generated (i.e. when the vehicle is in neutral). The piece of code below shows how this situation is considered.

```
if Gear==0
theRimpull=0;
else
theRPS=Speed*Reductions(Gear)/2/pi/WheelRadius;
theRimpull=Torque(theRPS)*((Efficiencies(Gear)*Reductions(Gear)/WheelRadius));
```

The function *theRimpull* calls the function *Torque(theRPS)*. The function *Torque(theRPS)* interpolates to get the value of torque at the current RPM. After doing the interpolation, this function returns the value of torque at current RPM and this allows the calculation of rimpull at current gear, current speed and current RPM.

```
theTorque=Interp1(RPM/60,EngTorque,rps,'spline');
```

In the above expression *Interp1* tells the program that an interpolation needs to be done. *RPM/60* and *EngTorque* are the values from which the interpolation will be done.

The *rps* is the value used to compare with *RPM/60* and then interpolates to get the value of torque. The parameter *spline* indicates which type of interpolation the program will perform.

If the vehicle is trying to slow down to *TargetSpeed* then the model calculates the distance and time required to reach target speed at the end of the segment with the vehicle traveling at current speed. If the value of target speed is less than maximum speed or speed at which the vehicle is traveling, then the program simulates the braking effect. The program uses a constant deceleration to model the application of the brakes. If the distance required to reach *TargetSpeed* is greater than the available distance, the program exits and displays a message that says that the available distance is not enough to simulate the braking effect.

When the ode (i.e. ordinary differential equation) function is handling events, the ode file has to be coded to return three values in response to the events flag. An example of how this function was set is shown below. The complete code is not shown, because we want to show how the function works. For further information on the whole function please refer to Appendix B.

```
function [value,isterminal,direction] = events(CurSpeed,Gear, TotalDistance, Distance)
..... some computations go here
value=[valueAccel,valueDeccel,TotalDistance-Distance];
isterminal=[1,1,1];
direction=[-1,-1,+1];
return;
```

The first output *value* is the vector of event function evaluated at the time and specified conditions. It is evaluated at the beginning and end of each integration, to check if any elements make transitions to, from or through zero (depending on the direction specified), the function uses extension formulas to determine the time when the transition occurred.

The argument *isterminal* is a logical vector of 1s and 0s that specifies whether a zero crossing of the corresponding value element is terminal. Terminal events halt the integration. A value of 1 corresponds to a terminal event; a value of 0 corresponds to a non-terminal event. The *direction* vector specifies a desired directionality positive (1), negative (-1) or don't matter (0), for each value element (MATLAB™).

The general format of the function used to call the differential equation solver is the following:

```
[tg,DandVg,TE,YE,IE]=ode45('FastAP',[CurTm:TimeDelta:TimeLimit], [CurD; CurV],  
    odeset('Events','on'), CurGear, Distance);
```

The entries in *tg* and *DandVg* are used to hold the values of time, distance and velocity, respectively while the model is solving the differential equation. Entries in *TE*, *YE*, and *IE* return, the time at which an event takes place, the solution of the equation at the time of the event, and the index of the event function that crosses zero at any instant. *IE* in our case holds the index for a gear change while accelerating, a gear change while decelerating or indicates that the total distance has been traveled. *FastAP* is a function that evaluates the right hand side of the differential equation. *CurTm*, *TimeDelta*, and *TimeLimit* are values that specify the interval of integration. *CurD* and *CurV* are the initial speed and initial distance used as initial conditions. *CurGear* and *Distance* are arguments passed to the differential equation to verify which event function crosses zero.

When the ode file is handling events and immediately after the calculation of acceleration and integration to get the values for distance and speed, the model checks for gear change. If the haul unit is trying to go as fast as possible, the model checks if the rimpull that can be provided by the next gear is higher than the one that can be provided by the current gear, the model will change one gear up for the equipment. If the model is trying to reach a target speed, the model checks if retarding pull provided by the lowest gear that precedes current gear is higher than the one that can be provided by the current gear. If this is the case the model change gears to current gear minus one. In addition, the

model checks if the travel distance has been reached at the current gear. The following piece of code shows how this process is modeled.

```

switch IE(1)
    case 1
        disp(['Shift from ', num2str(CurGear), ' to ',
num2str(CurGear+1), ' at time ', num2str(TE), ' and speed ',
num2str(YE(2)*3.6)]);
        CurGear=CurGear+1;
    case 2
        disp(['Shift from ', num2str(CurGear), ' to ',
num2str(CurGear-1), ' at time ', num2str(TE), ' and speed ',
num2str(YE(2)*3.6)]);
        CurGear=CurGear-1;
    case 3
        disp(['Travel distance reached while at gear ',
num2str(CurGear), ' at time ', num2str(TE), ' and speed ',
num2str(YE(2)*3.6)]);
        CurTm=TE;
        CurD=YE(1);
        CurV=YE(2);
        break;

```

In the piece of code shown above, Case 1 will take place when the machine is accelerating. In this case the machine will be changing gears from the current gear, increasing by one until it reaches the maximum speed. Case 2 will take place when the machine is decelerating, but not braking. In this case the machine will be changing gears in a decreasing mode (i.e. from current gear going down to current gear -1). Case 3 will take place when the total length of the haul road has been reached. When case 3 takes place the calculations stop and the program displays the time and speed at which total distance was reached.

The piece of code shows the decision making process to change gears or finish the calculation process when the total distance is reached. This stage is reached when the event handler receives an *isterminal* value to be equal to 1. All the calculations shown above take place until the vehicle has traveled the total length of the segment. This section explained the calculations performed in order to get the values of velocity and position with the calculations for acceleration also shown. The process shown for

accelerating mode is similar to the process for engine retardation mode with slight changes. Engine retardation is used to keep the vehicle traveling at a maximum speed while going downhill. Both functions can be seen as part of Appendix B.

This section presented the cases that the program considers in its calculations. Acceleration period, engine retardation period and braking simulation were presented and briefly discussed. The next section will explain the final results (i.e. travel time, profiles, etc.) after the vehicle has traveled the total length.

5.3.3 RESULTS

This section presents the results obtained with the program after all the calculations are performed. The primary result is the calculation of travel time for a haul unit in a certain haul road. As was mentioned earlier the program considers all the cases illustrated in Figure 5.4. The model is available to be used in the MATLAB™ environment. The model calculates travel time, generates speed and distance profiles and monitors equipment performance along the haul road under a set of conditions defined by the user. Other outputs include torque, rimpull, retarding torque and retarding pull curves that were obtained from the description that the user gave of the power and retarding power curves. These graphs can be seen in Figures 5.5, 5.6, and 5.7. In addition, the program prepares a table with information about the vehicle's performance in every segment. Information contained in that table includes segment number, distance, velocity and gear at the beginning of the segment, velocity and gear at the end of the segment, maximum speed at the end of the segment, and time taken to travel the segment. Table 5.2 is an example of the table generated by the program.

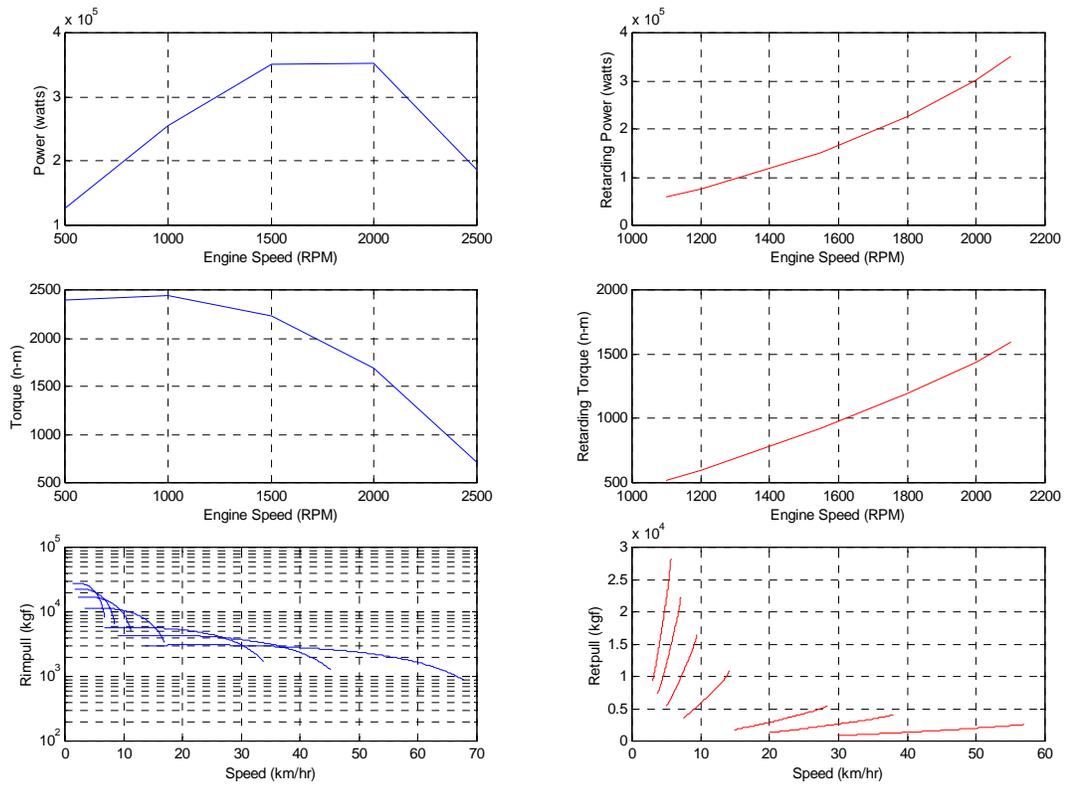


Figure 5.5 Rimpull, Torque, Power, Retpull, Rettorque and Retpower Curves for the haul unit

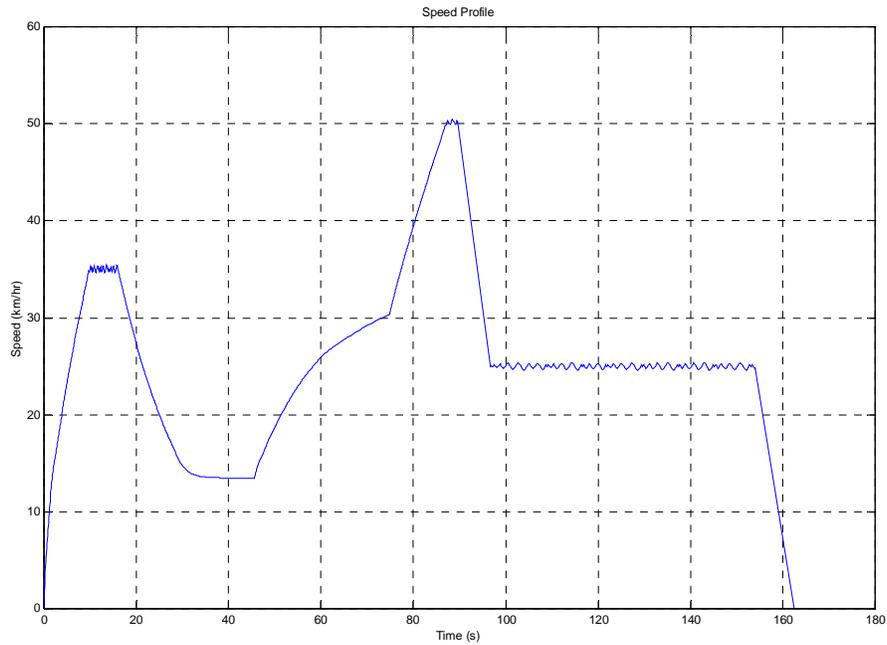


Figure 5.6: Speed Profile for a haul unit

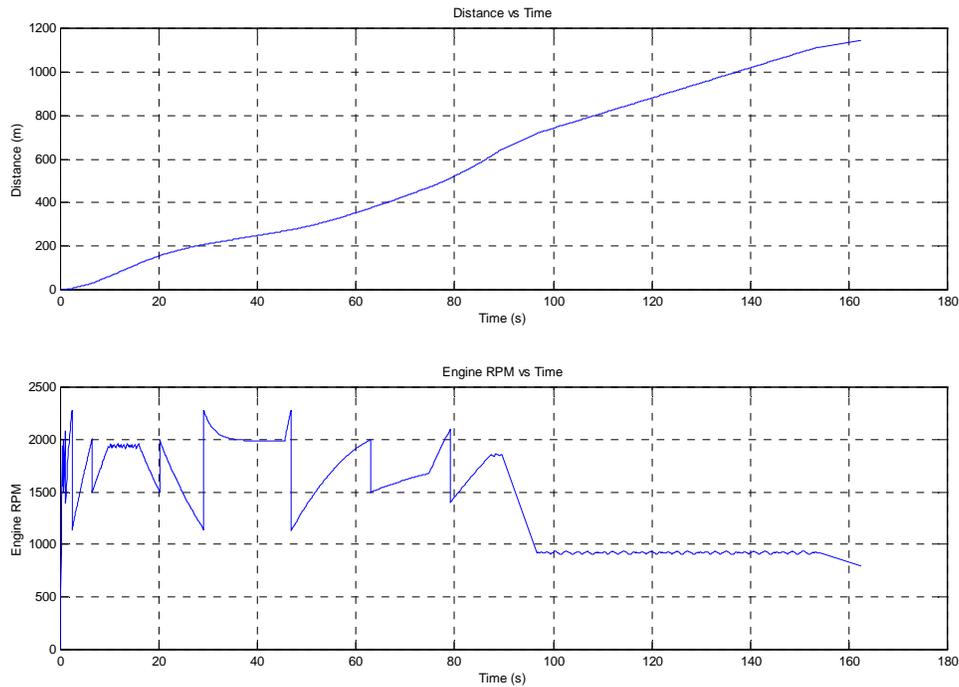


Figure 5.7: Distance vs. Time and Engine RPM vs. Time graphs

SegmentNumber	Length(mts)	EntranceSpeed(km/hr)	EntranceGear	EndingSpeed(km/hr)	EndingGear	MaxSpeed(km/hr)	Time(secs)
1	120	0	1	35.07	6	35.41	15.99
2	150	35.07	6	13.46	4	35.07	29.59
3	200	13.46	4	30.33	6	30.33	29.24
4	175	30.33	6	50.19	7	50.45	14.87
5	500	50.19	7	0	1	50.19	72.69

Table 5.2: Equipment Parameters by segment as output by the model

A brief description on the process used to calculate the travel time and to model equipment performance follows. The travel time calculated by the program is divided in two parts when the vehicle is trying to go as fast as possible and when the vehicle is trying to slow down to a target speed. The calculation when the vehicle is trying to go as fast as possible is taken directly from the time vector obtained from the calculations. The reasoning used for each of the situations will be explained in the following sections.

The program can model different scenarios. It has the capability to model the scenarios presented in Figure 5.4. The first scenario could be represented with the vehicle at rest (i.e. zero velocity), trying to go as fast as possible in that segment, which means that the user does not limit the maximum speed that the haul unit can reach. The second scenario represents the vehicle at rest going as fast as possible but trying to reach a target speed at the end of the segment. This target speed might be defined by the maximum speed of the other segment or any other particular situation. The third scenario is when there is a negative grade. If the machine enters the segment at a speed lower than the speed limit, the vehicles accelerates until it reaches the maximum speed of the segment. In this case the model simulates the braking effect if it has to reach a target speed, which could be zero or any other value specified by the user. If the target speed is greater or equal to the maximum speed, then the vehicle will try to go as fast as possible. For all the cases the model checks, when the vehicle enters the segment, if the current speed of the haul unit is greater than the maximum speed of the segment. If this is the case, then the model simulates the braking effect to slow the vehicle to speed limit of the segment.

When the vehicle is trying to go as fast as possible and the speed limit is not limited by the haul road, the model creates one velocity profile and then gets the results from this profile. The values of interest can be directly obtained from this profile.

When the vehicle is trying to go as fast as possible and the speed limit is dictated by either the maximum speed of the current haul road or the maximum speed of the next haul road, the model creates two velocity profiles and then gets the results from these profiles. The first velocity profile goes from the vehicle's current velocity until it reaches maximum speed or speed limit. The second velocity profile goes from maximum speed or speed limit decreasing until it reaches the target speed. This second profile gives the distance needed to go from speed limit to target speed. The travel time is calculated using the following procedure. The vehicle tries to go as fast as possible, until intersects with the speed reduction profile. As was mentioned the speed reduction profile will give the distance needed to start decreasing speed in order to reach the target speed at the end of the segment. The time taken from current velocity until it reaches the point of intersection

with the decreasing speed profile plus the time taken from decreasing speed profile until it reaches target speed gives the total travel time for that particular segment.

When there is a negative grade and the vehicle tries to slow down to reach a target speed the program prepares two velocity profiles. These scenarios could be represented by either cases d or e in Figure 5.4. The first velocity profile models the maximum speed or speed limit that the vehicle can sustain. This velocity is determined by using the engine retardation curves. The second velocity profile goes from maximum speed or speed limit decreasing until it reaches the target speed. This second profile gives the distance needed to go from speed limit to target speed. The travel time is calculated using the following procedure. The vehicle tries to go as fast as possible, until it intersects with the speed reduction profile. As was mentioned the speed reduction profile will give the distance needed to start decreasing speed in order to reach the target speed at the end of the segment. The time taken from current velocity until it reaches the point of intersection with the decreasing speed profile plus the time taken from decreasing speed profile until it reaches target speed gives the total travel time for that particular segment.

When the program is performing the calculations for braking, it calculates the time needed in order to reach zero velocity at the end of the segment, while the vehicle is traveling at the maximum speed specified by the user. The following formula is used to calculate the time consumed:

$$\textit{Time required} = \textit{Maximum Vehicle Speed in Segment} / \textit{Constant Deceleration}$$

Once the program has calculated the braking distance required to reach a zero velocity at the end of the segment, and then it proceeds to calculate the time required to go from the maximum vehicle speed to a zero velocity. The following formula is used to perform such calculation.

$$\textit{Distance Traveled} = \textit{Maximum Vehicle Speed in Segment} * \textit{Time Required} - 0.5 * \textit{Constant Acceleration} * \textit{Time Required}^2$$

This is a simple formula from engineering mechanics or physics. With the distance needed for the vehicle to come to a stop (i.e. zero velocity), the distance in which the vehicle is traveling without the braking effect can be calculated. This distance is equal to the total distance minus the distance needed for braking. With this value known, then the program checks for this value in the matrix that contains the values of distance, with a tolerance of 0.05 m, and gets the value that matches that distance from the matrix that contains the values of time. The program then adds both values, braking time plus non braking time, and this is the total travel time for the segment. In any of the cases, if the distance needed for braking is greater than the available distance, the program will display a message and will exit the calculations.

5.4 SUMMARY

In this chapter, the process of power transfer from the engine until it reaches the area of contact between the wheel and surface, methodology used to develop the model, and the model were explained. The terms and commands used in the computer program were explained and discussed. The data needed by the model was presented, the model itself was described in detail and the results obtained were discussed. It was shown that the model considers the parameters that have an effect in a detailed way. This model will allow the development of other models in future research such as probabilistic travel time, fuel consumption, brake heat buildup and wear, etc. The amount of detail used allows extensions as these to be easily included.

Chapter 6: Validation of the model and Comparison of Results with TALPAC and VehSim

Chapter 4 presented the methodology developed to estimate fundamental equipment data needed as input to the model. Chapter 5 explained the methodology used to develop the performance model and the model itself. This chapter presents an analytical validation of the model. In addition, the chapter presents a comparison of the results obtained with the program with two commercially available packages: Truck and Loaders Productivity and Costing (TALPAC) by Runge Mining Systems, and VehSim by Caterpillar.

6.1 VALIDATION OF THE MODEL

The model developed as part of this research followed fundamental laws of physics and dynamics. The model is analytical, and was validated by proving that the model output conforms to the laws of physics and dynamics.

To illustrate this, let's analyze typical output of the model, such as the one shown in Figure 6.1. This figure shows a graph of distance vs. time, a velocity profile, a graph of acceleration and rimpull vs. time, a graph of rpm vs. time, and a power curve. In order to conform to the principles of physics and dynamics, the slope (or first derivative) of the velocity profile should be equal to the acceleration at that instant where the derivative is computed. Similarly the slope or derivative of the distance profile curve should be equal to the instantaneous velocity of the vehicle at the instant where the slope is calculated. To verify the program output, several checks were performed using these simple principles of physics. The model validation was done by comparing the program output with the values back calculated from first derivatives. To illustrate this validation scheme, let's compute the first derivative of the displacement curve (Figure 6.1) at a time equal to 5 seconds. The vertical red line that crosses the graphs illustrates where the derivatives are taken, (at a time equal to 5 seconds). The derivative of the displacement curve at 5 seconds was calculated using output data from the model and the value was

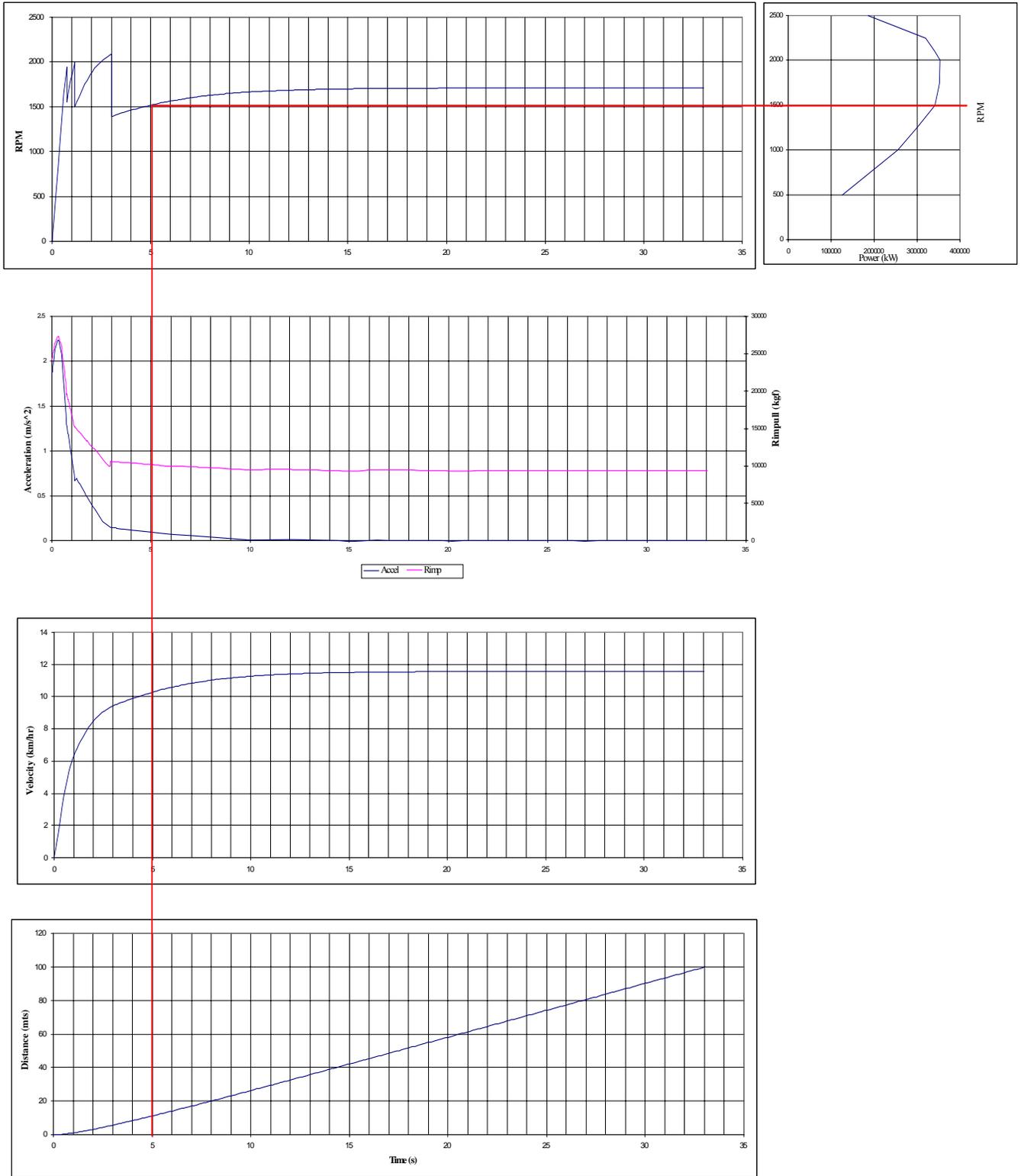


Figure 6.1: Distance vs. time, velocity profile, acceleration and rimpull vs. time, rpm vs. time, and power curve as obtained with the model

10.3 km/hr. If the model output is correct, we should obtain the same velocity value (at $t = 5$ s) from the velocity profile output. It can be seen, from Figure 6.1, that the velocity at time equal to 5 seconds is 10.3 km/hr. This suggests that the model is doing the right calculations. At time equal to 5 seconds, the derivative of velocity, calculated using output data, is equal to 0.103 m/s^2 . The value of acceleration at that time from the graph is equal to 0.10 m/s^2 . Again, the proximity in the results suggests that the program follows the laws of physics and dynamics. The rimpull obtained at the velocity is equal to 10,400 kgf.

To calculate the RPM we need to know the reductions for the gear and the current speed. For this particular piece of equipment the total reduction for the fourth gear is 56 and the total efficiency is 0.83. With this information, the RPM can be calculated as follows:

$$RPM = Reduction * speed * 60 / 2 / pi$$

$$RPM = 56 * 60 * 10.3 / 3.6 / 2 / pi$$

$$RPM \approx 1530$$

From the RPM vs. Time graph in Figure 6.1, it can be seen that the RPM at time equal to 5 seconds is a just a little bit higher than 1500, which suggests that the program follows the laws of physics and dynamics.

The power that the machine is developing at this speed can be obtained using the following equation:

$$Power = Rimpull * speed$$

$$Power = 10,400 * 10.3 / 3.6 * 9.81 / 1000$$

$$Power \approx 292 \text{ kW}$$

If the efficiencies are applied to this power, then we should obtain the maximum power that the engine is able to develop at this RPM. The maximum power that the machine can develop at this RPM is given by the following formula:

Maximum Power at current RPM = Power at current speed / efficiency

$$\text{Maximum Power} = 292/0.83$$

$$\text{Maximum Power} \approx 351.8 \text{ kW}$$

The maximum power calculated is similar to the maximum power given by the manufacturer for this machine at current engine speed, which is 350 kW. This value can be obtained from the power graph in Figure 6.1. The differences are due to rounding and approximations while reading from the graphs. With the values obtained, it can be said that the model is doing the right calculations.

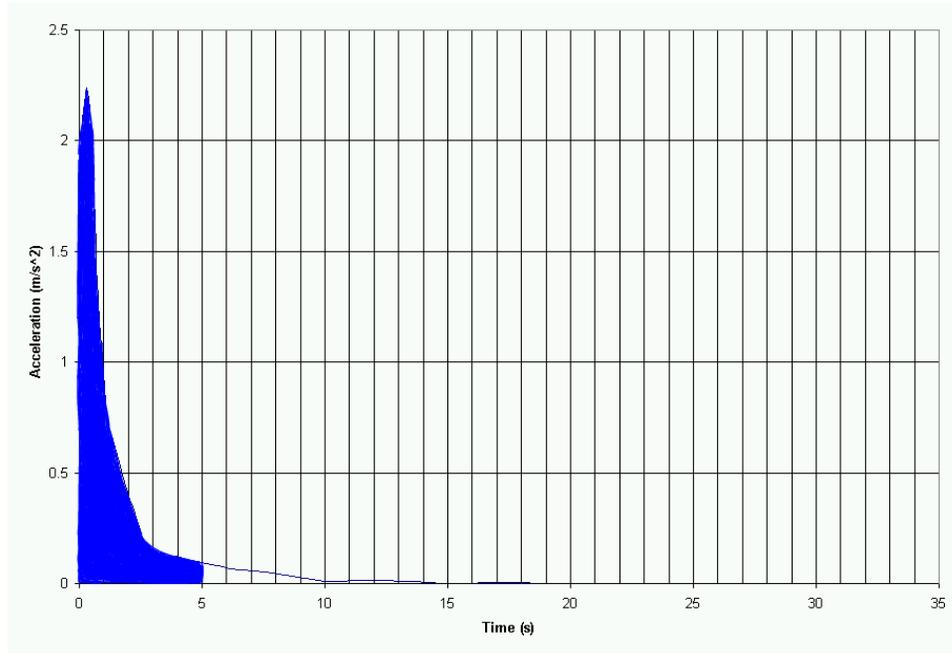
The same analysis was done at different values of time to verify that the program is doing the right calculations. Table 6.1 summarizes the values calculated using data output from the model and the values obtained from the graphs in Figure 6.1.

Time (s)	Acceleration (m/s ²)		Velocity (km/hr)		RPM		Maximum Power (kW)	
	Calculated	From Graph	Calculated	From Graph	Calculated	From Graph	Calculated	From Manufacturer
5.00	0.10	0.10	10.30	10.30	1530.01	1515.00	351.80	350.00
10.00	0.02	0.02	11.29	11.30	1677.07	1650.00	352.13	351.50
15.00	0.01	0.00	11.51	11.50	1709.75	1700.00	351.90	352.00
20.00	0.00	0.00	11.56	11.50	1717.18	1700.00	352.30	352.00
25.00	0.00	0.00	11.57	11.50	1718.66	1700.00	352.22	352.00

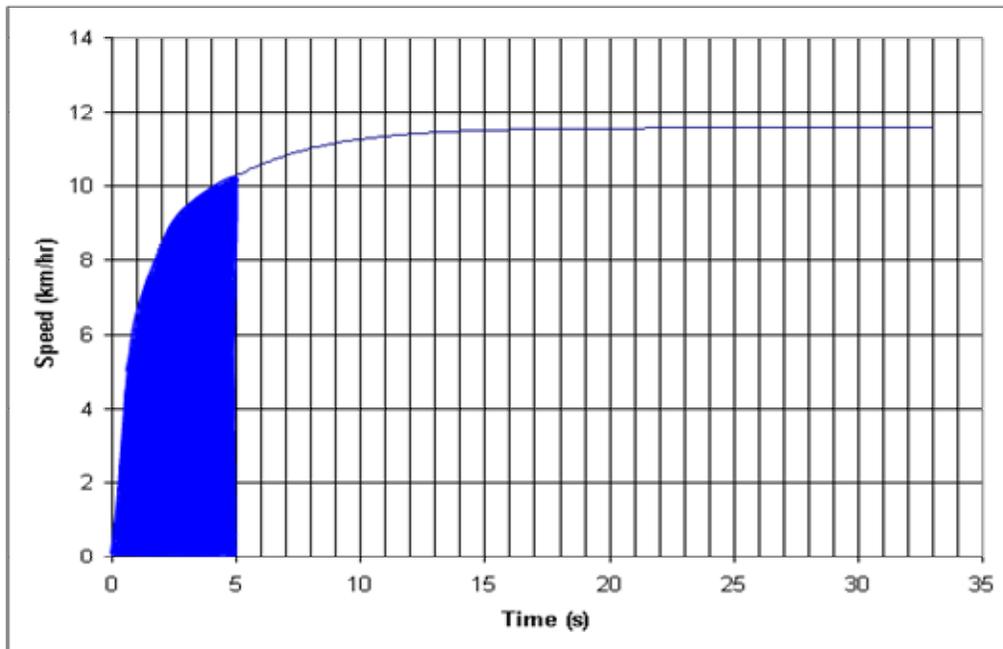
Table 6.1: Calculations at different values of time

A similar analytical analysis can be done to verify that the program is doing the right calculations by calculating the area below the velocity and acceleration profiles. An integration of the velocity profile should give the distance that has been traveled at that particular time. The velocity profile and acceleration profiles for the equipment can be seen in Figure 6.1. If integration is taken between any two points in the velocity profile, then we should obtain the distance traveled between those points. This is the same as the area under the curve. Similarly, if integration is taken between any two points in the acceleration profile, then we should obtain the difference in speed between those points. In order to get an accurate result, a digitizer should be used to calculate the area. Using a

simple numerical integration procedure (e.g. trapezoidal rule) one can obtain the area under the curve. Figure 6.2 illustrates a velocity profile and an acceleration profile.



(a)



(b)

Figure 6.2: Acceleration and Velocity Profiles

The area of interest is the shaded area. The value obtained for area under the acceleration profile between times 0 seconds and 5 seconds for this example was around 2.85 m/s² or 10.26 km/hr. The value of speed obtained from the velocity profile at time equal to 5 seconds is 10.3 km/hr. The difference in velocity between the two points is around 10.3 km/hr. The proximity of both values suggests that the program is doing the right calculations. Similarly, if the area between times equal to zero and 5 seconds is taken, then the distance traveled should be obtained. Using the same simple numerical integration procedure, the area under the velocity profile was around 11 meters. From the distance graph it can be seen that the distance traveled between times 0 and 5 seconds is equal to 11 meters. If more accurate integration methods are used, the two values will be the same. Based on this example it can be inferred that the model is doing the right calculations. The same procedure was done at different intervals of time. The results are summarized in Table 6.2.

Times		Velocity		Distance	
T1	T2	Integration	Graph	Integration	Graph
0.00	5.00	10.26	10.30	11.00	11.00
10.00	15.00	0.20	0.20	15.87	16.00
25.00	30.00	0.00	0.00	16.00	16.00

Table 6.2: Comparison of values obtained with integrations and values from the graphs

Based on the simple calculations described above it was shown that the model is doing the right calculations. The model gives the right results with the assumptions made while developing it. The model complies with the fundamentals laws of physics, such as power is equal to force multiplied by speed. If the power curve is constant for all gears, the ratio between the speed of the engine and the speed of the vehicle is equal to the reduction, the ratio between the power of the axle and the engine power is equal to efficiencies, then the model is doing the right calculations.

6.2 COMPARISON OF THE RIMPULL CURVES

Using the procedure described in Chapter 4, the efficiencies and reductions were calculated for Caterpillar equipment. The same methodology can be used to calculate the data for hauling equipment built by other manufacturers. With the efficiencies and reductions known, the next step was to prepare a rimpull with this data and then to compare this rimpull with the rimpull curve supplied by the manufacturer. This comparison will highlight the accuracy of the methodology developed to calculate efficiencies and reductions. If the methodology is accurate, then both curves should be the same and they should plot one on top of the other. Figure 4.3, illustrates a comparison of the rimpull curve prepared using the data calculated and the rimpull curve supplied by the user. It can be noted that both curves are the same and they plot one on top of the other. Figures 6.3 and 6.4 present other comparisons of rimpull curves for another articulated truck, and a rigid frame truck. In the graphs, it can be seen that both curves are the same, which proves that the methodology used to estimate efficiencies and reductions is appropriate since the values of rimpull calculated with this data are the same values supplied by the manufacturer. The data used to make this comparison of rimpull curves can be seen in Appendix C.

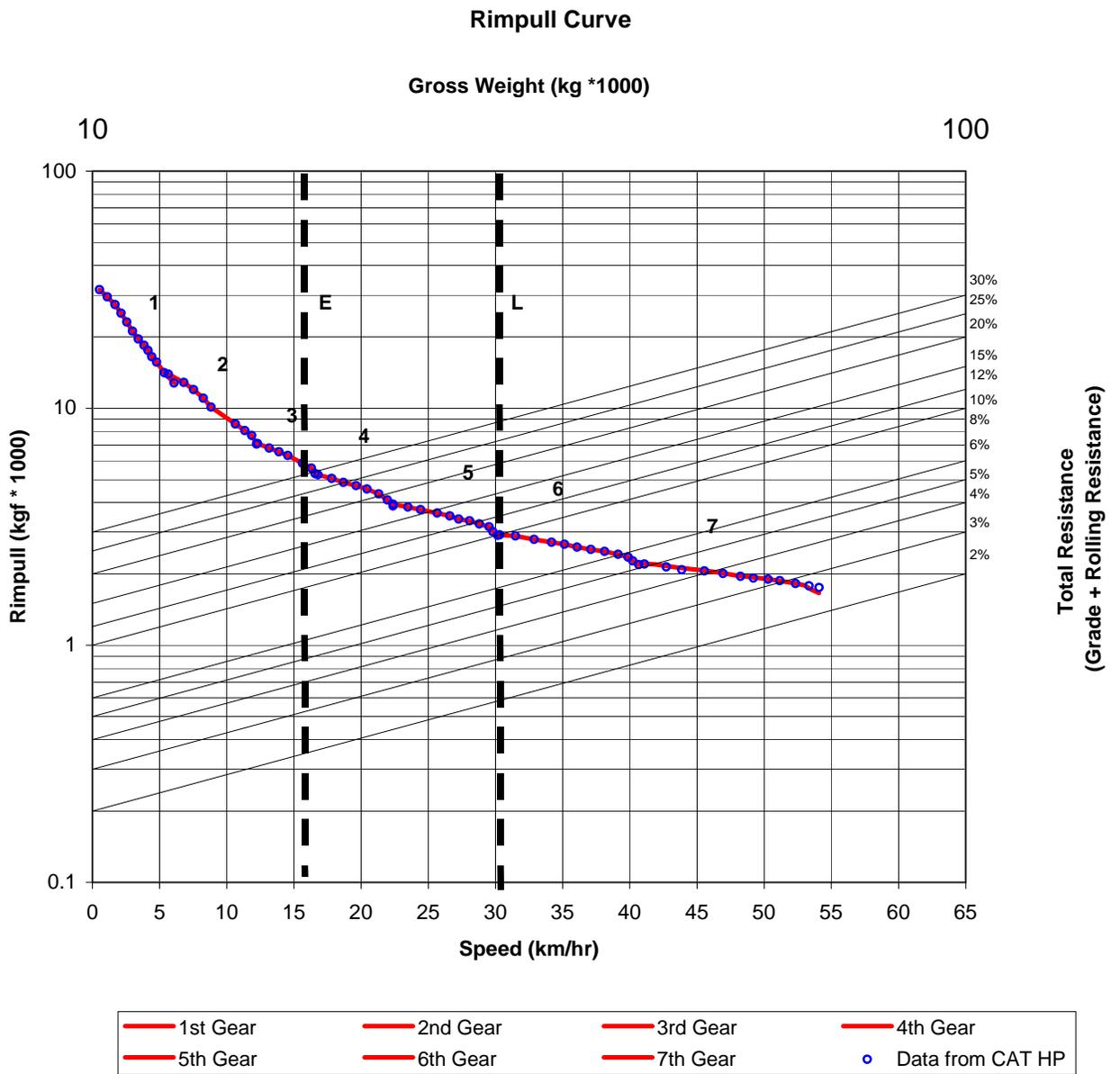


Figure 6.3: Comparison of Rimpull Curves for a CAT400 Series II Articulated Truck

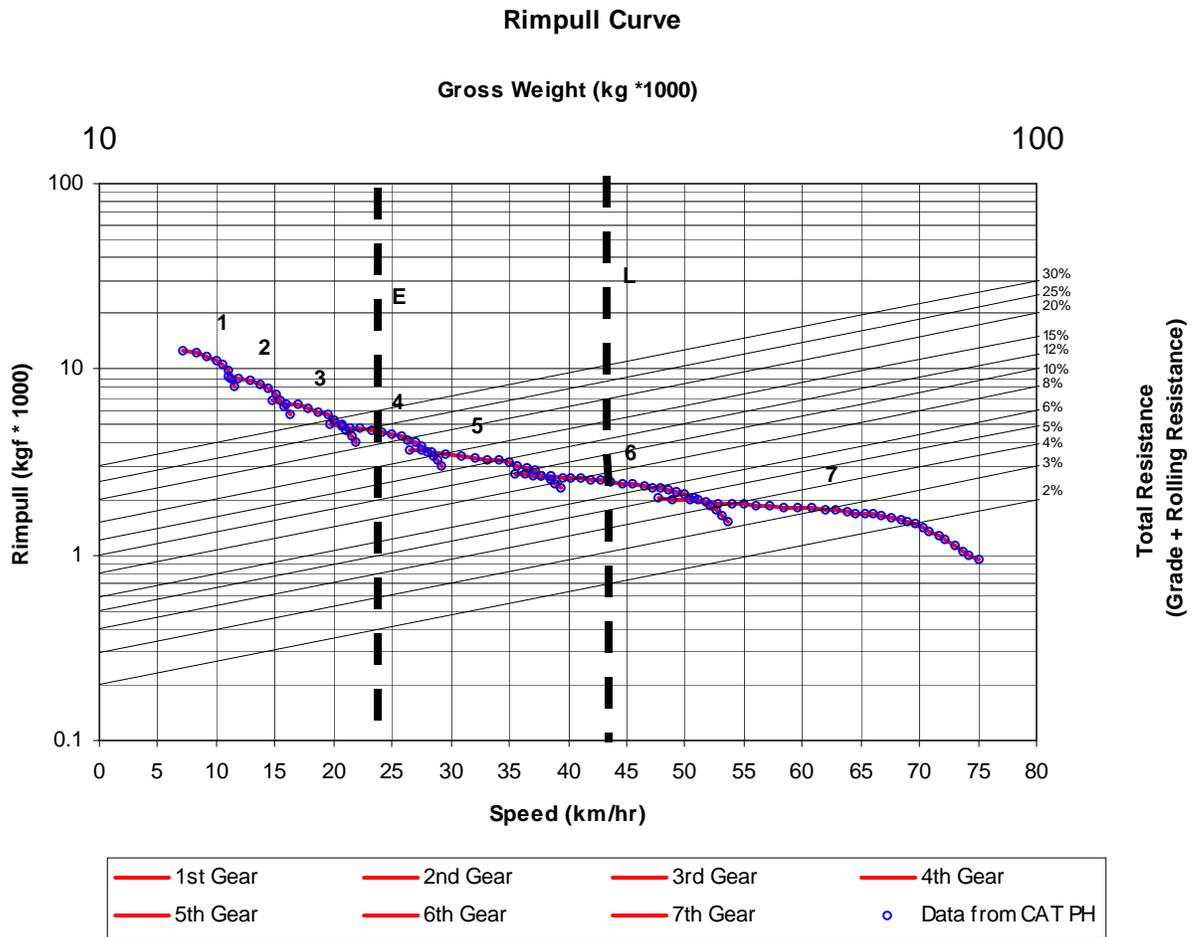


Figure 6.4: Comparison of Rimpull Curves for a CAT769D Rigid Frame Truck

6.3 PREPARING THE RIMPULL CURVE

This section presents the basic equations needed in order to prepare the rimpull curve from fundamental data. This section gives the equations needed to calculate torque, rimpull and speed once the fundamental data is available. Different lines that represent the maximum rimpull that the vehicle can develop under certain equivalent grades should be plotted in the same graph. The reader should refer to other sources if interested in learning in detail how to prepare a rimpull curve.

The data captured with DataThief to perform the calculations for efficiencies and reductions was the same data used to plot the rimpull curve supplied by the manufacturer. The data needed to construct a rimpull curve is the RPM of the engine, the power at the corresponding RPM, efficiencies, reductions, and the wheel radius. Once this data is available the following equations are used to obtain the points needed.

$$\text{Torque} = \text{Power} / \text{RPM} / 60 / 2 * \pi$$

$$\text{Rimpull} = \text{Torque} * \text{efficiencies} * \text{reductions} / \text{wheel radius}$$

$$\text{Speed} = \text{Efficiencies} * \text{Power} / \text{Rimpull}$$

6.4 COMPARISON OF TRAVEL TIMES

This section provides a comparison between the travel times obtained with the model with results obtained with TALPAC and VehSim. The comparison was made with the values assumed while developing the model. Various segments were defined and the travel times were calculated for a CATD25D articulated truck and a CAT777 rigid frame truck. Differences between the values obtained with TALPAC and VehSim and the values obtained with the model are expected. A more detailed study of the velocity profiles can be done between TALPAC and the model to highlight the differences. The same analysis cannot be done with VehSim because it operates as a black box and there are no velocity profiles as outputs. TALPAC sets the default maximum acceleration to 1.5 km/hr/s. In addition, some of the values used as maximum velocity for certain segments are less than the values given by the Caterpillar Performance Handbook. A comparison between the model and TALPAC given these conditions is not useful. In order to make a valid comparison, the maximum velocity for the segments in both the model and TALPAC should be set to the same values. In addition, the acceleration in TALPAC should be set to a high value. Table 6.3 presents the comparison of travel times for a CATD25D articulated. The acceleration in TALPAC was set to a big value (i.e. 35 km/hr/s) and the maximum velocity in the model was limited to the maximum value that TALPAC uses.

Road	Segment 1		Segment 2		Segment 3		Travel Time (mins)		
	Distance	EG (%)	Distance	EG (%)	Distance	EG (%)	TALPAC	VehSim	Model
1	200	10	500	0	0	0	1.79	1.36	1.76
2	300	-5	400	0	0	0	1.74	1.04	1.70
3	200	3	300	-3	200	4	1.51	1.28	1.48
4	400	-3	200	2	300	-2	1.66	1.30	1.62

Table 6.3: Travel Times for CATD25 Articulated

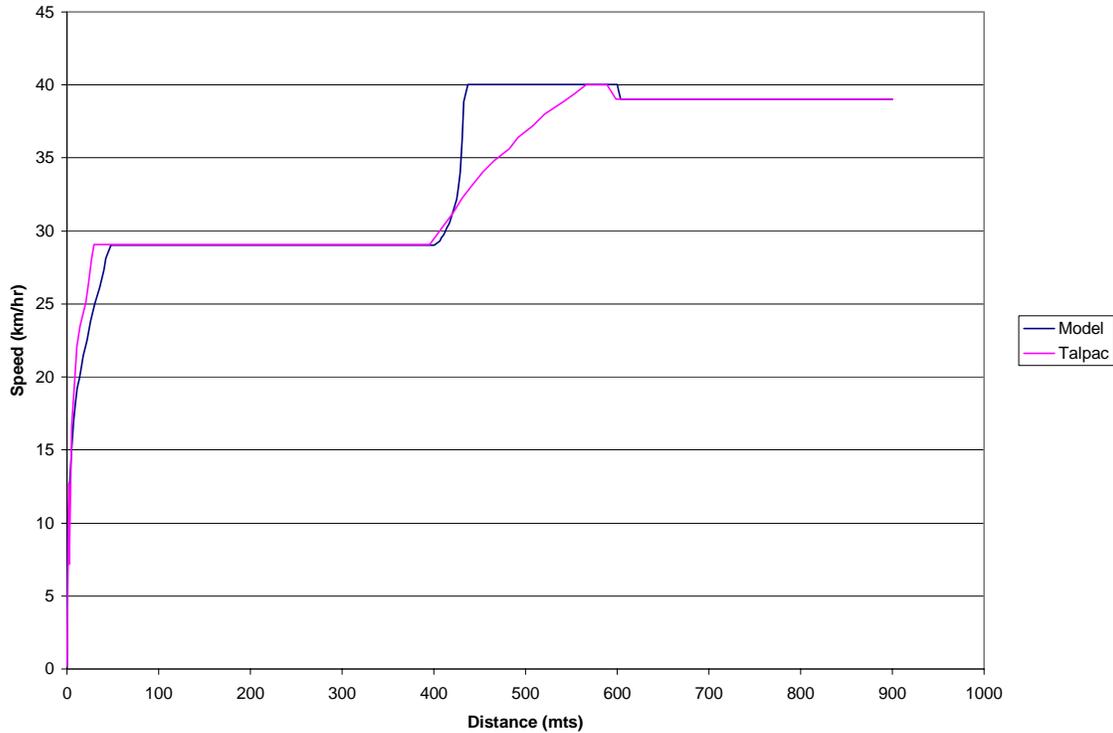


Figure 6.5: Velocity profiles generated by TALPAC and the model for a CATD25D

The profiles are quite similar, except in the range 400 meters minutes to 600 meters. The discrepancies before 100 meters are due to the fact that Talpac makes some simplifying assumptions about the truck's acceleration behavior by using approximations to describe the rimpull curve. It is obvious that in this case those assumptions are quite reasonable because its differences with our detailed model are minimal. Between 400 meters and 600 meters, the differences are mostly due to assumptions on operator behavior. Apparently, Talpac assumes that the operator will increase its speed gradually from the fastest speed it could develop in the prior segment (29 km/hr) to the speed it would be able to sustain in the next segment (39 km/hr). Our model, on the other hand, recognizes that the truck has

enough power to quickly accelerate to the maximum speed of the intermediate segment (40 km/hr). In addition, the model is able to determine how far ahead of the end of the intermediate segment it can start deceleration (or braking) so that it would enter the subsequent segment at its highest allowed speed. The model has, indeed, the capability to start deceleration after it enters the last segment by specifying an option. Thus, our assumptions on operator behavior reflect maximum possible performance, and for that reason the travel times reported by Talpac are greater than the travel times that the model reports. The difference is very small and indicates that Talpac's approximations and assumptions are acceptable for most uses.

Table 6.4 presents the travel times obtained with TALPAC, VehSim and the model for a Caterpillar 777 rigid frame truck. Again, there are differences between the values obtained with the model and the values obtained with TALPAC and VehSim. Similar to the analysis done for the CATD25D, the acceleration in TALPAC was set to a big value (i.e. 35 km/hr/s) and the maximum speeds in the model were limited to the values used by TALPAC.

Road	Segment 1		Segment 2		Segment 3		Travel Time (mins)		
	Distance	EG (%)	Distance	EG (%)	Distance	EG (%)	TALPAC	VehSim	Model
1	200	10	500	0	0	0	1.65	0.91	1.58
2	300	-5	400	0	0	0	1.04	0.99	1.00
3	400	-3	200	2	300	-2	1.00	1.15	0.95
4	200	3	300	-3	200	4	1.02	1.17	0.96

Table 6.4: Travel Times for CAT777 Rigid Frame Truck

The results obtained between the model and TALPAC are very close. The differences between the model and TALPAC can be highlighted by analyzing the velocity profiles presented in Figure 6.6.

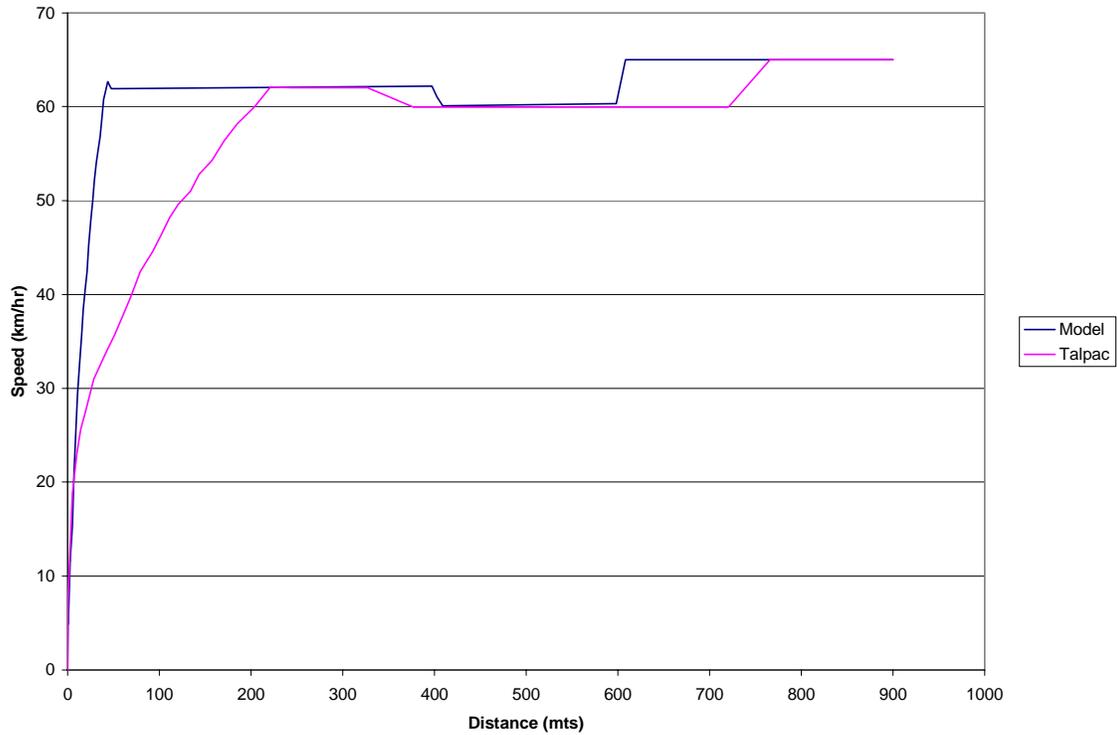


Figure 6.6: Velocity profiles generated by TALPAC and the model for a CAT777

The profiles are different due to differences in assumptions for acceleration behavior. The model assumes that the vehicle is traveling at maximum acceleration. Talpac, on other hand makes some simplifying assumptions about the truck's acceleration behavior. Talpac divides the segment into a series sub segments and they assume that the acceleration for the particular sub segment is constant. In this case, those assumptions produce results different than those given by the model. Our model is able to determine how far ahead of the end of the intermediate segment it can start deceleration (or braking) so that it would enter the subsequent segment at its highest allowed speed. Talpac operates in a similar way by assuming that the speed of the vehicle at the end of the current segment is equal to the maximum allowable speed of the next segment. The difference in the profiles is due basically to the constant deceleration assumed for braking. Our model uses a constant deceleration equal to 0.83 m/s^2 . This value was determined from data collected in the field. The user has the option to change the value of constant deceleration that the program will use for braking purposes. Talpac uses a

constant deceleration equal to 1.5 km/hr/s or 0.417 m/s². Between 400 meters and 600 meters, both the model and Talpac assume that the operator is willing to operate the machine at maximum allowable speed. Between 600 meters and 900 meters the differences are mostly due to assumptions on operator behavior. In the model, the vehicle's has enough power to quickly increase the speed from the maximum allowed in that segment (60 km/hr) to the speed it would be able to sustain in the next segment (65 km/hr). Talpac, on the other hand, assumes that the vehicle is traveling the majority of the last segment at the maximum allowed speed of the previous segment (60 km/hr). At the end of the last segment, Talpac assumes that the vehicle has enough power to reach the maximum allowable speed for the particular segment (65 km/hr). Our assumptions on operator behavior reflect maximum possible performance, and for that reason the travel times reported by Talpac are greater than the travel times that the model reports. The difference is very small and indicates that Talpac's approximations and assumptions are acceptable for most uses.

If any user intends to simulate equipment performance using the model, measures of equipment characteristics and haul road conditions are essential in order to input accurate values, thus get accurate values. The advantage of using this detailed model is that we have confidence in this model because we understand what is happening and it was shown that the model is doing the right calculations. In addition, some other applications could be incorporated very easily with the amount of detail included in this model. Among these applications are fuel consumption, brake heat build up and other applications that could depend on the engine RPM history.

6.5 COMPARISON WITH REALITY

The validation of the model was done in section 6.1. Calibration using field data is not necessary because this is an analytical model, therefore analytical methods should be used for validation. The things what would be validated with reality would be the parameters to the model such as maximum speed and accelerations. However, these items are not part this model. The results are guaranteed accurate so long as the inputs have

been validated and are accurate. If a user wants to compare the results obtained with the model with results from an actual operation, then the user has to measure equipment characteristics and haul road conditions accurately to input them in to the model. Several factors have to be considered when collecting such data. Equipment, such as dynamometers, is needed to obtain the power curves, efficiencies and reductions of the haul unit. These values should be measured in the haul unit that will be used because they can be different from the values given by the manufacturer due to use and aging of the equipment. Equipment to measure the value of the rolling resistance is needed on the particular segment. This data collection for travel times has to be controlled. The exact distance of the segment is needed. In addition, the operator has to maintain a 100% pressure to the throttle at all times. An attempt to compare the “uncalibrated” model with a Global Positioning Systems (GPS) data file was made. The file for a particular haul road was analyzed. High variability in travel times for the equipment was observed; therefore it was difficult to compare the values obtained with the “uncalibrated” model with what was observed in the field. In order to do a good comparison the model has to be calibrated first and the data collected from the operation should be uniform with respect to travel times observed. In addition, the conditions mentioned above should be met.

Any model, such as the one developed in this research, is an abstraction of reality and not reality itself. Similar to many models, this model is an approximation that might not exactly represent what is taking place in the field, but it is a good approximation of the process being modeled. Its validity depends on the purpose for which it is used and we believe that the abstractions made here make the model valid for travel time estimating. These abstractions are:

- The operator will always operate the machine to maximize performance when the machine is accelerating and decelerating due to road characteristics not braking.
- The way in which the torque converter works can be represented by an empirical approximation.

- Engine retardation is used to maintain a maximum speed when the vehicle is traveling downhill.
- The power curve is constant for all gears.
- A constant deceleration is used to simulate braking effect.

6.6 SUMMARY

This chapter presented an analytical validation of the model. The validation using laws of physics proved that the model is doing the right calculations. A comparison of the rimpull curves obtained using the fundamental data obtained using the reverse engineering methodology described in Chapter 4 and the rimpull curves provided by the manufacturer was made. The rimpull curve calculated matches the rimpull curve provided by the manufacturer, which proves that the reverse engineering methodology is adequate. Travel times obtained with the model were compared with TALPAC and VehSim. Collection of data in the field, such as equipment characteristics and road conditions, is essential in order to compare values with reality. The advantage of using the model over commercially available software was presented. The next chapter presents the conclusions and summarizes the findings of this research.

Chapter 7: Conclusions

This chapter presents a brief summary of this research, the accomplishments, and directions for future research.

7.1 SUMMARY

Earthmoving operations are part of almost every construction job. They are needed for leveling the surface by cutting or filling, in order to shape the ground to serve the needs of the parties involved in the project. In most projects earthmoving operations constitute a large portion of the project. Construction equipment assists in moving material from one point to another. The price of most of this heavy equipment is considerable, thus the purchase of any construction equipment constitutes a particularly large investment. The purpose of being in the construction industry is to make a profit in every job. Construction managers need to plan the operation and select the most appropriate equipment in order to maximize productivity. Maximization of productivity is the goal of every construction manager.

Similar to other construction activities, earthmoving operations are planned using a mixture of traditional and modern tools. In order to plan these operations efficiently it is important to understand the travel times of the hauling equipment. The available models do not consider the equipment characteristics (i.e. efficiencies, reductions, power curves, etc.) in the amount of detail needed. Chapter 2 presented a review of the previous work performed in the area of estimating travel time for hauling equipment. The chapter presented manual methods and computer models previously developed and used. Chapter 3 provided the background needed to understand the effect that the equipment characteristics, and haul road conditions have in travel time of the hauling unit. In addition, this chapter provided the knowledge needed to understand why these parameters are included as part of the model.

The purpose of this research was to develop a model to calculate travel time from a fundamental level considering equipment characteristics such as efficiencies, and reductions, as well as other characteristics that have an effect in the haul unit performance. This was accomplished by the development of a travel time calculation model that considers the variables that appear to have an effect, in the amount of detail needed. The level of detail needed and not incorporated in previous models was integrated in this model. Users can do more sophisticated studies and this model could serve as the basis and foundation for the development of many other models in such as probabilistic travel time, fuel consumption, and brake heat buildup and wear. The amount of detail used allows extensions as these to be easily included. A methodology was developed to estimate equipment fundamental data. This data is needed as input to the model. The approach taken to estimate this data is described in detail in Chapter 4 of this document. In addition an analytical approximation on how the torque converter works is explained in this chapter. Chapter 5 presented the calculations and formulas used while developing the model. Chapter 6 presented an analytical validation of the model and a comparison of the results obtained with the model with the results obtained with VehSim and TALPAC. Calibration of the model is essential in order to compare results or if someone wants to use the model for planning purposes. However, because of the level of detail used in the model developed, other studies can be easily incorporated. Examples of such applications include fuel consumption, brake heat build up and other applications that might depend on the engine RPM history.

7.2 CONCLUSIONS

The main conclusion of this research is that it is possible to develop a model to calculate travel times based on fundamentals. Computer software that can solve complex differential systems and include the amount of detail required is available. The model developed as part of this research is an example of how equipment performance can be estimated from fundamental data. By using this model, users can perform more sophisticated studies than those done with previous models. In addition, the amount of detail used allows for the development of other models.

This research also concluded that by making some assumptions it is possible to derive the values of interest (i.e. efficiencies and reductions) from rimpull curves published by the manufacturers using a process that was described in detail in Chapter 4. The determination of the parameters and methodology identified as part of this research was done only for Caterpillar hauling equipment, however the approach and methodology used to determine the efficiencies and reductions can be applied to hauling equipment from any other manufacturer to determine the same parameters.

The operator is the most important factor to consider. The GPS file presented great variability in travel times. If the same equipment is traveling in the same road, similar travel times should be observed. This variability might be due to the effect of the operator, who can limit the performance of the machine.

7.3 CONTRIBUTIONS

- The model developed as part of this research deviates from the traditional way that computer models have been developed to estimate equipment performance. The deviation from estimating equipment performance from rimpull curves by using fundamental equipment data allows the user to do more detailed and sophisticated studies.
- The fundamental data needed as inputs to the model are not readily available. A methodology to estimate the data needed as input was developed as explained in detail. This methodology can be used by other researchers that want to perform sophisticated studies with construction equipment.
- A numerical approximation of the torque converter operation was developed. The results obtained with the approximation are consistent with published literature with respect to the pattern between reductions, efficiencies and speed. This approximation is not a detailed study of the hydraulic flow and kinematics of

hydraulics inside the torque converter, but an empirical representation. A detailed study of the kinematics of the torque converter is out of the scope of this study.

- The model can be used to calculate travel time in earthmoving operations. In addition, the user can get profiles for speed and distance under specified conditions by the user.
- Most important, this detailed model is the basis and foundation for the development of many other models in future research such as probabilistic travel time, fuel consumption, brake heat buildup and wear, etc. The amount of detail used allows extensions as these to be easily included.

7.4 AREAS OF FUTURE RESEARCH

- Incorporate into the model the effect of the operator in the performance of the equipment. This is the most important factor to consider. The operator creates most of the variability in the system because of the factors that are under his control. The operator can limit the performance of the equipment by controlling the throttle position and the speed at which the machine is traveling. It might be possible that the operator is at full throttle throughout the haul activity. Moreover, it might be possible that the operator never reaches the position of the throttle to be 100%. There could be an infinite number of possibilities that could describe the position of throttle vs. time. The pressure that the operator applies to the accelerator depends on the level of comfort of the operator with actual road conditions, experience with the machine, and the actual speed at which the vehicle is traveling. The comfort of the operator might change constantly which in turn causes a change in the pressure that the operator applies to the accelerator. In addition, the way in which the operator applies the brakes should be studied in detail.

- Develop a formal procedure to measure haul road characteristics (i.e. rolling resistance) and other characteristics that might have an effect. The values used for rolling resistance while comparing the results obtained with the model with field data were taken from the Caterpillar Performance Handbook recommended values. These values used for the comparison might be misleading and could be different from the actual rolling resistance experienced by the haul unit.
- Develop other models such as probabilistic travel time, fuel consumption, brake heat buildup and wear, etc. The amount of detail used while developing the model will allow for these extensions to be included easily. Most of the machines used had a fuel consumption curve as part of the specifications. Integration can be performed to calculate the amount of fuel consumed in a certain segment.
- Develop a methodology to study the variations in pressure applied to the braking pedal due to actual speed, road characteristics and operator's comfort. A detailed study is needed in order to model the amount of pressure that the operator applies to the pedal and the subsequent heat build-up in the drum.
- Find accurate representations on the way in which the torque converter and braking system work and incorporate the effect of the torque converter, braking system and retarder in the travel time into the model.
- Develop procedures to measure equipment parameters in the field, such as efficiencies, reductions, and power curves, in order to input accurate data that represent equipment characteristics and road conditions into the model.

7.5 CLOSING THOUGHTS

Earthmoving operations are a basic part of every construction project in one degree or another. If the amount of soil to move is relatively large, heavy equipment is often used

to help to move this soil from one place to another. These huge machines fascinate people in the construction industry as well as people in other sectors. Because of the cost of this construction equipment, they constitute a large investment and owners need to make money (i.e. profit) when they use such equipment. Adequate planning is the key to a successful project. Understanding the performance of heavy equipment is the key to adequate planning. Tools to estimate equipment performance, such as the one presented here could enable more contractors to be more competitive by estimating their equipment performance considering actual parameters of the machine and field and ultimately improve the operation and make a profit through the successful completion of the project.

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Appendix A

Haul Performance Calculator User's Guide

Introduction

The purpose of this software is to analyze the travel of haul units by simulating performance from fundamental data. The program not only calculates the travel time for the haul time, but in addition it keeps track of the equipment performance over the specified haul road. The program requires fundamental data such as efficiencies, reductions, power curves, and wheel radius to perform the calculations. The program simulates the process that takes place to transfer the power from the engine until it reaches the area of contact between the wheel and surface. This document presents a guide on how the program can be used. The inputs needed and the format of those inputs will be explained. In order to run the program, the user has to accept the disclaimer. If the user selects “OK”, the program asks for the inputs. If the user selects “Cancel”, the program exits. Figure A.1 shows the disclaimer.

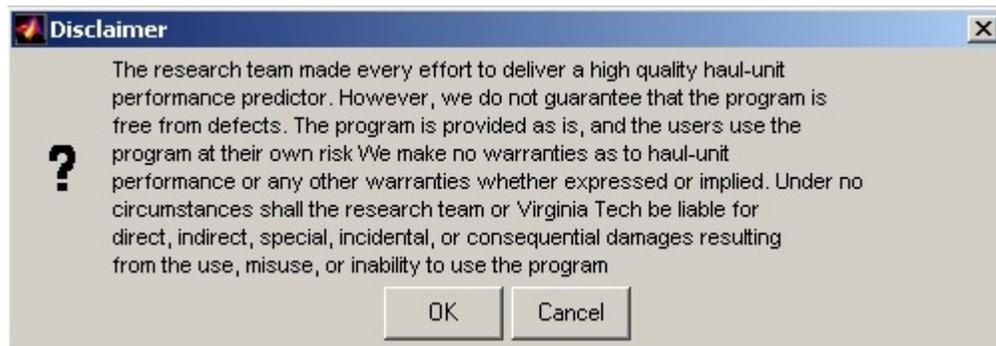


Figure A.1: Disclaimer

Inputs

The user has to save the data related to equipment characteristics and road characteristics in two different files. These files have to be stored in the same directory in which the MATLAB™ files are stored. In addition, the user has to input the load that the vehicle is

carrying in that segment. The format and order of the parameters will be discussed in the following section.

Equipment Characteristics

The user has to create a text file to describe equipment characteristics. This file is used as an input to the model. This file should include the following information in the following sequence in order for the program to read and use the information accurately. The power curve should be represented by a series of points that describe the power at a specific RPM. This number of points that describe the power curve should be included as well the values for power and RPM. This also applies for the retarding power curve. The torque and retarding torque curves are obtained from the power and retarding power curves. The other parameters that should be included in the file are: vehicle empty weight, efficiencies (both constant and gear dependent), reductions (both constant and gear dependent), radius of the wheel, and number of gears. In order to model the torque converter operation, the user has to specify it as another gear and assign the mechanical efficiencies and reductions of the torque converter equal to those of the first gear. An example file that describes the order in which the equipment characteristics should be entered follows. Letters in italics are used only to demonstrate the order. An example input file will be presented afterwards.

Vehicle Empty Weight in kilograms

Number of RPM points that describe the Power Curve

RPM that describes Power Curve

Power in Watts at the corresponding RPM

Number of RPM points that describe the Retarding Power Curve

RPM that describes Retarding Power at the corresponding RPM

Retarding Power in Watts

Wheel Radius in meters

Constant Reduction

Constant Efficiency

Number of gears

Reductions

Efficiencies

Rated RPM

Constant To Model Torque Converter

Exponent to Model Torque Converter

Stall Ratio

The following is an example of an input text file for the program. This file was created in Notepad, but the text file can be created in any application. The format of the file follows the format and order presented before.

30190
8
477 978 1583 1712 2000 2119 2200 2240
152178.47 204551.89 250104.36 260854.05 265000.00 264061.71 246614.89 227945.91
6
1200 1350 1500 1750 1950 2100
93310 111972 149296 223944 298592 354577
0.88
1
1
5
79 79 44 25 15
0.87 0.87 0.92 0.93 0.96
2000
1.47
-0.87
3

It is very important to follow the specified format when creating the file, so that the program can read the values in the correct sequence, perform calculations using the correct data and to get the accurate results.

Haul Road Characteristics

The user has to create a text file with the haul road characteristics. Inputs that describe haul road characteristics include rolling resistance, grade, speed limit of the segment, target speed and length of the segment. The values for rolling resistance and grade should be entered as a percent (%) not as a decimal. Speed Limit refers to the maximum speed at which the vehicle can travel along the segment. This value can be used to limit the maximum speed in cases where there are some factors that don't allow the vehicle to travel at the maximum speed that it can develop. Target speed refers to the desirable speed at the end of the segment. If the vehicle has to come to a stop at the end of the segment, then this value should be set to zero. If the vehicle can go as fast as possible then this value should be set equal or greater to the value of speed limit. Both values should be entered in km/hr. The length of the segment should be input in meters.

The text file is used as an input to the model. The data for all the segments should be input. The values should be separated by a space. This file should include the following information in the following sequence in order for the program to read and use the information accurately. The headings below illustrate the order in which the data should be input.

RR (%) Grade (%) Speed Limit (km/hr) Target Speed (km/hr) Distance (mts) Coefficient of Traction

These headings are shown to illustrate the order in which the parameters should be input and they should not be included in the file. An example of an input file that describes haul road characteristics follows. The model assumes that the vehicle starts from rest.

3 -5 45 500 120 0.36

```
2 8 500 500 150 0.36
3 1 45 500 200 0.36
3 -4 50 50 175 0.36
4 -2 25 0 500 0.36
```

The data in this file represent five different segments. Segments one and four have a negative equivalent grade, while the rest of the segments have a positive equivalent grade. In the first three segments the vehicle is trying to go as fast as possible. In the fourth segment the speed was limited to a value equal to 50 km/hr. This was done just for illustration purposes. The maximum velocity allowed in the next segment is 25 km/hr, therefore the program simulates braking effect at the beginning of the segment to reduce the velocity from 50 km/hr to the maximum allowed which is 25 km/hr. The program always checks if the current velocity at the beginning of the segment is greater than the maximum speed of the segment. If this is the case, a constant deceleration, equal to 0.83 m/s^2 , is used in order to reduce speed to the maximum value allowed in the segment. This value is an average of data taken in the field using GPS. The value for the constant deceleration can be changed. The user goes to the options.txt file and changes the 0.83 m/s^2 for the desired value. The vehicle has to stop at the end of the fifth segment. When the program performs the calculations for braking, it will calculate the time needed to reach zero velocity at the end of the segment, from the current speed at which the vehicle is traveling. A constant deceleration equal to 0.83 m/s^2 is used to simulate the braking effect. Again this value can be changed.

Load

The user has to input the load that the vehicle is carrying. It is important to specify the load of the truck. If the truck is traveling empty, a value of zero should be entered. If the truck is traveling fully loaded, enter the payload. If the vehicle is not traveling fully loaded, the load that it is carrying can be specified here. The value of the load should be input in kilograms. After the user enters this value the program starts the calculations. It is very important that user input the parameters that describe the piece of equipment and specific haul road in order to get accurate results.

The last input is the load distribution for that particular equipment.

It is very important that user input the parameters that describe the piece of equipment and specific haul road in order to get accurate results.

Running the program

The program is prepared to run in the MATLAB™ environment. The user needs to have this software in order to be able to run the travel time calculator. Once the user opens the MATLAB™ command prompt, the next step is to set the path to the directory in which the MATLAB™ files that contain the program are stored. This can be done by going to the File menu and selecting Set Path from this pull down menu or by typing the full path of the directory where the files are stored.

Once the path is set to the directory where the files are stored, the next step is to run the program by typing the name of the main file (i.e. TimeCalc) in the command prompt. The screen below shows how this is done. Once the name is typed the disclaimer appears. If the user selects “OK”, the program asks for the inputs. If the users selects “Cancel”, the program exits. The disclaimer is shown in Figure A.1.

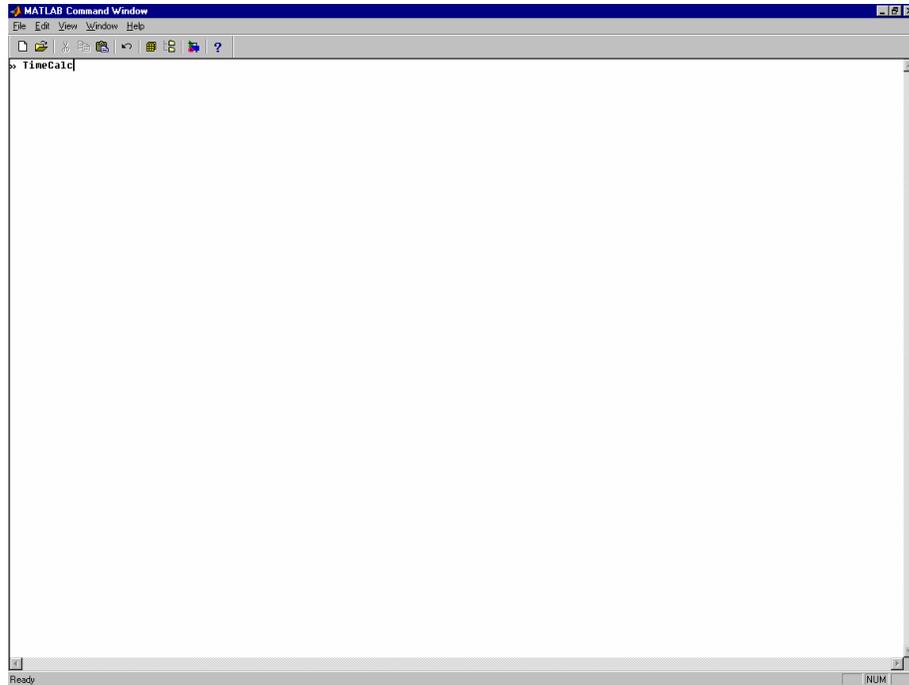


Figure A.2: Screenshot of MATLAB to show TimeCalc

The first input is the name of the file that describes equipment characteristics. Assuming that the file is stored in the same directory where the MATLAB™ files are stored, then the name of the file should be input with single quotations and the extension of the file should be included. If the file is stored in another directory, then the full path should be included. An example is shown below. First we show the statement that comes from the program and then the answer.

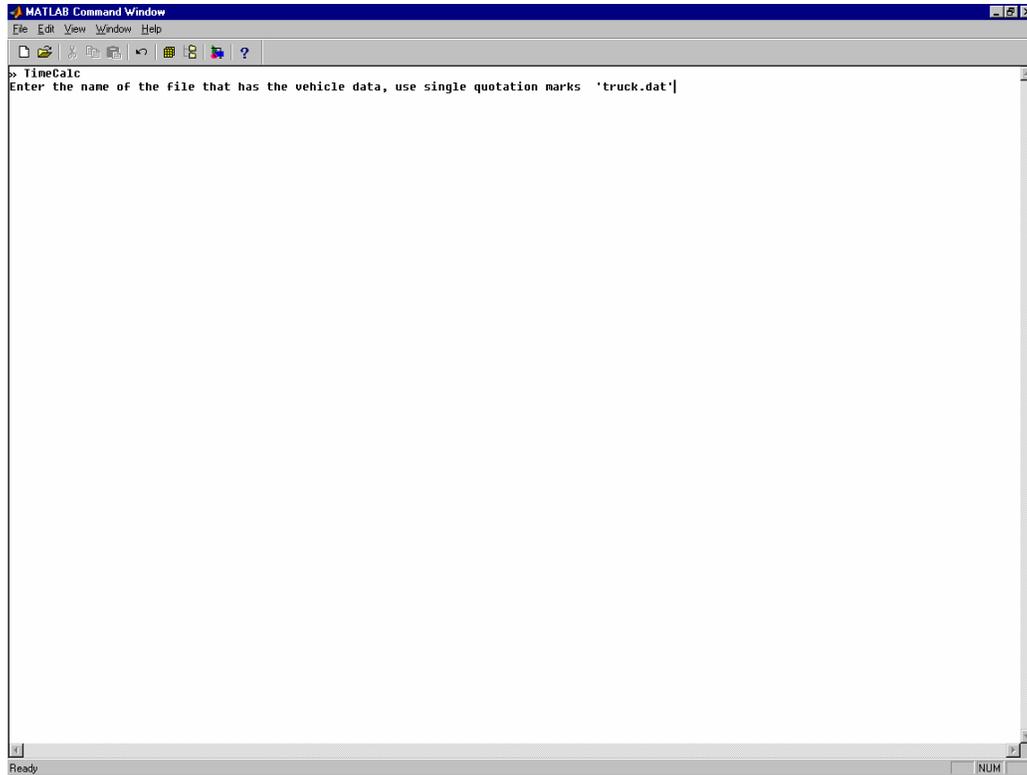


Figure A.3: Screenshot of MATLAB to show the truck data input

The statement is the following

Enter the name of the file that has the vehicle data, use single quotation marks

'truck.dat'

Next the program asks for the name of the file where the haul road data is stored as shown below. The statement that the program displays is the following

Enter the name of the file that has the road data, use single quotation marks

'road.dat'

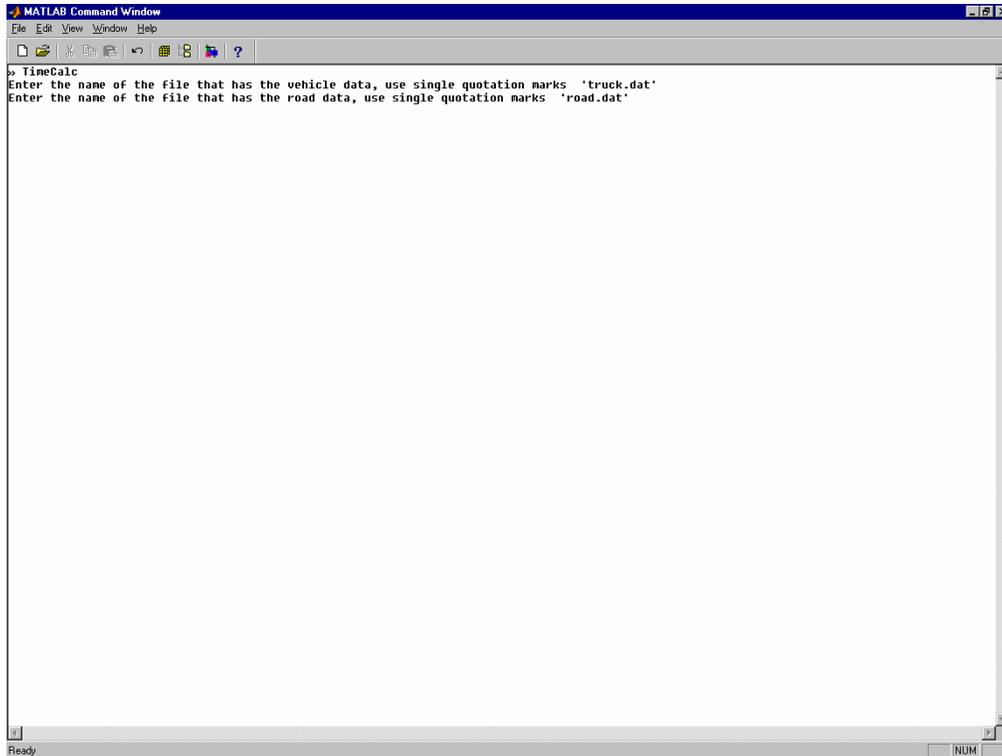


Figure A.4: Screenshot of MATLAB to show the road data input

The third input is the load that the vehicle is carrying. It is important to specify the load of the truck. If the truck is traveling empty, then enter a zero. If the truck is traveling fully loaded, enter the payload. If the vehicle is not traveling fully loaded, the load that it is carrying can be specified here. The value of the load should be input in kilograms. The statement that the program displays is the following.

Load (payload) that the vehicle is carrying in kgs? 0

The last input is the load distribution for that particular vehicle. After the user enters this value the program starts the calculations.

Load distribution for the vehicle? 0.67

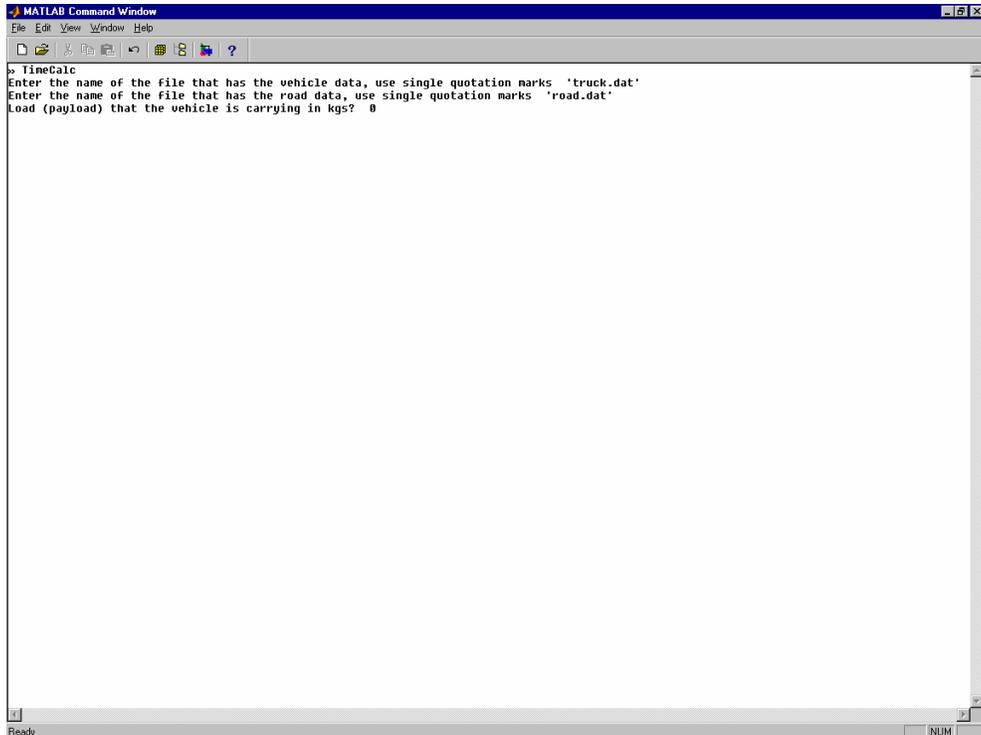


Figure A.5: Screenshot of MATLAB to show the load input

Results

The program outputs a statement in the MATLAB™ command prompt similar to the one shown below:

Total travel time is equal to 162.3775 seconds

This is the time taken to travel the specified haul road considering the characteristics specified by the user. In addition, the program plots a series of graphs. These graphs are shown in the following section.

The torque, rimpull, retarding torque and retarding pull curves were obtained from the description that the user gave of the power and retarding power curves. The following figure shows all these curves.

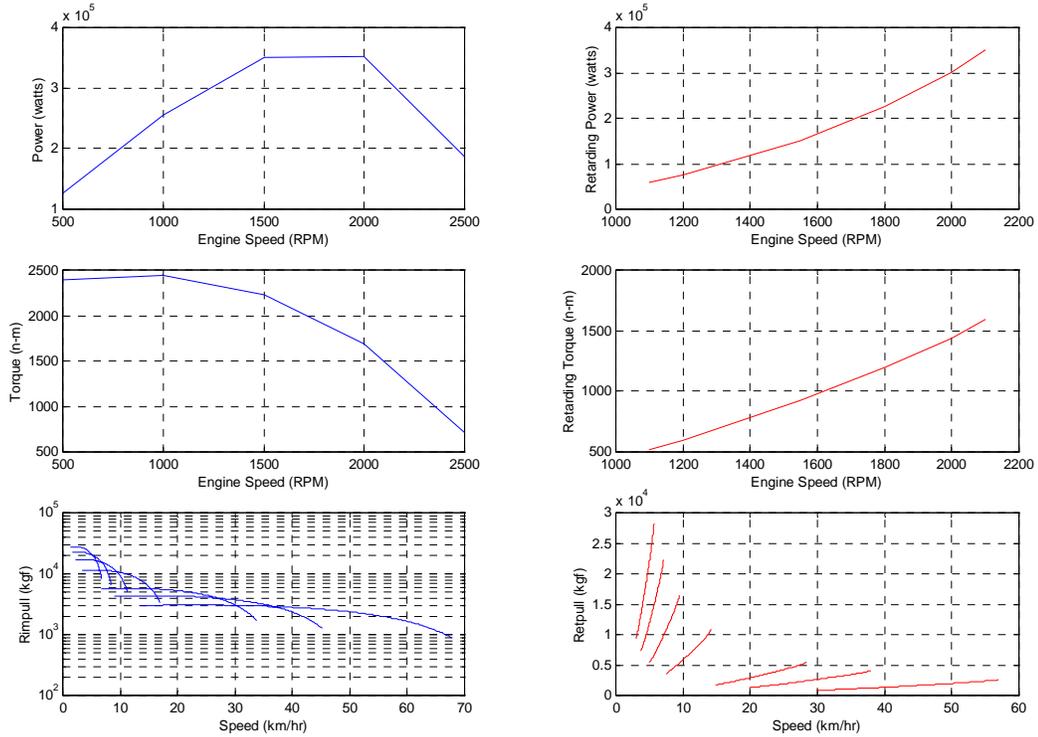


Figure A.6: Rimpull, Torque, Power, Retpull, Rettorque and Retpower Curves for the haul unit

The next figure shows the velocity profile. From the figure it can be seen that the vehicle was traveling as fast as it could in segment one. Given that segment two had a positive equivalent grade, the vehicle will lose some of the speed until it reaches the maximum velocity at which it can travel in that segment. This decrease in speed is due to road conditions and not braking effect, therefore there won't be a straight line in the velocity profile to simulate this decrease in speed. The vehicle again will try to go as fast as possible in segment 3. In segment four the vehicle is trying to go as fast as possible but it only reaches a velocity of 50 km/hr. This is the maximum velocity specified for the segment. The maximum speed allowed in the last segment is 25 km/hr. The model simulates braking effect in order to decrease the velocity from 50 km/hr to 25 km/hr. Because of the braking effect the velocity is decreasing linearly. The vehicle will keep a velocity of 25 km/hr until it has to start braking to come to a stop at the end of the segment. The changes in the speed profile in the last segment are due to the fact that the

speed is limited by other factors not related to equipment. The vehicle is able to develop a speed higher than the specified, but it has to maintain the speed limit set by the user.

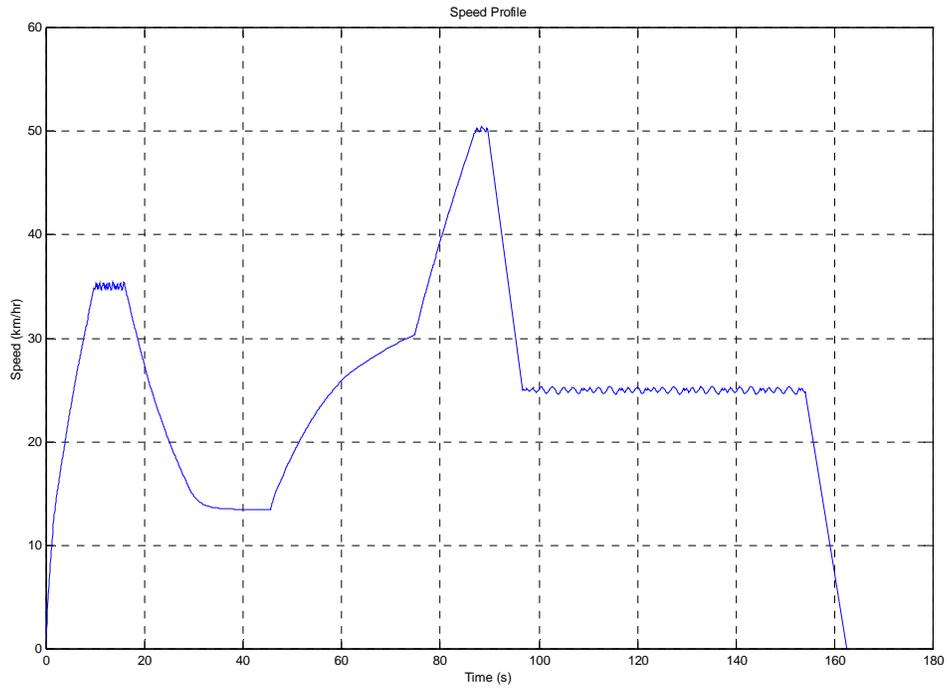


Figure A.7: Speed Profile for a haul unit

The next two figures illustrate the distance traveled against time and the RPM of the engine against time.

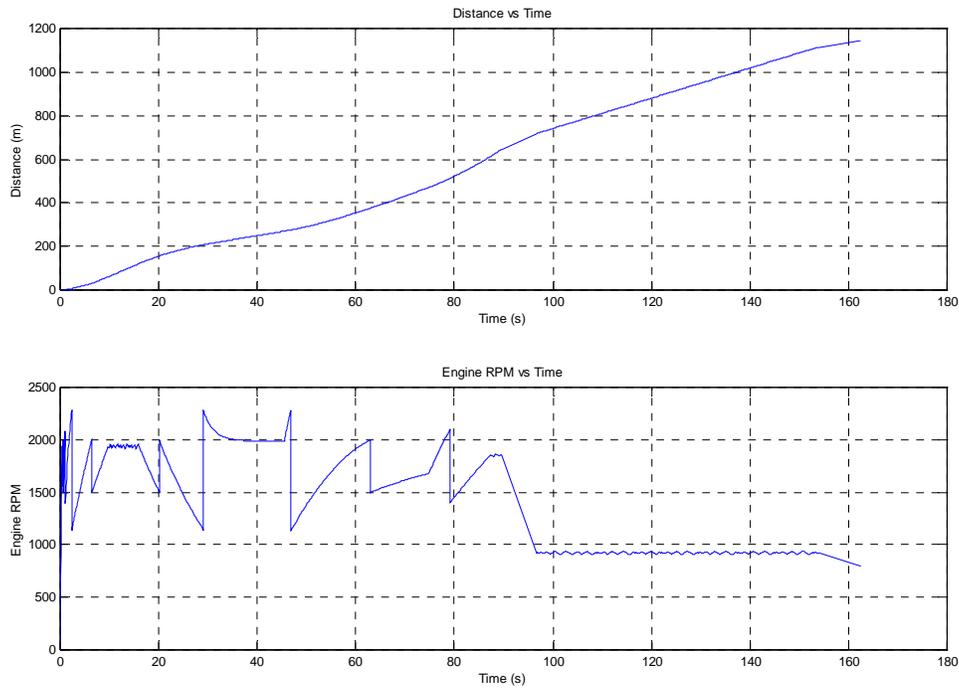


Figure A.8: Distance vs. Time and Engine RPM vs. Time graphs

In addition, the program prepares a table with information about the vehicle’s performance in every segment. Information contained in that table includes segment number, distance, velocity and gear at the beginning of the segment, velocity and gear at the end of the segment, maximum speed at the end of the segment, and time taken to travel the segment. An example file is shown below.

SegmentNumber	Length(mts)	EntranceSpeed(km/hr)	EntranceGear	EndingSpeed(km/hr)	EndingGear	MaxSpeed(km/hr)	Time(secs)
1	120	0	1	35.07	6	35.41	15.99
2	150	35.07	6	13.46	4	35.07	29.59
3	200	13.46	4	30.33	6	30.33	29.24
4	175	30.33	6	50.19	7	50.45	14.87
5	500	50.19	7	0	1	50.19	72.69

Table A1: Equipment Performance by segment

With this information, the performance of the vehicle can be monitored in every segment and better decisions regarding equipment to use (i.e. due to road characteristics), can be made based on this information.

APPENDIX B

Source Code Listings

Disclaimer

The research team made every effort to deliver a high quality haul-unit performance predictor. However, we do not guarantee that the program is free from defects. The program is provided "as is," and the users use the program at their own risk.

We make no warranties as to haul-unit performance or any other warranties whether expressed or implied. Under no circumstances shall the research team or Virginia Tech be liable for direct, indirect, special, incidental, or consequential damages resulting from the use, misuse, or inability to use the program.

```
function TimeCalc
```

```
    ButtonName=questdlg('The research team made every effort to deliver a high quality haul-unit performance predictor. However, we do not guarantee that the program is free from defects. The program is provided as is, and the users use the program at their own risk. We make no warranties as to haul-unit performance or any other warranties whether expressed or implied. Under no circumstances shall the research team or Virginia Tech be liable for direct, indirect, special, incidental, or consequential damages resulting from the use, misuse, or inability to use the program',...
```

```
    'Disclaimer', 'OK', 'Cancel','Cancel');
```

```
    switch ButtonName,
```

```
    case 'OK',
```

```
        clear
```

```
        truckdata= input('Enter the name of the file that has the vehicle data, use single quotation marks ');
```

```
        roaddata= input('Enter the name of the file that has the road data, use single quotation marks ');
```

```
        Load=input('Load (payload) that the vehicle is carrying in kgs? ');
```

```
        LoadDist=input('Load distribution for this vehicle? ');
```

```
        Test = TravelTime(truckdata,roaddata,Load,LoadDist);
```

```
    case 'Cancel',
```

```
        break
```

```
    end
```

```
return
```

```

function Test = TravelTime(truckdata,roaddata,Load)

global Times Distances Velocity Tentrance Dentrance TempTentrance TempDentrance
HaulRoadTime EndingSpeed EndingGear Efficiencies Reductions WheelRadius;
global Segments Load retRPM RetTorque RPM EngPower Efficiencies RetPower
GVW EG SpeedLimit TargetSpeed RPM retRPM EntRPSs RPM comp retRPM
Distance;
global EngTorque RetTorque StallRatio WheelRadius TempEff TempRed CurGear
GVW EG MaxSpeeds t p tct V SpeedLimit Regime T2Ent TempTm2 InitT2 minRPM
maxRPM minretRPM maxretRPM profile MaxSpeed timer SegTime;
global CT LoadDist

SegmentNumber=1;
TotTime1=0;
TotTime2=0;
TotTime3=0;
TotTravelTime=0;
TempRPSs=[];
Times2=[];

fido = fopen('Table.xls','w');
fprintf(fido,'SegmentNumber\t Length(mts)\t EntranceSpeed(km/hr)\t EntranceGear\t
EndingSpeed(km/hr)\t EndingGear\t MaxSpeed(km/hr)\t Time(secs)\n');

if (SegmentNumber==1);
    CurV=0;
    CurGear=1;
else
    CurV=EndingSpeed;
    CurGear=EndingGear;
end

fid = fopen (truckdata);

TW = fscanf (fid,'%g',1);

if isempty(TW);
    disp(['No Data in file that has the truck data']);
    break
end

RPM_NUMBER_OF_POINTS =fscanf (fid,'%g',1);
RPM = fscanf (fid,'%g',[1,RPM_NUMBER_OF_POINTS]);

```

```

EngPower =fscanf (fid,'%g',[1,RPM_NUMBER_OF_POINTS]);
RET_RPM_NUMBER_OF_POINTS =fscanf (fid,'%g',1);
retRPM = fscanf (fid,'%g',[1,RET_RPM_NUMBER_OF_POINTS]);
RetPower = fscanf (fid,'%g',[1,RET_RPM_NUMBER_OF_POINTS]);
WheelRadius= fscanf (fid,'%g',1);
ConstRed = fscanf (fid,'%g',1);
ConstEff = fscanf (fid,'%g',1);
NGEARS= fscanf (fid,'%g',1);
Reduction= fscanf (fid,'%g',[1,NGEARS]);
Efficiency= fscanf (fid,'%g',[1,NGEARS]);
RatedRPM=fscanf (fid,'%g',1);
TCGear=fscanf (fid,'%g',1);
TCCoeff=fscanf (fid,'%g',[1,TCGear]);
TCExp=fscanf (fid,'%g',[1,TCGear]);
StallRatio=fscanf (fid,'%g',1);

```

```

minRPM=RPM(1);
maxRPM=RPM(RPM_NUMBER_OF_POINTS);
minretRPM=retRPM(1);
maxretRPM=retRPM(RET_RPM_NUMBER_OF_POINTS);

```

```

Reductions=Reduction*ConstRed;
Efficiencies=Efficiency*ConstEff;
GVW=TW+Load;
TempEff=Efficiencies;
TempRed=Reductions;

```

```

EngTorque=EngPower./(RPM/60*2*pi);
RetTorque=RetPower./(retRPM/60*2*pi);

```

```

fid = fopen (roaddata);

```

```

while (1<2)

```

```

    RR = fscanf (fid,'%g',1);

```

```

    if isempty(RR);

```

```

        break

```

```

    end

    Grade=fscanf (fid,'%g',1);
    SpeedLimit=fscanf (fid,'%g',1)/3.6;
    TargetSpeed=fscanf (fid,'%g',1)/3.6;
    Distance=fscanf (fid,'%g',1);
    CT=fscanf (fid,'%g',1);

    EG=(RR+Grade)/100;

    TimeDelta= 0.1;
    TimeLimit= 360000;

    DandV=[0,CurV];
    t=[0];
    %Braking effect if coming into the segment with a higher speed than SpeedLimit
    if (CurV>SpeedLimit)
        FirstTime=(CurV-SpeedLimit)/1.0;
        FirstDistance=CurV*FirstTime-0.5*FirstTime^2;
        Distance=Distance;
        if (FirstDistance>=Distance);
            disp(['Not enough distance to brake, the program will exit now']);
            break;
        else
            CurV=SpeedLimit;
            a=[FirstDistance,SpeedLimit];
            t=cat(1,t,FirstTime);
            DandV=cat(1,DandV,a);
        end
    else
        FirstTime=0;
        FirstDistance=0;
        Distance=Distance;
    end

    if (EG>=0 & TargetSpeed<SpeedLimit);

        %Start the calculation process

        %t=[]; %to hold the time vector from t=0 to timelimit
        t2=[]; %to hold subset of t that does not include gear-change deceleration time
        %DandV=[]; %to hold pairs of distance and velocity that correspond to elements in t
        RPSs=[]; %to hold engine RPSs that correspond to elements in t2

```

```

% Current time and distance for beginning of first integration
CurTm=FirstTime;
CurD=FirstDistance;

% to profile calculation process
tic;
tic;
AcelTime=0;
AcelDist=0;
while ~(CurTm>TimeLimit | CurD>Distance)

    if (TempInV==0);
        %Modeling TC effect
        if (CurGear<=TCGear);
            if (CurV==0);
                Reds=StallRatio;
                Effs=TCCoeff(1)*Reds^TCExp(1);
            else
                Reds=RatedRPM*2*pi*WheelRadius/(60*CurV);
                Effs=TCCoeff(1)*Reds^TCExp(1);
            end
        else
            Reds=1;
            Effs=1;
        end
        Efficiencies(CurGear)=Efficiencies(CurGear)*Effs;
        Reductions(CurGear)=Reductions(CurGear)*Reds;
    end

    [tg,DandVg,TE,YE,IE]=ode45('FastAP',[CurTm:TimeDelta:TimeLimit], [CurD;
CurV], odeset('Events','on'), CurGear, Distance);

%calc RPSs and add to previous results
RPSs=cat(1,RPSs,RPSFromGearAndSpeed(CurGear, DandVg(:,2)));
b=length(RPSs);
for (i=1:b);
    if (RPSs(i)*60 > maxRPM);
        RPSs(i)=maxRPM/60;
    else
        RPSs(i)=RPSs(i);
    end
end
end

%add Distance and Velocity to those previously computed

```

```

DandV=cat(1,DandV,DandVg);

%add the times to those previousle added
t=cat(1,t,tg);
t2=cat(1,t2,tg);

if isempty(TE) % happens if TimeLimit reached without reaching gear changing
condition
    CurTm=TimeLimit; % there should actually be an assert that last element of t is
TimeLimit
    CurD=DandVg(size(tg,1),1);

%    disp(['Time limit reached in gear ', num2str(CurGear), ' at time ', num2str(TE),
' and speed ', num2str(DandVg(size(tg,1),2)*3.6)]);
    break; % break out of loop is timelimit reached
end

switch IE(1)
    case 1
        %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear+1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
        CurGear=CurGear+1;
    case 2
        %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear-1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
        CurGear=CurGear-1;
    case 3
        %disp(['Travel distance reached while at gear ', num2str(CurGear), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
        CurTm=TE;
        CurD=YE(1);
        CurV=YE(2);
        break;
    case 4
        %disp(['Cruising Speed reached ']);
        CurTm=TE;
        CurD=YE(1);
        CurV=YE(2);
        AcelVel=CurV;
        AcelTime=CurTm;
        AcelDist=CurD;
        Limitant=1;
        break;

```

```

end

% Current time, speed and distance for the gear-changing deceleration integration
CurTm=TE;
CurD=YE(1);
CurV=YE(2);

end
TotalTime=CurTm;
EndingGear=CurGear;
EndingSpeed=CurV;
ABS=DandV;

AcelVel=CurV;

fid = fopen ('options.txt');
ConsAcel= fscanf (fid,'%g',1);
DeltaTime=EndingSpeed/ConsAcel;
Dist=EndingSpeed*DeltaTime-0.5*ConsAcel*(DeltaTime)^2;

%Checking if distance available is enough for braking
if (Dist>=Distance);
    disp(['Not enough distance to brake, the program will exit now!']);
    break;
end;

AcelDist=Distance-Dist;
p=1;
profile=[];
timer=[];
TRPSs=[];
testtimes2=[];
while((DandV(p,1)-AcelDist) <0.5);
    act=DandV(p,:);
    tct=t(p);
    tRPSs=RPSs(p);
    ttime2=t2(p);
    profile=cat(1,profile,act);
    timer=cat(1,timer,tct);
    TRPSs=cat(1,TRPSs,tRPSs);
    testtimes2=cat(1,testtimes2,ttime2);
    p=p+1;
end

```

```

if (TargetSpeed==0);
    EndingSpeed=0;
    EndingGear=1;
    LastRPSs=800/60;
else
    EndingSpeed=TargetSpeed;
    EndingGear=EndingGear;
    LastRPSs=RPSFromGearAndSpeed(EndingGear, EndingSpeed);
end

temp=[Distance,EndingSpeed];
TimeAcel=p*TimeDelta;
DeltaTime=DeltaTime+tct;
TotalTime=DeltaTime;

profile=cat(1,profile,temp);
timer=cat(1,timer,DeltaTime);
testtimes2=cat(1,testtimes2,DeltaTime);
TRPSs=cat(1,TRPSs,LastRPSs);

MaxSpeed=max(profile(:,2));
TotTime1=TotalTime;

zip=length(timer);
SegTime=timer(zip);

%Vehicle trying to go as fast as possible

elseif (EG>=0 & TargetSpeed>=SpeedLimit);

    %t=[]; %to hold the time vector from t=0 to timelimit
    t2=[]; %to hold subset of t that does not include gear-change deceleration time
    %DandV=[]; %to hold pairs of distance and velocity that correspond to elements in t
    RPSs=[]; %to hold engine RPSs that correspond to elements in t2

    % Current time and distance for beggining of first integration
    CurTm=FirstTime;
    CurD=FirstDistance;

    % to profile calculation process
    tic;
    tic;
    AcelTime=0;

```

```

AcelDist=0;
TempInV=CurV;
while ~(CurTm>TimeLimit | CurD>Distance)
    %Modeling TC effect
    if (TempInV==0);
        %Modeling TC effect
        if (CurGear<=TCGear);
            if (CurV==0);
                Reds=StallRatio;
                Effs=TCCoeff(1)*Reds^TCExp(1);
            else
                Reds=RatedRPM*2*pi*WheelRadius/(60*CurV);
                Effs=TCCoeff(1)*Reds^TCExp(1);
            end
        else
            Reds=1;
            Effs=1;
        end
        Efficiencies(CurGear)=Efficiencies(CurGear)*Effs;
        Reductions(CurGear)=Reductions(CurGear)*Reds;
    end

    [tg,DandVg,TE,YE,IE]=ode45('FastAP',[CurTm:TimeDelta:TimeLimit], [CurD;
CurV], odeset('Events','on'), CurGear, Distance);

    %calc RPSs and add to previous results
    RPSs=cat(1,RPSs,RPSFromGearAndSpeed(CurGear, DandVg(:,2)));
    b=length(RPSs);
    for (i=1:b);
        if (RPSs(i)*60 > maxRPM);
            RPSs(i)=maxRPM/60;
        else
            RPSs(i)=RPSs(i);
        end
    end
    %add Distance and Velocity to those previously computed
    DandV=cat(1,DandV,DandVg);

    %add the times to those previousle added
    t=cat(1,t,tg);
    t2=cat(1,t2,tg);

    if isempty(TE) % happens if TimeLimit reached without reaching gear changing
condition

```

```

    CurTm=TimeLimit; % there should actually be an assert that last element of t is
TimeLimit
    CurD=DandVg(size(tg,1),1);

    %disp(['Time limit reached in gear ', num2str(CurGear), ' at time ',
num2str(TE), ' and speed ', num2str(DandVg(size(tg,1),2)*3.6)]);
    break; % break out of loop is timelimit reached
end

switch IE(1)
case 1
    %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear+1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
    CurGear=CurGear+1;
case 2
    %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear-1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
    CurGear=CurGear-1;
case 3
%    disp(['Travel distance reached while at gear ', num2str(CurGear), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
    CurTm=TE;
    CurD=YE(1);
    CurV=YE(2);
    break;
case 4
    %disp(['Cruising Speed reached ']);
    CurTm=TE;
    CurD=YE(1);
    CurV=YE(2);
    AcelVel=CurV;
    AcelTime=CurTm;
    AcelDist=CurD;
    Limitant=1;
    break;

end

% Current time, speed and distance for the gear-changing deceleration integration
CurTm=TE;
CurD=YE(1);
CurV=YE(2);

```

```

end
    TotalTime=CurTm+FirstTime;
    EndingGear=CurGear;
    EndingSpeed=CurV;
    ABS=DandV;

profile=DandV;
timer=t;
testtimes2=t2;
TRPSs=RPSs;
%Tentrance=TotalTime;
%Dentrance=Distance;
zip=length(timer);
SegTime=timer(zip);

MaxSpeed=max(profile(:,2));

%Happens if there is a negative slope
elseif (EG<0)

    %t=[]; %to hold the time vector from t=0 to timelimit
    t2=[]; %to hold subset of t that does not include gear-change deceleration time
    %DandV=[]; %to hold pairs of distance and velocity that correspond to elements in t
    RPSs=[]; %to hold engine RPSs that correspond to elements in t2

    SandD=DandV;
    % Current time and distance for beggining of first integration
    CurTm=FirstTime;
    CurD=FirstDistance;

    TempInV=CurV;

    % to profile calculation process
    tic;
    AcelTime=0;
    AcelDist=0;
    Regime=-1;
    while ~(CurTm>TimeLimit | CurD>Distance)

        if (TempInV==0);
            %Modeling TC effect
            if (CurGear<=TCGear);
                if (CurV==0);

```

```

    Reds=StallRatio;
    Effs=TCCoeff(1)*Reds^TCExp(1);
    else
    Reds=RatedRPM*2*pi*WheelRadius/(60*CurV);
    Effs=TCCoeff(1)*Reds^TCExp(1);
    end
else
    Reds=1;
    Effs=1;
end
Efficiencies(CurGear)=Efficiencies(CurGear)*Effs;
Reductions(CurGear)=Reductions(CurGear)*Reds;

[tg,SandDg,TE,YE,IE]=ode45('FastAP',[CurTm:TimeDelta:TimeLimit],[CurD;
CurV],odeset('Events','on'),CurGear,Distance);

else
[tg,SandDg,TE,YE,IE]=ode45('RetMode',[CurTm:TimeDelta:TimeLimit],[CurD;
CurV],odeset('Events','on'),CurGear,Distance);
end

%calc RPSs and add to previous results
RPSs=cat(1,RPSs,RPSFromGearAndSpeed(CurGear,SandDg(:,2)));
b=length(RPSs);
for (i=1:b);
    if (RPSs(i)*60 > maxRPM);
        RPSs(i)=maxRPM/60;
    else
        RPSs(i)=RPSs(i);
    end
end

%add Distance and Velocity to those previously computed
SandD=cat(1,SandD,SandDg);

%add the times to those previousle added
t=cat(1,t,tg);
t2=cat(1,t2,tg);

if isempty(TE) % happens if TimeLimit reached without reaching gear changing
condition
    CurTm=TimeLimit; % there should actually be an assert that last element of t is
TimeLimit
    CurD=SandDg(size(tg,1),1);

```

```

        %disp(['Time limit reached in gear ', num2str(CurGear), ' at time ',
num2str(TE), ' and speed ', num2str(SandDg(size(tg,1),2)*3.6)]);
        break; % break out of loop is timelimit reached
    end

    switch IE(1)
        case 1
            %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear+1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
            CurGear=CurGear+1;
        case 2
            %disp(['Shift from ', num2str(CurGear), ' to ', num2str(CurGear-1), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
            CurGear=CurGear-1;
        case 3
            %disp(['Travel distance reached while at gear ', num2str(CurGear), ' at time ',
num2str(TE), ' and speed ', num2str(YE(2)*3.6)]);
            CurTm=TE;
            CurD=YE(1);
            CurV=YE(2);
            break;
    end

    % Current time, speed and distance for the gear-changing deceleration integration
    CurTm=TE;
    CurD=YE(1);
    CurV=YE(2);

end

    TotalTime=CurTm;
    EndingGear=CurGear;
    EndingSpeed=CurV;
    ABS=SandD;

    AcelVel=CurV;

    profile=[];
    timer=[];
    TRPSs=[];
    testtimes2=[];

```

```

if (TargetSpeed>=SpeedLimit);
    TotalTime=CurTm;
    EndingGear=CurGear;
    EndingSpeed=CurV;
    profile=cat(1,profile,SandD);
    timer=cat(1,timer,t);
    testtimes2=t2;
    TRPSs=RPSs;
    DeltaTime=0;

else
    fid = fopen ('options.txt');
    ConsAcel= fscanf (fid,'%g',1);
    DeltaTime=abs(EndingSpeed-TargetSpeed)/ConsAcel;
    Dist=EndingSpeed*DeltaTime-0.5*ConsAcel*(DeltaTime)^2;

    %Checking if distance available is enough for braking
    if (Dist>=Distance);
        disp(['Not enough distance to brake, the program will exit now']);
        break;
    end;
AcelDist=Distance-Dist;
p=1;

%Truncation of the vector to get the profile
while((SandD(p,1) - AcelDist) < 0.2);
act=SandD(p,:);
tct=t(p);
profile=cat(1,profile,act);
timer=cat(1,timer,tct);
tRPSs=RPSs(p);
ttime2=t2(p);
TRPSs=cat(1,TRPSs,tRPSs);
testtimes2=cat(1,testtimes2,ttime2);
    p=p+1;

end

if (TargetSpeed==0);
EndingSpeed=0;
EndingGear=1;
LastRPSs=800/60;
else
EndingSpeed=EndingSpeed;
EndingGear=EndingGear;
LastRPSs=RPSFromGearAndSpeed(EndingGear, EndingSpeed);

```

```

end
end
CurV=EndingSpeed;
CurGear=EndingGear;

if (TargetSpeed<SpeedLimit)
    temp=[Distance,EndingSpeed];
    TimeAcel=p*TimeDelta;
    DeltaTime=DeltaTime+tct;
    TotalTime=DeltaTime;
    profile=cat(1,profile,temp);
    timer=cat(1,timer,DeltaTime);
    testtimes2=cat(1,testtimes2,DeltaTime);
    TRPSs=cat(1,TRPSs,LastRPSs);
else
end

```

```

zip=length(timer);
SegTime=timer(zip);
MaxSpeed=max(profile(:,2));
TotTime3=TotalTime;

```

```

end

```

```

Vout=EndingSpeed;
CurV=EndingSpeed;
CurGear=EndingGear;
NGearOut=EndingGear;
TempTm2=testtimes2;
TempTime=timer;
NVectorLengthOut=length(profile);
TempDist=profile(:,1);
LengthT2=length(testtimes2);

```

```

if (SegmentNumber==1);
    InitTime=0;
    InitGear=1;
    InitDist=0;
    InitT2=0;
    Times=[];
    TpRPSs=[];
    Distances=[];

```

```

Velocity=[];
Times2=[];
HaulRoadTime=TotalTime;
InitVel=0;
else
Times=Times;
Distances=Distances;
Velocity=Velocity;
Times2=Times2;
InitTime=Tentrance;
InitDist=Dentrance;
InitT2=T2Ent;
HaulRoadTime=HaulRoadTime+TotalTime;

end

for (i=1:NVectorLengthOut);
TempTime(i)=TempTime(i)+InitTime;
TempDist(i)=TempDist(i)+InitDist;
end
for (j=1:LengthT2);
TempTm2(j)=TempTm2(j)+InitT2;
end

TempRPSs=cat(1,TempRPSs,TRPSs);

Times=cat(1,Times,TempTime);
Distances=cat(1,Distances,TempDist);
Velocity=cat(1,Velocity,profile(:,2));
Times2=cat(1,Times2,TempTm2);

Tentrance=TempTime(i);
Dentrance=TempDist(i);
T2Ent=TempTm2(j);

fprintf(fido, '%6.2ft %6.2ft %6.2ft %6.2ft %6.2ft %6.2ft %6.2ft %6.2fn',
SegmentNumber, Distance, InitVel*3.6, InitGear, EndingSpeed*3.6, EndingGear,
MaxSpeed*3.6, SegTime);
InitVel=EndingSpeed;
InitGear=EndingGear;

SegmentNumber=SegmentNumber+1;
TotTravelTime=TotTravelTime+TotTime1+TotTime2+TotTime3;

```

```
end
```

```
ST=fclose('all');  
l=length(Times);  
disp(['Total Travel Time is equal to ', num2str(Times(l)), ' seconds']);
```

```
figure(1);
```

```
subplot(3,2,1);  
plot(RPM,EngPower,'b');%,'o',500:10:2500,Interp1(RPM,EngPower,500:10:2500,'spline'),'b');  
xlabel('Engine Speed (RPM)');  
ylabel('Power (watts)');  
grid;
```

```
subplot(3,2,3);  
plot(RPM,EngTorque,'b');%,'o',500:10:2500,Interp1(RPM,EngTorque,500:10:2500,'spline'),'b');  
xlabel('Engine Speed (RPM)');  
ylabel('Torque (n-m)');  
grid;
```

```
subplot(3,2,5);  
PlotRimpullCurve;
```

```
figure(1);
```

```
subplot(3,2,2);  
plot(retRPM,RetPower,'r');%,'or',500:10:2500,Interp1(retRPM,RetPower,500:10:2500,'spline'),'r');  
xlabel('Engine Speed (RPM)');  
ylabel('Retarding Power (watts)');  
grid;
```

```
subplot(3,2,4);  
plot(retRPM,RetTorque,'r');%,'or',500:10:2500,Interp1(retRPM,RetTorque,500:10:2500,'spline'),'r');  
xlabel('Engine Speed (RPM)');  
ylabel('Retarding Torque (n-m)');  
grid;
```

```
subplot(3,2,6);  
PlotRetpullCurve;
```

```
figure(2);
```

```

plot(Times,Velocity*3.6);
title('Speed Profile');
xlabel('Time (s)');
ylabel('Speed (km/hr)');
grid;

```

```

figure(3);
subplot(2,1,1);
plot(Times,Distances);
xlabel('Time (s)');
ylabel('Distance (m)');
title('Distance vs Time');
grid;

```

```

subplot(2,1,2);
plot(Times2,TempRPSs*60);
xlabel('Time (s)');
ylabel('Engine RPM');
title('Engine RPM vs Time');
grid;

```

```

return;

```

```

%-----
function theRPS=RPSFromGearAndSpeed(Gear, Speed)

```

```

global Reductions TempRed WheelRadius;

```

```

theRPS=Speed*Reductions(Gear)/2/pi/WheelRadius; %numSpeeds rows and numGears
columns

```

```

return;

```

```

%-----
function thePower = Power (rps)

```

```

global RPM EngPower;
thePower=Interp1(RPM/60,EngPower,rps,'spline');

```

```

return;

```

```

%-----
function theTorque = Torque (rps)

```

```

global RPM EngTorque;
theTorque=Interp1(RPM/60,EngTorque,rps,'spline');

return;

%-----
function PlotRimpullCurve

global Efficiencies Reductions WheelRadius minRPM maxRPM;
RPMInterval=10;
vectRPS=(minRPM:RPMInterval:maxRPM)/60;
RimPull= Torque(vectRPS)*(Efficiencies.*Reductions/(WheelRadius)); %N
Speed=Power(vectRPS)*Efficiencies./RimPull;%m/s
semilogy(Speed*3.6,RimPull/9.81,'b-');
grid;
xlabel('Speed (km/hr)');
ylabel('Rimpull (kgf)');

return;

%-----
function PlotRetpullCurve

global TempEff TempRed WheelRadius minretRPM maxretRPM;
RPMInterval=10;
vectRPS=(minretRPM:RPMInterval:maxretRPM)/60;
RetPull= RetTorque(vectRPS)*(TempRed./TempEff./WheelRadius); %N
Speed=RetPower(vectRPS)*(1./TempEff)./RetPull;%m/s
plot(Speed*3.6,RetPull/9.81,'r-');
grid;
xlabel('Speed (km/hr)');
ylabel('Retpull (kgf)');

return;

%-----
function theTorque = RetTorque (rps)

global retRPM RetTorque;
if rps*60<min(retRPM) | rps*60 >max(retRPM)
    theTorque=0;
else
    theTorque=Interp1(retRPM/60,RetTorque,rps,'spline');
end

return;

```

```
%-----  
function thePower = RetPower (rps)  
  
global retRPM RetPower;  
if rps*60<min(retRPM) | rps*60 >max(retRPM)  
    thePower=0;  
else  
    thePower=Interp1(retRPM/60,RetPower,rps,'spline');  
end  
  
return;
```

```

%-----
function varargout=test(t,DandV,flag,Gear,Distance)

global GVW EG SpeedLimit Regime;
Regime=1;

%DandV contains Distance and Velocity
%VandA should return Velocity and Acceleration

switch Regime
    case +1 % try to go as fast as possible
        switch flag
            case "
                if DandV(2)>=SpeedLimit
                    Accel=-(abs(RimpullFromSpeedAndGear(DandV(2),Gear)-
GVW*EG*9.81)/GVW);
                else
                    Accel=(RimpullFromSpeedAndGear(DandV(2),Gear)-
GVW*EG*9.81)/GVW;
                end
                varargout{1}=[DandV(2);Accel];
            case 'events'
                [varargout{1:3}]=events(DandV(2),Gear, DandV(1), Distance);
            otherwise
                error('Unhandled flag in VelAndAccelG2')
            end
        case -1 % try to slow down to SpeedLimit
            switch flag
                case "
                    if DandV(2)<=SpeedLimit
                        Accel=0;
                    else
                        Accel=(-RetpullFromSpeedAndGear(DandV(2),Gear)-
GVW*EG*9.81)/GVW;
                    end
                    varargout{1}=[DandV(2);Accel];
                case 'events'
                    [varargout{1:3}]=RetEvents(DandV(2),Gear, DandV(1), Distance);
                otherwise
                    error('Unhandled flag in VelAndAccelG2')
                end
            end
        end

return;

%-----

```

```
function [value,isterminal,direction] = events(CurSpeed,Gear, TotalDistance, Distance)
```

```
global Reductions;
```

```
    if Gear<size(Reductions,2) & Gear~=0
        valueAccel=ExtraRimPInNextGear(CurSpeed,Gear);
    else
        valueAccel=-10; % constant
    end

    if Gear>1
        valueDeccel=-ExtraRimPInNextGear(CurSpeed,Gear-1);
    else
        valueDeccel=-10;% constant
    end
```

```
    value=[valueAccel,valueDeccel,TotalDistance-Distance];
    isterminal=[1,1,1];
    direction=[-1,-1,+1];
return;
```

```
%-----
function [value,isterminal,direction] = RetEvents(CurSpeed,Gear, TotalDistance,
Distance)
```

```
global Reductions WheelRadius retRPM;
```

```
if Gear<size(Reductions,2) & Gear~=0
    theRPS=CurSpeed*Reductions(Gear)/2/pi/WheelRadius;

    if (theRPS*60 >max(retRPM))
        valueAccel=+1;
    else
        valueAccel=0; % constant
    end
else
    valueAccel=0; % constant
end
```

```
if Gear>1
    theRPS=CurSpeed*Reductions(Gear)/2/pi/WheelRadius;

    if (theRPS*60<min(retRPM))
        valueDeccel=-1;
    else
```

```

        valueDeccel=0; % constant
    end
else
    valueDeccel=0; % constant
end

value=[valueAccel,valueDeccel>TotalDistance-Distance];
isterminal=[1,1,1];
direction=[+1,+1,+1];
return;

%-----
function theRimpull=RimpullFromSpeedAndGear(Speed,Gear)
global Reductions WheelRadius Efficiencies EG GVW CurV LoadDist CT;

if Gear==0
    theRimpull=0;
else
    theRPS=Speed/3.6*Reductions(Gear)/2/pi/WheelRadius;
    theRimpull=Torque(theRPS)*((Efficiencies(Gear)*Reductions(Gear)/WheelRadius));
    MaxForce=GVW*CT*9.81*LoadDist;
    ForceNeeded=GVW*EG*9.81;
    if (theRimpull>MaxForce)
        theRimpull=MaxForce;
    end

    if(Speed ==0 & ForceNeeded > theRimpull)
        disp(['The vehicle cannot 1 go over that grade']);
        break
    end

end

return;

%-----
function theTorque = Torque (rps)

global RPM EngTorque;
theTorque=Interp1(RPM/60,EngTorque,rps,'spline');

return;

%-----
function theRetpull=RetpullFromSpeedAndGear(Speed,Gear)

```

```

global Reductions WheelRadius Efficiencies;

if Gear==0
    theRetpull=0;
else
    theRPS=Speed*Reductions(Gear)/2/pi/WheelRadius;
    theRetpull=RetTorque(theRPS)*((Reductions(Gear)/Efficiencies(Gear)/WheelRadius));
end

return;

%-----
function theTorque = RetTorque (rps)

global retRPM RetTorque;
if (rps*60<min(retRPM) | rps*60 >max(retRPM)) & 1>2
    theTorque=0;
else
    theTorque=Interp1(retRPM/60,RetTorque,rps,'spline');
end

return;

%-----
function theExtraRimpull=ExtraRimPInNextGear(x,Gear)

global Reductions WheelRadius Efficiencies;

theExtraRimpull=RimpullFromSpeedAndGear(x, Gear)-
RimpullFromSpeedAndGear(x,Gear+1);

return;

%-----
function theExtraRimpull=ExtraRetPInNextGear(x,Gear)

global Reductions WheelRadius Efficiencies;

theExtraRimpull=RetpullFromSpeedAndGear(x, Gear)-
RetpullFromSpeedAndGear(x,Gear+1);

return;

```

```

%-----
function varargout=RetMode(t,SandD,flag,Gear,Distance)

global GVW EG SpeedLimit TargetSpeed Regime;

Regime=-1;

%VandD contains Distance and Velocity
%VandA should return Velocity and Acceleration

switch Regime
    case +1 % try to go as fast as possible
        switch flag
            case "
                if SandD(2)>=SpeedLimit
                    Accel=-(RimpullFromSpeedAndGear(SandD(2),Gear)-GVW*EG*9.81)/GVW;
                else
                    Accel=(RimpullFromSpeedAndGear(SandD(2),Gear)-
GVW*EG*9.81)/GVW;
                end
                varargout{1}=[SandD(2);Accel];
            case 'events'
                [varargout{1:3}]=events(SandD(2),Gear, SandD(1), Distance);
            otherwise
                error('Unhandled flag in VelAndAccelG2')
            end
        case -1 % try to slow down to TargetSpeed
            switch flag
                case "
                    if SandD(2)== SpeedLimit
                        Accel=0;
                    elseif SandD(2)< SpeedLimit
                        Accel=(RimpullFromSpeedAndGear(SandD(2),Gear)-
GVW*EG*9.81)/GVW;
                    elseif SandD(2)> TargetSpeed
                        Accel=(-RetpullFromSpeedAndGear(SandD(2),Gear)-
GVW*EG*9.81)/GVW;
                    end
                    varargout{1}=[SandD(2);Accel];
                case 'events'
                    [varargout{1:3}]=RetEvents(SandD(2),Gear, SandD(1), Distance);
                otherwise
                    error('Unhandled flag in VelAndAccelG2')
                end
            end
        end
end

```

```

return;

%-----
function [value,isterminal,direction] = events(CurSpeed,Gear, TotalDistance, Distance)

global Reductions;

    if Gear<size(Reductions,2) & Gear~=0
        valueAccel=ExtraRimPInNextGear(CurSpeed,Gear);
    else
        valueAccel=-10; % constant
    end

    if Gear>1
        valueDeccel=-ExtraRimPInNextGear(CurSpeed,Gear-1);
    else
        valueDeccel=-10;% constant
    end

    value=[valueAccel,valueDeccel,TotalDistance-Distance];
    isterminal=[1,1,1];
    direction=[-1,-1,+1];
return;

%-----
function [value,isterminal,direction] = RetEvents(CurSpeed,Gear, TotalDistance,
Distance)

global Reductions WheelRadius retRPM;

if Gear<size(Reductions,2) & Gear~=0
    theRPS=CurSpeed*Reductions(Gear)/2/pi/WheelRadius;

    if (theRPS*60 >max(retRPM))
        valueAccel=+1;
    else
        valueAccel=0; % constant
    end
else
    valueAccel=0; % constant
end

if Gear>1
    theRPS=CurSpeed*Reductions(Gear)/2/pi/WheelRadius;

```

```

if (theRPS*60<min(retRPM))
    valueDeccel=-1;
else
    valueDeccel=0; % constant
end
else
    valueDeccel=0; % constant
end

value=[valueAccel,valueDeccel>TotalDistance-Distance];
isterminal=[1,1,1];
direction=[+1,+1,+1];
return;

%-----
function theRimpull=RimpullFromSpeedAndGear(Speed,Gear)
global Reductions WheelRadius Efficiencies;

if Gear==0
    theRimpull=0;
else
    theRPS=Speed*Reductions(Gear)/2/pi/WheelRadius;
    theRimpull=Torque(theRPS)*((Efficiencies(Gear)*Reductions(Gear)/WheelRadius));
end

return;

%-----
function theTorque = Torque (rps)

global RPM EngTorque;
theTorque=Interp1(RPM/60,EngTorque,rps,'spline');

return;

%-----
function theRetpull=RetpullFromSpeedAndGear(Speed,Gear)
global Reductions WheelRadius Efficiencies;

if Gear==0
    theRetpull=0;
else
    theRPS=Speed*Reductions(Gear)/2/pi/WheelRadius;
    theRetpull=RetTorque(theRPS)*((Reductions(Gear)/Efficiencies(Gear)/WheelRadius));
end

```

```

return;

%-----
function theTorque = RetTorque (rps)

global retRPM RetTorque;
if (rps*60<min(retRPM) | rps*60 >max(retRPM)) & 1>2
    theTorque=0;
else
    theTorque=Interp1(retRPM/60,RetTorque,rps,'spline');
end

return;

%-----
function theExtraRimpull=ExtraRimPInNextGear(x,Gear)

global Reductions WheelRadius Efficiencies;

theExtraRimpull=RimpullFromSpeedAndGear(x, Gear)-
RimpullFromSpeedAndGear(x,Gear+1);

return;

%-----
function theExtraRimpull=ExtraRetPInNextGear(x,Gear)

global Reductions WheelRadius Efficiencies;

theExtraRimpull=RetpullFromSpeedAndGear(x, Gear)-
RetpullFromSpeedAndGear(x,Gear+1);

return;

```

Appendix C

Data Used to Compare the Rimpull Curves

Data For CAT350 Series II Articulated

Data as Calculated with Efficiency and Reductions Estimated

RP and Speed of CAT350 Series II articulated truck Wheels of Radius 0.8764 m

1st Gear

	Variable	Constant	Total	Wheel = 26.5R25
e	0.87	1.00	0.87	Radius = 0.88
R	78.81	1.00	78.81	
$ed*ek*Rd*Rk/ rw$			78.305044	

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
476.97	3046.70	152.18	24319.25	2.00	24.32
696.97	2424.08	176.93	19349.40	2.92	19.35
977.57	1998.14	204.55	15949.51	4.10	15.95
1226.91	1676.19	215.36	13379.59	5.14	13.38
1628.49	1482.01	252.73	11829.64	6.83	11.83
2000.00	1265.28	265.00	10099.69	8.38	10.10
2098.31	971.64	213.50	7755.76	8.79	7.76

2nd Gear

	Variable	Constant	Total
e	0.92	1.00	0.92
R	44.46	1.00	44.46
$ed*ek*Rd*Rk/ rw$			46.60

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1149.26	1604.18	193.06	7620.77	8.54	7.62
1391.66	1590.07	231.73	7553.77	10.34	7.55
1617.77	1482.09	251.08	7040.78	12.02	7.04
1808.88	1381.47	261.69	6562.80	13.44	6.56
2000.00	1265.28	265.00	6010.81	14.86	6.01
2104.98	1118.78	246.62	5314.84	15.64	5.31
2158.82	1015.64	229.61	4824.85	16.04	4.82
2193.81	921.97	211.81	4379.87	16.30	4.38

3rd Gear

	Variable	Constant	Total
e	0.93	1.00	0.93
R	25.45	1.00	25.45
$ed*ek*Rd*Rk/ rw$			27.01911667

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1255.78	1590.23	209.12	4379.87	16.30	4.38
1424.50	1576.43	235.16	4341.87	18.49	4.34
1583.20	1508.54	250.10	4154.87	20.55	4.15
1711.86	1431.20	256.57	3941.88	22.22	3.94
1851.31	1345.52	260.85	3705.89	24.03	3.71
2000.00	1265.28	265.00	3484.89	25.96	3.48
2119.41	1189.76	264.06	3276.90	27.51	3.28
2199.54	1070.68	246.61	2948.91	28.55	2.95
2239.60	971.93	227.95	2676.92	29.07	2.68

4th Gear

	Variable	Constant	Total
e	0.96	1.00	0.96
R	14.72	1.00	14.72
$ed*ek*Rd*Rk/ rw$			16.08742241

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1226.11	1690.90	217.11	2772.91	27.52	2.77
1300.96	1604.32	218.57	2630.92	29.20	2.63
1415.46	1576.27	233.64	2584.92	31.77	2.58
1529.96	1535.41	246.00	2517.92	34.34	2.52
1644.46	1482.36	255.27	2430.93	36.91	2.43
1747.83	1431.14	261.94	2346.93	39.23	2.35
1828.02	1381.75	264.51	2265.93	41.03	2.27
1914.01	1310.41	262.65	2148.93	42.96	2.15
2000.00	1265.28	265.00	2074.94	44.89	2.07
2086.43	1200.04	262.20	1967.94	46.83	1.97
2138.12	1158.57	259.41	1899.94	47.99	1.90

CAT350 Series II
Data From CAT PH As collected with DataThief

1st Gear

Speed (km/hr)	RP (kg*1000)	RP (kg)
2.00	24.32	24320.00
2.92	19.35	19350.00
4.10	15.95	15950.00
5.14	13.38	13380.00
6.83	11.83	11830.00
8.38	10.10	10100.00
8.79	7.76	7756.00

2nd Gear

10.34	7.55	7554.00
12.02	7.04	7041.00
13.44	6.56	6563.00
14.86	6.01	6011.00
15.64	5.32	5315.00
16.04	4.83	4825.00
16.30	4.38	4380.00
16.30	4.38	4380.00

3rd Gear

16.30	4.38	4380.00
18.49	4.34	4342.00
20.55	4.16	4155.00
22.22	3.94	3942.00
24.03	3.71	3706.00
25.96	3.49	3485.00
27.51	3.28	3277.00
28.55	2.95	2949.00
29.07	2.68	2677.00

4th Gear

27.52	2.77	2773.00
29.20	2.63	2631.00
31.77	2.59	2585.00
34.34	2.52	2518.00
36.91	2.43	2431.00
39.23	2.35	2347.00
41.03	2.27	2266.00
42.96	2.15	2149.00
44.89	2.08	2075.00
46.83	1.97	1968.00
47.99	1.90	1900.00
49.67	1.68	1680.00

Rimpull and Speed of CAT400 Series II

1st Gear

	Variable	Constant	Total
e	0.70	1.00	0.70
R	124.09	1.00	124.09

$$ed*ek*Rd*Rk/ rw \quad 86.89$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
177.71	3564.72	66.34	31572.00	0.54	31.57
367.83	3327.50	128.17	29471.00	1.12	29.47
557.78	3089.72	180.47	27365.00	1.69	27.37
699.35	2838.95	207.91	25144.00	2.12	25.14
840.89	2608.51	229.70	23103.00	2.55	23.10
982.26	2384.16	245.24	21116.00	2.98	21.12
1124.16	2213.89	260.62	19608.00	3.42	19.61
1266.38	2077.61	275.52	18401.00	3.85	18.40
1361.02	1980.96	282.34	17545.00	4.13	17.55
1455.15	1859.02	283.28	16465.00	4.42	16.47
1573.68	1763.17	290.56	15616.00	4.78	15.62
1762.78	1594.59	294.36	14123.00	5.36	14.12
2000.00	1441.94	302.00	12771.00	6.08	12.77

2nd Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	66.35	1.00	66.35

$$ed*ek*Rd*Rk/ rw \quad 54.78$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
993.77	2489.14	259.04	13899.00	5.65	13.90
1198.10	2298.77	288.41	12836.00	6.81	12.84
1325.48	2145.65	297.82	11981.00	7.53	11.98
1452.57	1971.22	299.85	11007.00	8.25	11.01
1553.97	1811.12	294.73	10113.00	8.83	10.11
1872.57	1536.68	301.34	8580.60	10.64	8.58
2000.00	1441.94	302.00	8051.60	11.36	8.05
2089.24	1374.77	300.78	7676.50	11.87	7.68
2152.07	1263.21	284.68	7053.60	12.23	7.05

3rd Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	51.81	1.00	51.81

$$ed*ek*Rd*Rk/ rw \quad 42.92$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1690.37	1620.83	286.91	7090.80	12.30	7.09
1810.35	1553.31	294.48	6795.40	13.17	6.80
1910.12	1496.57	299.36	6547.20	13.90	6.55
2000.00	1441.94	302.00	6308.20	14.55	6.31
2149.52	1338.67	301.33	5856.40	15.64	5.86
2239.26	1276.24	299.27	5583.30	16.29	5.58
2278.71	1210.46	288.85	5295.50	16.58	5.30

4th Gear

	Variable	Constant	Total
e	0.84	1.00	0.84
R	36.89	1.00	36.89
ed*ek*Rd*Rk/ rw		31.03	

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1643.90	1656.19	285.11	5239.50	16.80	5.24
1743.61	1595.54	291.33	5047.60	17.82	5.05
1829.04	1537.18	294.43	4863.00	18.69	4.86
1921.62	1488.79	299.59	4709.90	19.64	4.71
2000.00	1441.94	302.00	4561.70	20.44	4.56
2085.23	1374.61	300.17	4348.70	21.31	4.35
2149.04	1296.73	291.82	4102.30	21.96	4.10
2191.41	1223.36	280.74	3870.20	22.39	3.87

5th Gear

	Variable	Constant	Total
e	0.85	1.00	0.85
R	26.86	1.00	26.86
ed*ek*Rd*Rk/ rw		22.79	

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1595.31	1692.66	282.78	3932.00	22.40	3.93
1673.17	1647.97	288.75	3828.20	23.49	3.83
1740.63	1604.49	292.46	3727.20	24.44	3.73
1828.82	1553.83	297.58	3609.50	25.67	3.61
1896.28	1512.84	300.42	3514.30	26.62	3.51
1942.87	1465.36	298.14	3404.00	27.27	3.40
2000.00	1441.94	302.00	3349.60	28.08	3.35
2051.86	1396.61	300.09	3244.30	28.80	3.24
2103.65	1359.89	299.58	3159.00	29.53	3.16
2124.16	1296.61	288.42	3012.00	29.82	3.01
2149.88	1249.43	281.29	2902.40	30.18	2.90

6th Gear

	Variable	Constant	Total
e	0.85	1.00	0.85
R	19.59	1.00	19.59
ed*ek*Rd*Rk/ rw		16.74	

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1575.69	1710.18	282.19	2917.60	30.33	2.92
1636.33	1691.54	289.85	2885.80	31.49	2.89
1708.29	1638.08	293.04	2794.60	32.88	2.79
1776.45	1594.65	296.65	2720.50	34.19	2.72
1825.66	1560.83	298.40	2662.80	35.14	2.66
1874.86	1519.68	298.37	2592.60	36.09	2.59
1927.91	1487.44	300.30	2537.60	37.11	2.54
1980.90	1455.85	302.00	2483.70	38.13	2.48
2033.90	1417.45	301.90	2418.20	39.15	2.42
2071.72	1380.17	299.43	2354.60	39.87	2.35
2090.48	1329.88	291.13	2268.80	40.24	2.27
2113.08	1281.46	283.56	2186.20	40.67	2.19

7th Gear			
	Variable	Constant	Total
e	0.86	1.00	0.86
R	14.73	1.00	14.73
$ed*ek*Rd*Rk/ rw$		12.72	

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1575.69	1710.18	282.19	2217.03	40.32	2.22
1636.33	1691.54	289.85	2192.87	41.87	2.19
1708.29	1638.08	293.04	2123.57	43.71	2.12
1776.45	1594.65	296.65	2067.26	45.45	2.07
1825.66	1560.83	298.40	2023.42	46.71	2.02
1874.86	1519.68	298.37	1970.07	47.97	1.97
1927.91	1487.44	300.30	1928.28	49.33	1.93
1980.90	1455.85	302.00	1887.32	50.68	1.89
2033.90	1417.45	301.90	1837.55	52.04	1.84
2071.72	1380.17	299.43	1789.22	53.01	1.79
2090.48	1329.88	291.13	1724.02	53.49	1.72
2113.08	1281.46	283.56	1661.26	54.07	1.66

CAT400 Series II Articulated
Data Collected from CAT Performance Handbook
 Speed (km/hr) RP (kg*1000) RP(kg)

1st Gear

0.54	31572.00	31.57
1.12	29471.00	29.47
1.69	27365.00	27.37
2.12	25144.00	25.14
2.55	23103.00	23.10
2.98	21116.00	21.12
3.42	19608.00	19.61
3.85	18401.00	18.40
4.13	17545.00	17.55
4.42	16465.00	16.47
4.78	15616.00	15.62
5.36	14123.00	14.12
6.08	12771.00	12.77

2nd Gear

5.65	13899.00	13.90
6.81	12836.00	12.84
7.53	11981.00	11.98
8.25	11007.00	11.01
8.83	10113.00	10.11
10.64	8580.60	8.58
11.36	8051.60	8.05
11.87	7676.50	7.68
12.23	7053.60	7.05

3rd Gear

12.30	7090.80	7.09
13.17	6795.40	6.80
13.90	6547.20	6.55
14.55	6308.20	6.31
15.64	5856.40	5.86
16.29	5583.30	5.58
16.58	5295.50	5.30

4th Gear

16.80	5239.50	5.24
17.82	5047.60	5.05
18.69	4863.00	4.86
19.64	4709.90	4.71
20.44	4561.70	4.56
21.31	4348.70	4.35
21.96	4102.30	4.10
22.39	3870.20	3.87

5th Gear

22.40	3932.00	3.93
23.49	3828.20	3.83
24.44	3727.20	3.73
25.67	3609.50	3.61
26.62	3514.30	3.51
27.27	3404.00	3.40
28.08	3349.60	3.35
28.80	3244.30	3.24
29.53	3159.00	3.16
29.82	3012.00	3.01
30.18	2902.40	2.90

6th Gear

30.33	2917.60	2.92
31.49	2885.80	2.89
32.88	2794.60	2.79
34.19	2720.50	2.72
35.14	2662.80	2.66
36.09	2592.60	2.59
37.11	2537.60	2.54
38.13	2483.70	2.48
39.15	2418.20	2.42
39.87	2354.60	2.35
40.24	2268.80	2.27
40.67	2186.20	2.19

7th Gear

41.11	2197.40	2.20
42.71	2139.00	2.14
43.88	2082.50	2.08
45.56	2059.50	2.06
46.94	2004.90	2.00
48.25	1951.80	1.95
49.20	1920.50	1.92
50.30	1899.70	1.90

Data Calculated for a CAT769 Rigid Frame Truck

1st Gear

	Variable	Constant	Total	Wheel = 26.5R25
e	0.84	1.00	0.84	Radius= 0.7986
R	57.04	1.00	57.04	

$$ed*ek*Rd*Rk/ rw = 59.80$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1362.96	2042.19	291.48	12449.49	7.19	12.45
1584.31	2019.55	335.06	12311.51	8.36	12.31
1750.51	1931.81	354.12	11776.57	9.24	11.78
1889.13	1827.33	361.50	11139.65	9.97	11.14
2000.00	1728.42	362.00	10536.72	10.56	10.54
2083.37	1616.84	352.75	9856.50	11.00	9.86
2139.27	1462.83	327.71	8917.62	11.29	8.92
2195.17	1323.49	304.24	8068.22	11.59	8.07

2nd Gear

	Variable	Constant	Total
e	0.86	1.00	0.86
R	43.71	1.00	43.71

$$ed*ek*Rd*Rk/ rw = 46.82$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1596.78	1931.75	323.02	9220.25	11.00	9.22
1724.12	1868.36	337.33	8917.68	11.88	8.92
1872.66	1807.06	354.37	8625.12	12.90	8.63
2000.00	1728.42	362.00	8249.76	13.78	8.25
2085.09	1634.95	356.99	7803.61	14.36	7.80
2191.23	1529.41	350.95	7299.87	15.09	7.30
2255.26	1414.84	334.14	6753.03	15.53	6.75
2297.81	1323.52	318.47	6317.18	15.83	6.32
2361.84	1210.84	299.48	5779.34	16.27	5.78

3rd Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	32.12	1.00	32.12

$$ed*ek*Rd*Rk/ rw = 33.54$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	RP/1000
1579.13	1975.20	326.63	6754.06	14.80	6.75
1703.74	1910.39	340.84	6532.45	15.97	6.53
1812.88	1868.36	354.70	6388.75	16.99	6.39
1906.44	1807.06	360.77	6179.14	17.87	6.18
2000.00	1728.42	362.00	5910.23	18.75	5.91
2077.99	1653.23	359.75	5653.12	19.48	5.65
2140.50	1563.80	350.53	5347.31	20.06	5.35
2203.02	1462.84	337.48	5002.09	20.65	5.00
2249.85	1368.41	322.40	4679.18	21.09	4.68
2296.79	1280.09	307.89	4377.17	21.53	4.38
2343.84	1184.22	290.66	4049.36	21.97	4.05

4th Gear

	Variable	Constant	Total
e	0.84	1.00	0.84
R	24.05	1.00	24.05

$$ed*ek*Rd*Rk/ rw = 25.40$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1568.23	1931.72	317.24	5000.98	19.63	5.00
1649.89	1910.36	330.06	4945.69	20.65	4.95
1708.29	1868.34	334.23	4836.91	21.38	4.84
1778.28	1847.68	344.08	4783.42	22.26	4.78
1859.94	1807.01	351.96	4678.14	23.28	4.68
1930.01	1767.27	357.18	4575.26	24.16	4.58
2000.00	1728.42	362.00	4474.68	25.04	4.47
2058.41	1671.69	360.34	4327.80	25.77	4.33
2105.15	1598.93	352.48	4139.44	26.35	4.14
2151.89	1546.49	348.49	4003.66	26.94	4.00
2198.71	1479.17	340.58	3829.40	27.52	3.83
2245.45	1383.70	325.37	3582.24	28.11	3.58
2280.60	1323.50	316.08	3426.37	28.55	3.43
2304.01	1251.89	302.05	3241.00	28.84	3.24
2339.17	1171.10	286.87	3031.84	29.28	3.03

5th Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	17.22	1.00	17.22

$$ed*ek*Rd*Rk/ rw = 17.80$$

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1515.47	2019.61	320.51	3663.82	26.50	3.66
1573.92	1997.28	329.19	3623.32	27.52	3.62
1624.08	1953.34	332.21	3543.61	28.39	3.54
1690.88	1931.73	342.05	3504.41	29.56	3.50
1766.03	1889.23	349.39	3427.30	30.88	3.43
1832.89	1847.66	354.64	3351.90	32.05	3.35
1891.34	1807.03	357.90	3278.19	33.07	3.28
1949.84	1767.29	360.86	3206.08	34.09	3.21
2000.00	1728.42	362.00	3135.58	34.97	3.14
2041.75	1671.70	357.43	3032.67	35.70	3.03
2091.91	1616.84	354.19	2933.16	36.57	2.93
2125.36	1563.76	348.04	2836.85	37.16	2.84
2158.88	1479.19	334.41	2683.44	37.74	2.68
2200.69	1399.20	322.45	2538.32	38.48	2.54
2225.85	1323.51	308.50	2401.01	38.92	2.40
2250.96	1251.90	295.10	2271.10	39.35	2.27

6th Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	16.21	1.00	16.21

$ed*ek*Rd*Rk/ rw$ 13.48

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1529.00	1997.27	319.80	2743.50	35.56	2.74
1560.44	1975.22	322.77	2713.20	36.29	2.71
1591.83	1953.38	325.62	2683.20	37.02	2.68
1623.22	1953.38	332.04	2683.20	37.75	2.68
1660.89	1931.75	335.99	2653.50	38.62	2.65
1698.56	1910.42	339.81	2624.20	39.50	2.62
1729.95	1889.24	342.25	2595.10	40.23	2.60
1767.66	1868.34	345.85	2566.40	41.11	2.57
1805.33	1847.74	349.32	2538.10	41.98	2.54
1843.00	1827.29	352.66	2510.00	42.86	2.51
1880.67	1807.05	355.89	2482.20	43.74	2.48
1918.38	1767.30	355.04	2427.60	44.61	2.43
1956.05	1747.79	358.01	2400.80	45.49	2.40
2000.00	1728.42	362.00	2374.20	46.51	2.37
2031.43	1690.42	359.61	2322.00	47.24	2.32
2056.55	1671.71	360.02	2296.30	47.83	2.30
2087.98	1634.95	357.49	2245.80	48.56	2.25
2119.42	1581.29	350.96	2172.10	49.29	2.17
2150.81	1546.49	348.32	2124.30	50.02	2.12
2182.24	1479.23	338.04	2031.90	50.75	2.03
2201.12	1430.67	329.77	1965.20	51.19	1.97
2238.87	1353.28	317.28	1858.90	52.07	1.86
2264.07	1265.92	300.14	1738.90	52.65	1.74
2282.95	1184.24	283.12	1626.70	53.09	1.63
2308.15	1107.80	267.77	1521.70	53.68	1.52

7th Gear

	Variable	Constant	Total
e	0.83	1.00	0.83
R	11.80	1.00	11.80

$ed*ek*Rd*Rk/ rw$ 9.75731476

RPM	Torque(N-m)	Power (kW)	RP (kgf)	V(km/hr)	
1492.61	2020.25	315.78	2009.40	47.68	2.01
1533.74	1997.93	320.89	1987.20	49.00	1.99
1579.45	1975.81	326.80	1965.20	50.46	1.97
1620.61	1932.38	327.94	1922.00	51.77	1.92
1652.60	1910.96	330.71	1900.70	52.79	1.90
1689.16	1889.85	334.29	1879.70	53.96	1.88
1721.15	1889.85	340.62	1879.70	54.98	1.88
1753.15	1868.94	343.12	1858.90	56.01	1.86
1794.31	1848.33	347.30	1838.40	57.32	1.84
1830.87	1807.61	346.57	1797.90	58.49	1.80
1867.43	1807.61	353.49	1797.90	59.66	1.80
1903.99	1787.60	356.42	1778.00	60.83	1.78
1940.56	1767.89	359.26	1758.40	61.99	1.76
1968.01	1748.29	360.30	1738.90	62.87	1.74
2000.00	1728.99	362.12	1719.70	63.89	1.72
2022.85	1690.98	358.20	1681.90	64.62	1.68
2045.73	1672.28	358.25	1663.30	65.35	1.66
2068.58	1653.78	358.24	1644.90	66.08	1.64
2091.44	1635.48	358.19	1626.70	66.81	1.63
2114.32	1599.49	354.14	1590.90	67.54	1.59
2141.74	1564.30	350.85	1555.90	68.42	1.56
2160.05	1512.93	342.22	1504.80	69.01	1.50
2178.36	1463.26	333.80	1455.40	69.59	1.46
2201.25	1399.62	322.63	1392.10	70.32	1.39
2219.56	1353.67	314.64	1346.40	70.91	1.35
2242.47	1266.30	297.37	1259.50	71.64	1.26
2260.78	1211.20	286.75	1204.70	72.22	1.20
2288.27	1120.52	268.51	1114.50	73.10	1.11
2306.61	1059.89	256.01	1054.20	73.69	1.05
2324.92	1002.56	244.09	997.18	74.27	1.00

Data collected from CAT Performance Handbook Using DataThief

Speed (km/hr) RP (kg*1000) RP (kg)

1st Gear

7.19	12451.00	12.45
8.36	12313.00	12.31
9.24	11778.00	11.78
9.97	11141.00	11.14
10.56	10538.00	10.54
11.00	9857.70	9.86
11.29	8918.70	8.92
11.59	8069.20	8.07

2nd Gear

11.00	9221.30	9.22
11.87	8918.70	8.92
12.90	8626.10	8.63
13.77	8250.70	8.25
14.36	7804.50	7.80
15.09	7300.70	7.30
15.53	6753.80	6.75
15.83	6317.90	6.32
16.27	5780.00	5.78

3rd Gear

14.80	6753.80	6.75
15.97	6532.20	6.53
16.99	6388.50	6.39
17.87	6178.90	6.18
18.75	5910.00	5.91
19.48	5652.90	5.65
20.06	5347.10	5.35
20.65	5001.90	5.00
21.09	4679.00	4.68
21.53	4377.00	4.38
21.97	4049.20	4.05

4th Gear

19.63	5001.90	5.00
20.65	4946.60	4.95
21.38	4837.80	4.84
22.26	4784.30	4.78
23.28	4679.00	4.68
24.16	4576.10	4.58
25.03	4475.50	4.48
25.76	4328.60	4.33
26.35	4140.20	4.14
26.93	4004.40	4.00
27.52	3830.10	3.83
28.10	3582.90	3.58
28.54	3427.00	3.43
28.84	3241.60	3.24
29.28	3032.40	3.03

5th Gear

26.50	3663.50	3.66
27.52	3623.00	3.62
28.40	3543.30	3.54
29.57	3504.10	3.50
30.88	3427.00	3.43
32.05	3351.60	3.35
33.07	3277.90	3.28
34.09	3205.80	3.21
34.97	3135.30	3.14
35.70	3032.40	3.03
36.58	2932.90	2.93
37.16	2836.60	2.84
37.75	2683.20	2.68
38.48	2538.10	2.54
38.92	2400.80	2.40
39.36	2270.90	2.27
35.56	2743.50	2.74
36.29	2713.20	2.71
37.02	2683.20	2.68
37.75	2683.20	2.68
38.62	2653.50	2.65
39.50	2624.20	2.62

6th Gear

40.23	2595.10	2.60
41.11	2566.40	2.57
41.98	2538.10	2.54
42.86	2510.00	2.51
43.74	2482.20	2.48
44.61	2427.60	2.43
45.49	2400.80	2.40
46.51	2374.20	2.37
47.24	2322.00	2.32
47.83	2296.30	2.30
48.56	2245.80	2.25
49.29	2172.10	2.17
50.02	2124.30	2.12
50.75	2031.90	2.03
51.19	1965.20	1.97
52.07	1858.90	1.86
52.65	1738.90	1.74
53.09	1626.70	1.63
53.68	1521.70	1.52
47.68	2009.40	2.01
49.00	1987.20	1.99
50.46	1965.20	1.97
51.77	1922.00	1.92
52.79	1900.70	1.90
53.96	1879.70	1.88

7th Gear

54.98	1879.70	1.88
56.01	1858.90	1.86
57.32	1838.40	1.84
58.49	1797.90	1.80
59.66	1797.90	1.80
60.83	1778.00	1.78
61.99	1758.40	1.76
62.87	1738.90	1.74
63.89	1719.70	1.72
64.62	1681.90	1.68
65.35	1663.30	1.66
66.08	1644.90	1.64
66.81	1626.70	1.63
67.54	1590.90	1.59
68.42	1555.90	1.56
69.01	1504.80	1.50
69.59	1455.40	1.46
70.32	1392.10	1.39
70.91	1346.40	1.35
71.64	1259.50	1.26
72.22	1204.70	1.20
73.10	1114.50	1.11
73.69	1054.20	1.05
74.27	997.18	1.00
75.00	943.24	0.94

VITA

Jose Luis Perdomo was born in Mayaguez, Puerto Rico on August 15, 1972. He is the youngest son of Maria J. Rivera and Luis Perdomo. He graduated from high school in Hormigueros, Puerto Rico in May 1990. He has an Associated Degree in Construction Technology from the University of Puerto Rico, Ponce Campus. In addition, he has a Bachelor's Degree in Civil Engineering from the University of Puerto Rico, Mayaguez Campus. After finishing his Bachelor's Degree he went to work for a heavy/highway contractor as a field engineer and as a project administrator. He went to graduate school at Virginia Polytechnic Institute and State University to pursue a Master's Degree in Construction Engineering and Management under the guidance of Dr. Julio Martinez. His research focused in heavy equipment performance in earthmoving operations. After finishing his Master's degree he expects to join the Department of Architecture to pursue a doctoral degree in Environmental Design and Planning, Building Construction and Management option. He is married to Arliz Lizardo. They are the proud parents of two beautiful kids, Gaby and Amanda.