AN ABSTRACT OF THE THESIS OF

Matamyo Simwanda for the degree of Master of Science in Forest Engineering presented on April 26, 2010.

Title: Modeling Biomass Transport on Single Lane Forest Roads and Monitoring GPS Accuracy for Vehicle Tracking under Different Forest Canopy Conditions

Abstract approved:

John Sessions

The transportation of wood and biomass resources from landing and other collection locations to processing and distribution sites is a substantial cost within the wood supply chain. These high costs provide a basis for research aimed at improving biomass transportation planning decisions and potentially reducing biomass transportation costs. Chip vans have been identified to be the most cost-efficient mode of transporting biomass provided the roads are suitable for the trucks which are generally built for highway use. Research to develop chip van performance simulation models for travel time prediction could potentially reduce biomass transportation costs by improving transportation planning decisions. GPS technology has the ability to record information such as location (longitude, latitude and elevation), movement (speed, heading) and travel time which makes it an attractive tool for data collection to develop, test and validate vehicle simulation models. In spite of several studies investigating the accuracy and performance of GPS under different forest conditions, the reliability of GPS receiver measurements for moving vehicles under forest canopy and in mountainous terrain has not been examined.

This dissertation includes two manuscripts. One manuscript presents a Chip Van Travel Time Prediction Simulation Model (CHIP-VAN) that was developed using data collected by GPS receivers to track and monitor chip vans. The vans were exclusively used for transporting chipped (ground) biomass from forest operation sites in western Oregon.

The other manuscript examines the accuracy and reliability of GPS for vehicle tracking under different forest canopy conditions and mountainous terrain.

The model, CHIP-VAN, is developed based on the maximum limiting speeds on each road segment as limited by road grade, stopping sight distance (SSD) and road alignment as well as modeling the driver's behavior as these road conditions change. A two pass simulation was used in the model; the first pass simulation calculates the maximum limiting speeds on each road segment and the second pass simulates the driver's behavior and calculates the travel time. To emulate the driver's behavior, four cases that determine whether a driver will accelerate, decelerate or continue at current speed, were developed. The model has been tested for validation using the data collected for the study. The validation tests suggest that the model is appropriate for predicting travel time for chip vans on single lane forest roads with acceptable accuracy.

The findings in the second study demonstrate that the GPS tracking accuracy of vehicles on forested roads are clearly influenced by the composition of the surrounding canopy, with the strongest influence being from heavy forest canopy cover. Accuracy is generally improved in areas with less forest canopy. The study concludes that the consumer-grade GPS receiver measurements determined are acceptable for tracking and improving biomass transport from forest supply locations to distribution and processing centers. The analysis of the range of accuracies found for vehicles operating within heavy forest canopy cover demonstrates that the accuracies are probably acceptable for many forest transportation monitoring and planning applications, including the mapping of forest road locations and other forest transportation operations.

It is expected that the CHIP-VAN model and GPS accuracy studies will aid forest transportation managers in decision making and transportation planning in biomass operations. Most importantly it is hoped that the results of this research will increase transportation management planning efficiency for biomass and lead to improved methods for developing biomass cost assessments

Modeling Biomass Transport on Single Lane Forest Roads and Monitoring GPS Accuracy for Vehicle Tracking under Different Forest Canopy Conditions

by

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Matamyo Simwanda, Author

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF APPENDIX FIGURES

LIST OF APPENDICES TABLES

Table Page

Modeling Biomass Transport on Single Lane Forest Roads and Monitoring GPS Accuracy for Vehicle Tracking under Different Forest Canopy Conditions

CHAPTER 1. INTRODUCTION

The transportation of wood and biomass resources from landing and other collection locations to processing and distribution sites is a substantial cost within the wood supply chain. Several studies have found transportation of wood and biomass as a major contributing factor to the delivered costs. Angus-Hankin et al. (1995) reported that in spite of being the simplest of the handling phases in transporting fuel wood from its point-of-origin to the ultimate processing point, secondary transport is typically responsible for between 20% and 40% of the delivered cost. Many have also cited McDonald et al. (2001) who reported that transportation of wood fiber accounts for about 25% to 50% of the total delivered costs and this is likely to increase as fuel prices increase.

Chip vans have been identified to be the most cost-efficient mode of transporting biomass chips provided the roads are suitable for the trucks carrying the vans which are generally built for highway use (Rawlings et al. 2004). The efficiency of chipped biomass transportation on forest roads depends upon the ability for trucks pulling chip vans to access forest supply points. Conventional chip vans differ from log trucks in that they have greater off-tracking, lower clearance, higher center of gravity, are often heavier, and must return to the forest pulling the empty trailer which reduces gradeability for the empty vehicle (Sessions et al. 2010). Several studies and models have been developed to predict log truck travel times (Byrne et al. 1960, Botha et al. 1977, Jackson 1986, Shiess and Shen 1990, McCormack and Douglas 1992, Jalinier and Nader 1993, Shen 1993, Moll and Copstead 1996) but there have been limited studies to predict travel time of chip vans over forest roads (Rawlings et al. 2004).

Research to develop chip van performance simulation models for travel time prediction could potentially reduce biomass transportation costs by improving transportation planning decisions. To develop truck performance simulation models information about the truck specifications, observed travel times (loaded, unloaded or round trip) and the road geometry are required. Several approaches have been taken to obtain this information. Truck specifications required for most simulation models are obtained from manufacturers and sometimes assumptions may be made. Travel times are usually obtained for the purpose of testing and validation of the simulation models. In the past, tools ranging from stopwatches (Lavoie 1979) to hand held computers (Jackson 1986) have been used. Road parameters are usually obtained from survey profiles. As part of the development of the truck performance simulation program OTTO, Jalinier and Courteau (1993), carried out forest road surveys with a GPS receiver placed in a moving vehicle to produce road data compatible with OTTO. The ability of GPS receivers to record information such as location (longitude, latitude and elevation), movement (speed, heading) and travel time, make them very attractive for data collection to test and validate simulation models.

GPS receivers have been used for studies on various forest operations such as harvesting machines performance evaluations (Cordero et al. 2004, Veal et al. 2001) and forest vehicle tracking (Sikanen et al. 2005, Devlin et al. 2007, Devlin and McDonnell 2009). To our knowledge, no study has used data collected using GPS receivers to develop and validate a travel time prediction model to predict travel time for forest vehicles on forest roads and hence chip vans. The accuracy and performance of GPS under different forest conditions have been investigated in several studies (Deckert and Bolstad 1996, Karsky et al. 2001, Yoshimura and Hasegawa 2003, Hasegawa and Yoshimura 2007, Wing et al. 2005, Rodríguez-Pérez et al. 2007, Wing and Eklund 2007, Wing 2009). These studies have determined that GPS receivers are capable of recording positions to within several meters of true location under forest canopy with certain GPS receiver configurations. However, the reliability of GPS receiver measurements for moving vehicles under forest canopy and in mountainous terrain has not been examined.

This dissertation includes two manuscripts. One manuscript presents a Chip Van Travel Time Prediction Simulation Model (CHIP-VAN) that was developed using data collected by GPS receivers to track and monitor chip vans that were exclusively used for transporting chipped (ground) biomass from forest operation sites in western Oregon. The other manuscript examines the accuracy and reliability of GPS for vehicle tracking under different forest canopy conditions and mountainous terrain.

Therefore the objectives of this dissertation were as follows:

i) To develop and validate a travel time prediction model for chip vans on forest roads.

ii) To monitor conventional chip vans using GPS technology.

iii) To determine the accuracy and reliability of GPS for vehicle tracking in forested terrain.

iv) To investigate GPS technology applications for improving biomass transportation.

CHAPTER 2. LITERATURE REVIEW

Global Positioning Systems (GPS)

Overview

The Global Positioning System is a satellites-based navigation system developed to communicate with ground-based receivers to record real time position information. The interaction of the satellites and the GPS receivers generally provides 3- dimensional information (longitude, latitude and elevation) of the receiver position. According to Wing (2008), the receiver uses satellite signal information to calculate a distance (known as range) to the satellites from which it receives signals. The results of the receiver position includes three ranges giving the longitude and latitude and four other ranges that help account for ambiguities resulting from timing imperfections and lead to the determination of an elevation in addition to longitude and latitude coordinates. There are four GPS satellite systems. The Navigation Signal Timing and Ranging (NAVSTAR) system developed by the United States department of Defense; the Global Navigation System (GLONASS) which is still under development by the Russian Federation; a satellite navigation system called Galileo which is also still in the process of development by the European union (EU); and a Chinese government sponsored Satellite system also still being developed called Beidou satellite system (Wing 2008). The NAVSTAR GPS, which currently has 33 operational satellites freely available to users worldwide, is the most widely used through out North America and in many other parts of the world (Wing 2009). The NAVSTAR GPS comprises three basic segments. The space segment which is a constellation of available satellites in orbit at an altitude of 20,000 kilometers above the Earth; the ground-based control segment under the US Department of Defense which has monitoring and ground control stations and a master control station; and the user segment – comprised of all of the users making observations with GPS receivers (Baral 2004).

GPS equipment, costs and applications in forestry

GPS receivers equipment are generally classified based on their accuracy (in terms of measurement) and functional capabilities which has a direct effect on their costs. The GPS receivers are classified into three main categories, namely Survey grade, Mapping-grade, and Consumer grade (Wing et al. 2005, Serr et al. 2006). Survey-grade GPS receivers are capable of providing mean accuracies of less than 1 cm from true position (Wing 2008, Bettinger 2008). Survey grade receivers have very high requirements for quality and consistence that are most of the times unachievable under forest canopy and thus there is very limited use of these receivers in forestry applications (Wing and Kellogg 2004). Nonetheless, survey grade GPS receivers can be used to establish control points in forest clearings or high points that are near study locations, and other measurement tools such as laser range finders can proceed from these determined positions into forested areas where GPS signals are difficult to maintain (Wing 2008). Although these receivers are capable of giving measurements with higher accuracies than other receiver grades, they are generally the most expensive often at least $10,000. Ruzos (as cited in Wing and Kellogg 2004) states that survey grade receivers will typically cost users in excess of $ 25,000, Betttinger reports a cost $10,000 or more per unit and Wing (2008) gives a price range beginning around $12,000.

Mapping grade receivers are viewed as falling between survey grade and consumer grade receivers, as they have been reported to have less measurement accuracy than survey grade receivers but better than consumer grade receivers. Mapping-grade GPS receivers can return accuracies typically within 2–5 m of true position, depending on the quality of the equipment and operator skill (Wing et al. 2005) and some receivers are capable of measurements of less than 1 m from true position (Wing 2008). Mapping-grade receivers come in styles that are designed for use in forested settings and inclement weather (Wing 2008) and thus are frequently used in many forestry applications. However, these receivers have limitations in cases were there is poor satellite coverage or under a heavy canopy cover (Karsky et al. 2001). Bettinger (2008) reports that mapping-grade GPS receivers will cost in the range of $1500 to $10,000 and Wing (2008) reports a range of $1000 to $12,000. These are also high prices and might limit some potential users from using these receivers.

The availability of consumer-grade GPS receivers on the market have dramatically increased over the past decade. Despite the modest functionality and estimated accuracies, consumer-grade GPS receivers are accessible technology for many potential users and organizations (Wing 2009). Consumer grade GPS receivers are available for several hundred dollars or less and have been found to collect measurements with accuracies that are acceptable for many forestry applications (Wing and Eklund 2007). However, consumer grade receivers have several limitations: they are not able to set minimum standards for satellite geometry for data collection; they are limited to 500 coordinate pairs; and are not able to differentially correct data after field data collection without third-party software (Wing and Eklund 2007). Differential correction is implemented to reduce the amount of error from GPS receiver measurements. Differential corrections are carried out by comparing coordinates recorded by GPS receivers with known coordinates from GPS base stations and use the difference as a correction factor that can be time stamped and applied to measurements collected by other GPS receivers operating in the vicinity. Atmospheric interference of satellite signals is known to be the cause of potentially large errors addressed by differential correction (Wing 2009).

GPS Accuracy under Forest Canopy

All GPS receiver position measurements are derived from communications with satellite systems to calculate positions and are subject to several potential error sources. Errors can come from a number of factors including imprecision in accounting for time, satellite orbits, atmospheric conditions, and other factors (Wing 2008). In a forest setting, the major sources of error have been reported to be the forest canopy cover and terrain which may obstruct GPS receivers from capturing satellite signals since GPS signal reception is dependent upon a line-of-sight between satellites and a receiver. The accuracy of data recorded using GPS under forest canopy has therefore been of interest to a number of researchers and practitioners. Most research reported in the literature, has concentrated on GPS accuracy based on stationary positions. Deckert and Bolstad (1996) conducted a study to determine the effect of forest canopy, terrain, and distance effects on GPS point accuracy. The study determined the effects of canopy type and terrain on horizontal positional accuracies through point location measurements over a range of canopy, terrain, and satellite geometry conditions. Karsky (2001) compared five GPS receivers under a forest canopy after Selective Availability (SA) was turned off at different stations established in the study. Yoshimura and Hasegawa 2003 carried out tests on horizontal and vertical positional errors of GPS positioning at different points to clarify the performance of the GPS in forested areas after selective availability (SA) was turned off. Wing et al. (2005) tested the accuracy and reliability of six consumer-grade GPS receivers on three sets of six measurement stations from three established measurement testing courses in open sky, young forest, and closed canopy setting.

The concentration of studies on GPS accuracy based on stationary positions has also been observed in recent studies. Rodríguez-Pérez et al. (2007) carried out 33 positional assessments on low-cost GPS receivers' accuracy and precision in forest environments in 18 forest locations. Wing (2009) examined the performance of consumer grade GPS receivers in an urban forest setting. The study used two distinct test courses, one located in an open field and the other in an urban forest landscape with partial tree canopy cover and several buildings blocking a view of the horizon to examine the receivers that collected data simultaneously. In all these studies, GPS accuracy has generally been reported to decrease as one moves from open to dense forest canopies.

Research on GPS accuracy under different forest conditions related to mobile machines has also been carried out on mobile harvesting equipment and forest vehicles. Spruce et al. (as cited in Devlin and McDonnell 2009) used a typical mapping-grade GPS receiver to track forest machines and reported degraded GPS accuracies under forest canopy as compared to open sky. Jalinier and Courteau (1993), examined the ability of a GPS receiver (SERCEL NR 101) that was attached to a vehicle traversing forest roads to develop a rapid, accurate and economical means of surveying forest roads and produce input data for a OTTO truck performance simulation program. The study indicated that under the right conditions, GPS in differential mode had full potential to survey roads in three dimensions with great accuracy. The accuracy was also not affected by vehicle speed and acceleration. However, the study also indicated that surveys in proximity to dense forest cover yielded questionable results. Veal et al. (2001) quantified errors in GPS positions recorded during operation of wheeled skidders in three different canopy conditions and at two different ground speeds using two different commercially available GPS receivers. The study reported significant differences in the accuracy of positions recorded by the two receivers with accuracy decreasing as canopy conditions changed from open to dense canopy. However, the machine speeds tested did not appear to affect accuracy of GPS positions. Recent research by Devlin et al. (2007) evaluated the positional accuracy of a dynamic non-differential global positioning system (non-DGPS) for tracking an articulated truck across the Irish road network. The study was carried out using a Trimble GeoXT handheld mapping-grade GPS receiver in non-differential mode. The GPS receiver was operated in conjunction with an external magnetic antenna that was fitted to the cab of the articulated truck. The level of positional accuracy (expressed as a horizontal root mean square (HRMS) error measured at 63% confidence level) observed in this study ranged from 6.9 m to 3.2 m. The results showed that dynamic non-differential GPS could be successfully implemented to track the position and movement of an articulated truck across the Irish public road network. Devlin et al. (2007) determined that the level of accuracy provided by the relatively low-cost, non-differential GPS was well suited to track positions and movement of timber trucks.

Devlin and McDonnell (2009) studied the GPS performance accuracy (at 63% HRMS confidence level) of real-time vehicle tracking systems for timber transport trucks travelling on both the internal forest road network and the public road network of Ireland. The objective of the study was to quantify GPS performance under varying forest environments. The study involved the installation of Bluetree GPS asset tracking systems onto two timber transport trucks. The HRMS accuracy values for this study ranged from 2.47 m to 2.55 m for public roads. The HRMS accuracy of the recorded values on the internal forest road network differed as much as 27 m in one of the two trucks and as much as 41 m in the other. These differences were attributed to forest canopy. Devlin and McDonnell (2009) believed that vehicle tracking systems worked well for monitoring purposes given that GPS positions could be recorded throughout forested areas.

Vehicle Performance Simulation Models

Over the past six decades a wide range of vehicle performance simulation programs have been developed. The first attempt to use scientific methods to understand commercial vehicle performance was presented by Saal (1948) at the Society of Automotive Engineers (SAE) Annual Meeting in Detroit on January 13, 1948 (Smith 1970). Taborek (1957) described the use of graphical integration to develop time speed and time distance curves for vehicles. There has since been an increase in the development of vehicle performance simulation models ranging from simple spreadsheet models to more sophisticated programs. Two distinct approaches have been taken: one is an averaging approach, which takes in a rough characterization of road conditions and provides an average cost of operating the vehicle; and the other is a deterministic view approach that takes specifics such as road surface type and the alignment along the complete haul as inputs and gives outputs such as road speed, engine speed (rpm), gear change requirement and fuel consumption as a function of position along the road (Douglas. 1999).

Watanatada et al. (1987) categorized vehicle operating cost models into two broad approaches: aggregate-correlative models and micro-mechanistic models, and proposed an aggregate-mechanistic approach that combines the advantages of the two approaches. Aggregate-correlative models and micro-mechanistic models are similar to the averaging and deterministic approaches described by Douglas (1999) respectively. Aggregate-correlative models generally involve large empirical data bases obtained from vehicle operator surveys as well as field experiments using specially-instrumented vehicles and tend to rely heavily on trends indicated by the data (Watanatada et al. 1987). These models present their results in tabular or graphic form or regressions formulas and are limited in their applications. They assume that trucks are operating under steady conditions; they are validated for the local and matching conditions the data are collected; they cannot account for the components of the system, such as driver and/or road alignment; and their road classifications are arbitrary (Shen 1993). Mechanistic models are developed through simulations that use road alignment parameters such as the gradient, radius of curvature and superelevation for short homogeneous road subsections, vehicle mechanics and assumptions related to driver behavior to give a speed profile of the vehicle as it traverses the road section (Watanatada et al. 1987). Mechanistic models have several advantages: they do not rely on large data bases from single studies. They give readily interpretable results such as desired speeds; acceleration/deceleration, engine performance (power used) and can thus draw upon previous work. Unknown parameters can be determined by relatively small experiments and results can be easily extrapolated (Watanatada et al. 1987). However, mechanistic models are less efficient in large or policy level decisions than aggregate-correlative models (Watanatada et al. 1987, Shen. 1993). Aggregate-mechanistic models are a hybrid of the two broad model approaches and combine the comparative advantages from each of the two models. Table 2.1 is a summary comparison of the aggregate-correlative, micro-mechanistic and aggregate-mechanistic approaches as presented by Watanatada (1987) showing the advantages of each approach and indicating the ultimate superiority of the aggregate-mechanistic over the other two approaches.

Table 2.1. Summary comparison of aggregate-correlative micro-mechanistic and aggregate-mechanistic approaches vis-a-vis research objectives and state of model quantification (Watanatada et al. 1987).

	Modeling approach		
Research Objective	**Aggregate-correlative**	**Micro- mechanistic**	**Aggregate-mechanistic**
Aggregate formulation	Yes	No	Yes
Policy sensitivity	Mostly medium[1]	Mostly high[1]	Mostly high[1]
Extrapolative ability	Mostly low	Mostly high	Mostly high
Local adaptability	Mostly low-medium	Mostly high	Mostly high
State of model quantification completion of this study	Mostly extensive	Lacking at validation and surface effect	Mostly extensive

[1] If relevant policy variables are incorporated.

Examples of Aggregate-Correlative Models

There are several models using the aggregate-correlative model approach that have been developed. One of the first models to use this approach was the travel time model presented by Bryne et al. (1960) in the USDA Forest Service Logging Road Handbook often referred to as BNG. The model was created to aid road designers and forest engineers in estimating the effects of road design on truck haul times and hauling costs. The collection of empirical data for this study was done over a 12-year period (1947-1959). To obtain travel time estimates observations were carried out to obtain data on the operation of conventional trucks and trailers weighing between 28,400 lbs and 207, 000 lbs over different road surface types (paved, gravel and dirt) , road widths and road designs. BNG is classified as semi-empirical because its travel time theoretical calculations are augmented by field test results Moll and Copstead (1996). Some of the results presented by BNG included graphs showing plots of travel time (in minutes per mile) against road grade, radius of curves, number of curves per mile, plots of speed (mph) against distances traveled during acceleration/deceleration and plots showing costs of operating time versus time per round trip mile (minutes). Tables included travel times per round trip for different road widths, design and surface types, road hauling costs for various truck and trailer combinations, and log hauling costs per round trip mile. BNG is probably still the most comprehensive and widely used model in the USDA forest Service for various applications by forest engineers and transportation managers. Moll (1996) conducted a verification study comparing BNG to two other travel time prediction models, OTTO and UWTRUCK, which are described later in the paper and found that the BNG predicts travel times more accurately than the other two models.

Lavoie (1979) in a study on transportation of tree lengths by truck trains used a multiple regression equation to determine the standard performance per round trip. Time and motion studies aided by stopwatches and tachographs were carried out. The regression equations developed expressed standard time in minutes as a function of distances traveled on four different road classes that were established in the study. Groves et al. (1987) (as cited in Shen 1993) carried out a study to predict logging truck travel times and estimating costs of log haulage using a regression model. The study related truck performance to roads that were classified based on different s attributes and/or characteristics. The classifications included. primary roads with good surfaces, few bends and very adverse grades; secondary roads with moderately good to rough surface, many curves and /or some adverse curves; and tertiary roads with rough surface, many tight corners and sharp curves and/or steep gradients. The regression model developed through this method was used to estimate travel times of both loaded and unloaded trucks on specified routes and their fixed, variable and total haulage costs per ton.

Jackson (1986) conducted a study on log truck performance on curves and favorable grades on single and double lane roads. The study compared observed speeds of log trucks on curves and favorable grades with speeds predicted by BNG and a Vehicle Operating Cost Model (VOCM) developed by Sullivan in 1977. The study developed regression equations for both loaded and unloaded trucks with speed as a function of various independent variables including grade, curve radius, width, ditch depth, super elevation, sight distance, time of day, and maximum engine braking horsepower. The results indicated that only grade and curve radius had an effect on speed. Speed comparison results were reported in a range of grade percentages. The results of the study indicated that speeds were independent of grade for favorable grades less than 11 percent but were strongly influenced by steeper grades. Comparison results on road sections that were not controlled by alignment suggested that both BNG and VOCM predicted downhill speeds reasonably well for favorable grades between approximately 11% and 16%. However, the two models over predicted speeds on grades steeper than 16%.

Others examples cited in the literature that have developed aggregate-correlative models include. Hide et al. (1975) who carried out a road transport cost study to research on vehicle operating costs in Kenya; Morosiuk and Abaynayaka (1982) developed a model for estimating vehicle operating costs in the Caribbean in an experimental study of vehicle performance; CRRI (1982) in a road user cost study in India; GEIPOT (1982) from research on the interrelationships between costs of highway construction maintenance and utilization; and Hide (1982) from results of a survey of vehicle operating costs in the Caribbean (Watanatada et al.1987).

Examples of Mechanistic Models

The most popular development has been mechanistic models. Access to computer power dramatically increased possibilities of simulation modeling (McCormack and Douglas 1992). Smith (1970) presented a hand calculation technique and a computer program for simulating truck acceleration, speed, distance and fuel economy. Levesque (1975) developed a deterministic simulation of logging truck performance. The model was programmed to represent movement of logging trucks for specified actual and/or proposed alignment and truck parameters and give information on the speed and time. Performance assessments of vehicle systems were also compared with observed data.

Truck simulations have been embedded in road investment models to identify opportunities to improve transportation efficiency. Petropoulos (1971) developed a vehicle simulation model as part of traffic model to simulate movement of trucks and cars on single lane forest roads. Botha et al. (1977) developed simulated truck performance as part of road investment analysis.

The development of heavy Vehicle Mission Simulators (VMS) such as the Cummins VMS model spurred the development of models specifically for the logging sector (McCormack and Douglas 1992). Smith (1981) using the Cummins VMS model tested 5-axle, 6-axle and 7-axle truck/trailer combinations against digitized road data of grade and alignment through a mathematical procedure (McCormack and Douglas 1992).

Other models using the mechanistic approach have attempted to model drivers' behavior. Truck simulations need detailed control logic to emulate the more important aspects of this highly discretionary driver behavior and the two most important functions are gearshifting and precautionary braking (McCormack 1990). McCormack, in a log truck performance simulator, TRUCKSIM, used gear shifting (upshift or downshift) during simulation that was initiated whenever engine RPM changed based on user-defined limits. Shen (1993) developed a vehicle performance simulation model UWTRUCK and modeled the driver's behavior through an inference mechanism and several sub-models that find the resistive forces (air, grade, rolling), normal force at the wheels and simulate the cruising up and down, gear shifting, braking, accelerating and has a function that updates the truck status parameters. The acceleration or deceleration rates are calculated based on the engine horsepower, traction of the distance interval, current speed and the engine RPM. Unlike TRUCKSIM and UWTRUCK, Jalinier et al. (1993) developed a truck performance simulation program OTTO and attempted to model the driver's behavior empirically. Jalinier et al. carried out tests on more than 60 drivers and used the empirical results to derive five driving techniques: fastest driver (A), slowest driver (B), highest consumption (C), lowest consumption (D), and reference driver (E). A driver technique is selected as one of the inputs to the model to incorporate driver behavior simulation in the model.

A big challenge in simulation models has been validation. Watanatada et al. (1987) used a modeling approach they referred to as an aggregate-mechanistic model approach. This modeling approach constructed mechanistic models for speed and fuel consumption and validated them with independent data and then transformed those using numerical techniques into aggregate form. This has also been seen in recent models that have been developed. Lucic (2001) proposed a simple constant power vehicle dynamics model for estimating maximum vehicle acceleration levels based on a vehicle’s tractive effort and aerodynamic, rolling, and grade resistance forces. A database of systematic field data that can be utilized for the validation of vehicle performance models was assembled and the model was tested and validated using this data. According to Watanatada et al. (1987) the main advantages of this approach are not only that deep insights could be gained into the physical-behavioral phenomena, but also that once validated to satisfaction, the models could be treated as a close approximation of the "truth" and consequently used as a benchmark for developing and testing aggregate-mechanistic.

Interaction with Other Vehicles

Many forest roads are low traffic volume, single lane roads. However vehicle interactions do occur which affect travel time. When vehicles meet, one must stop in a turnout to permit the other to pass. It is customary for the loaded truck to have the right-of-way. Few simulation models have considered the effect of traffic on trip time. BNG (1960) provides a travel time multiplier for the unloaded truck based on vehicles per hour. Petropolous (1971) simulated the deceleration, waiting time, and acceleration of empty trucks in turnouts.

Summary

The literature search clearly shows that several studies and models have been developed but there have been limited studies to predict travel time of chip vans. Conventional chip vans differ from log trucks in that they have greater off-tracking, lower clearance, higher center of gravity, are often heavier, and must return to the forest pulling the empty trailer which reduces gradeability for the empty vehicle (Sessions et al. 2010). Modeling driver’s behavior has also been one of the most difficult steps in vehicle simulation models. The varying operation patterns of drivers and their responses to changing road conditions make it difficult to develop a standard for simulating the drivers influence on the truck performance. This suggests that the development of new and easier ways for simulating drivers can lead to better simulation models. Most models also seem to lack empirical validation and adjustments. Empirical validation and adjustments through the combined advantages carried by aggregate- mechanistic models have a significant potential to increase the scope of application for the models. The interaction between vehicles on the forest road can affect unloaded vehicle travel time on single lane roads. An approach to modeling unloaded chip van travel time on single lane forest roads would be useful.

CHAPTER 3. MODELING BIOMASS TRANSPORT ON SINGLE LANE FOREST ROADS

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Introduction

The transportation of wood and biomass resources from landing and other collection locations to processing and distribution sites is a substantial cost within the wood supply chain. Several studies have found transportation of wood and biomass as a major contributing factor to the delivered costs. Angus-Hankin et al. (1995) reported that in spite of being the simplest of the handling phases in transporting fuel wood from its point-of-origin to the ultimate processing point, secondary transport is typically responsible for 20 to 40 percent of the delivered cost. Many have also cited McDonald et al. (2001) who reported that transportation of wood fiber accounts for about 25 to 50 percent of the total delivered costs and this is likely to increase as fuel prices increase.

Chip vans have been identified to be the most cost-efficient mode of transporting biomass chips provided the roads are suitable for the trucks carrying the vans which are generally built for high way use (Rawlings et al. 2004). The efficiency of chipped biomass transportation on forest roads depends upon the ability for trucks pulling chip vans to access forest supply points. Conventional chip vans differ from log trucks in that they have greater off-tracking, lower clearance, higher center of gravity, are often heavier, and must return to the forest pulling the unloaded trailer which reduces gradeability for the unloaded vehicle (Sessions et al. 2010). Several studies and models have been developed to predict log truck travel times (Byrne et al. 1960, Botha et al. 1977, Jackson 1986, Shiess and Shen 1990, McCormack and Douglas 1992, Jalinier and Nader 1993, Shen 1993, Moll and Copstead 1996) but there have been limited studies to predict travel time of chip vans over forest roads (Rawlings et al. 2004)

This study presents a Chip Van Travel Time Prediction Simulation Model (CHIP-VAN). CHIP-VAN was developed using data collected through Ground Positioning System (GPS) technology to track and monitor chip vans that were exclusively used for transporting chipped (ground) biomass from forest operation sites in western Oregon. Simulation models are classified as aggregate-correlative models and mechanistic models. Aggregate-correlative models are derived from empirical data and present their results in tabular or graphic form or regressions formulas (Shen 1993). These models are limited in their applications: they assume that trucks are operating under steady conditions; they are validated for the local and matching conditions the data are collected; they cannot account for the components of the system, such as driver and/or road alignment (Shen 1993). Aggregate-correlative models, however, are efficient for large-scale or policy level decisions (Watanatada et al. 1987, Shen 1993). Mechanistic models, on the other hand, are usually developed by simulation using a detailed description of the road alignment, truck parameters (engine, transmission, weight), physical principles of motion, and some aspects of driver behavior (reaction times, maximum deceleration rates).

An attempt to develop an aggregate-correlative model using regression was made, but this was not possible because the data collected could not meet the assumptions required for carrying out a regression. Regression requires four assumptions to be satisfied: Normality which requires that the variables follow a normal distribution; Homoscedasticity which requires constant variance of all the errors; Independence which requires that the errors are not correlated; and Linearity which requires a linear relationship between the dependent and independent variable. After attempting to estimate the travel time of chip vans on forest roads using regression to investigate the effect of variables such as speed, horizontal alignment and vertical alignment on travel time, it was observed that the assumptions of normality, homoscedasticity and linearity were not met. Nonlinear transformations were also attempted but these assumptions were still not satisfied. A simulation approach was therefore chosen. Unlike other mechanistic models such as UWTRUCK (Shen 1993) that lack empirical adjustments in their development, the development of CHIP-VAN tried to combine the benefits of both aggregate-correlative models and mechanistic models by using empirical data to determine the road geometry parameters and mechanically simulating the chip van travel time based on those road geometry parameters.

The performance of loaded and unloaded chip vans in this study is restricted to single lane forest roads. On these roads the loaded trucks have the right-of-way and unloaded trucks use the turnouts to permit the loaded trucks to pass. Detailed traffic flow interaction on single lane forest roads has been simulated by Petropoulos (1971).

Simulation models such as UWTRUCK (Shen 1993), OTTO (Jalinier and Nader 1993) and TRUCKSIM (McCormack 1990) ignore delay times created by turnouts. BNG provides a trip time multiplier for unloaded trucks based on traffic frequency. In this model we consider trip time delays in turnouts, but the number of stops is specified exogenously.

GPS receivers have been used for studies on various forest operations such as harvesting machines performance evaluations (Cordero et al. 2004, Veal et al. 2001) and forest vehicle tracking (Sikanen et al. 2005, Devlin et al. 2007, Devlin and McDonnell 2009). To our knowledge, no study has used data collected using GPS receivers to develop a travel time prediction model to predict travel time for forest vehicles on forest roads and hence chip vans. Moll and Copstead (1996) used GPS receivers to collect log truck travel time data to assess the accuracy of a log truck travel time prediction model developed by Byrne et al. (known as BNG) and two log truck performance simulation models. The GPS receivers used in this study collected location and speed information each second and provided a detailed assessment of chip van movement. Several recent studies (Wing and Eklund 2007, Wing et al. 2008, Devlin and McDonnell 2009, Wing 2009) have determined that GPS receivers are capable of collecting positions to within several meters of true location under dense forest canopy. However, since the reliability of GPS receiver measurements for moving vehicles under forest canopy and in mountainous terrain remained uncertain, a separate analysis (Simwanda et al. 2010) was carried out to validate and evaluate the accuracy of the data for the development of the model, by comparing measurements from three GPS receivers that were placed within each chip van. Therefore, the objectives of this study were to develop and validate a travel time prediction model for chip vans on single lane forest roads and to monitor conventional chip vans using GPS technology

Materials and Methods

Study Site

This study was conducted on chip vans that were exclusively transporting biomass from four biomass harvesting operations in Western Oregon, USA. Three of the operations were situated on stands owned by Roseburg Forest Products Company in Dillard, about 12 miles south of the Roseburg Forest Products Company. One operation was situated on lane forests south east of Eugene, in Oregon. The forest roads leading to all the operation sites included both paved and unpaved sections, and had a range of gradients from relatively level to 19%.

Data Collection

The GPS receiver that was used to record location and speed information on the chip trucks was a consumer-grade Visiontac VGPS-900 (Figure 3.1) which has a 51 channel MTK chipset with enhanced positioning system technology (up to 1.5 m accuracy with DGPS Support). The Visiontac VGPS-900 also comes with a MicroSD Slot with support for up to 2GB of storage capacity (about 25,000,000 locations, also referred to as waypoints). The measurement parameters recorded by this GPS receiver include date, time, latitude, longitude, altitude, speed, heading, fix mode, Percent Dilution of Position (PDOP), Horizontal Dilution of Precision (HDOP), and Vertical Dilution of Precision (VDOP) (www.visiontac.com/v900_feature.htm).

Figure 3.1. The Visiontac VGPS-900 GPS receiver.

At least four chip vans were used in each operation and a set of three GPS units was placed within each chip van. The operations were carried out on seven separate days and each chip van made an average of three trips on each day. Each GPS unit recorded an average of 60,000 points at one second intervals on each day which summed up to

5,040,000 points of chip van location and speed information available for developing and testing the model.

Data Preparation

The data collected was managed and analyzed using Windows Microsoft Excel and ESRI's ArcGIS desktop 9.3.1 software to prepare it for the development of the model. The data were downloaded from the GPS receivers and uploaded into ArcMap using the default World Geodetic System of 1984 (WGS 84) map projection. The data were then reprojected to the North American Datum of 1983 (NAD 83) Oregon Statewide Lambert (International foot) projection and Xtools Pro was used to add the x and y coordinates. The re-projection was necessary to get the default longitude and latitude coordinates into a projected coordinate system that could support horizontal distance calculations. The GPS measurements were than sieved so that all periods when the chip trucks were not in motion were removed from the databases. After sieving in ArcGIS, the data was exported to Microsoft Excel where the Model was developed using Visual Basic Programming.

Chip Truck Specifications

The tractors pulling the chip van trailers included: a 2007 Peterbilt (Model 378SB) with a 500 HP Cummins ISX engine, with an 18-speed transmission and a 3.90 rear end ratio; a 1999 Peterbilt (Model 379) with a 425HP Cummins N14E engine , with a 13 Speed transmission and a 3.70 rear end ratio; a 2009 Kenworth (Model T800) with a 525 HP Cummins ISX engine , with an 18-speed transmission and a 4.10 rear end ratio; and a 2001 Kenworth (Model T800) with a 550 HP Cat-C-15 , with an 18-speed transmission and a 3.70 rear end ratio. The tractor and trailer combinations included; tandem axle 45 feet long live floor chip van trailers with 18 to 22 feet tractors with 3 or 4 axles; and a tri-axle 48 feet chip trailer with a drop center combined with 18 to 22 feet tractors with 3 or 4 axles. One of the axles on the four axle tractors was a drop axle and was not utilized during the operations on forest roads. The gross vehicle weight (loaded weight) ranged from 65,000 pounds to 80,000 pounds. On average, the tare weight ranged from 30,000 pounds to 34,000 pounds.

Figure 3.2. Chip Trucks used in the study. A tandem driving axle 20-foot tractor, drop axle in raised position, with a tandem axle 45 feet live floor chip van trailer (Top); and a tandem 18-foot tractor with a tri- axle 48-foot chip van trailer with a drop center (bottom).

Processing GPS Data Points to Determine Road Geometry

To describe the road geometry of the roads traversed by the chip vans, the data points on the entire road section were processed in two separate steps. The first step was to process the data points into separate road curves, count and assign a number to each road curve, and indicate the turn direction for that road curve. Using visual inspection conducted in ArcGIS, a method to process the data points into separate road curves was designed based on the change in the heading of each point recorded by the GPS receiver. The change in heading was calculated as the difference in the heading values between one point and the immediate previous point. The turn direction and curve count was also determined using the change in heading at each point. This was all implemented using visual basic programming in Windows Microsoft Excel 2007 (Appendix H).

The second step was the computation of the road geometry parameters of curve radius, curve distance and road gradient using the GPS points on each separate road curve as determined in the first step. The computations carried out to determine these road geometry parameters are described below.

Curve Distance. The distance formula (Equation 1) was used to calculate the horizontal distance from one point to the next point. The total distance on each road curve was found by calculating the sum of the horizontal distances on that curve (Figure 1).

$$S = \sum \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \qquad (1)$$

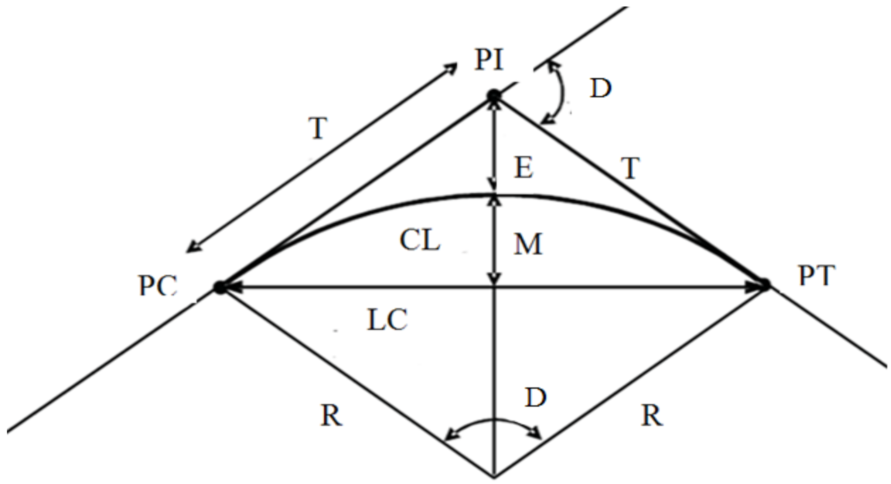
Where; *S* is the distance between the two points, x_2 and y_2 are the x, y coordinates for one point and, $x_1$and y_1 are the x, y coordinates for the next point.

Curve Radius. To calculate the curve radius, the central angle (degree of curve) was first calculated using the heading information recorded by the GPS units. The central angle was based on the deflection angle between the headings at the point of curvature (PC) and at the point of tangency (PT) (Figure.1). The curve radius was then calculated using Equation 2.

$$R = \frac{S}{(d)(0.0174533)} \qquad (2)$$

Where; *R* is the radius of the curve, ft, *S* is the curve distance, ft and *d* is the central angle, degrees.

Road Gradient. The elevation (z-axis) coordinates generated from GPS data have been known to lack precision and accuracy. Moll and Copstead (1996) conducted a verification study comparing travel time prediction models for haul vehicles on forest roads with GPS generated data. The study indicated that the elevation (z-axis) coordinates could not be used to determine road section alignment due to lack of precision which was caused by a jolting of truck and GPS antenna on rough roads. In this study, the GPS units with a built in antenna were firmly mounted on the truck's dashboards to avoid excessive movement and other disturbance. Road grade data was also collected manually using an Abney, a forest tool used for estimating grades on forest roads to obtain an estimate of grades to expect from the GPS units. Road gradient (in percent) is calculated in units of vertical rise divided by the horizontal distance (Sessions 2007). The vertical rise and horizontal distance in this study was calculated for every 5 second points to determine the road gradient using the *z-axis* coordinate and the *x and y –axis* coordinates respectively. These GPS generated road grades were compared with the road grades estimated by the Abney to validate the accuracy of the road grades generated from GPS data.



Definitions

P.I = Point of Intersection	R = Curve radius
P.C = Beginning point of the curve	M = Middle Ordinate
P.T = Ending point of the Curve	D = Central angle
C.L = Curve Length	T = Tangent Distance
L.C = Long Chord	E = External Distance

Figure 3.3. Road Curve Geometry

Building the Model and Assumptions

The formulation and structure for the model presented uses a somewhat similar approach taken by the vehicle performance simulation model UWTRUCK developed at the University of Washington, College of Forest Resources by Shen (1993). UWTRUCK requires xyz coordinates of road control points as input data and uses a curve fitting procedure and concepts of instantaneous radii of curvature and grade to determine the road alignment (Shen 1993). The xyz coordinates are provided by the user. UWTRUCK uses a two pass simulation procedure: a backward procedure that calculates the maximum allowable speeds of the truck from the end of the road to the beginning for each section of the road and a forward procedure that simulates the truck's performance by using the limit speeds from the first pass to simulate the driver's reaction to road conditions ahead. The maximum allowable speeds in the first pass are based on road conditions at each point on the road limited by the road curvature, lateral traction coefficient and factors related to user experience (road width, oncoming traffic, sight distance, road surface e.t.c) (Shen 1993). This pass calculates the potential performance of a vehicle based on the physical properties of the vehicle and of the road but ignores the effects of vertical alignment on truck speed to determine the road alignment that governs the truck performance (Shen 1993). The second pass calculates the truck speed based on the power train (engine rpm and torque) and the vertical alignment and road surface characteristics (grade, traction coefficient) (Shen 1993). The second pass also has a driver's "look ahead feature" during simulation that compares the current truck speed to the speeds ahead (calculated in the first pass) that indicates whether to accelerate, brake or cruise and the gears in use, engine speed, truck travel speed etc., are then recalculated for every short distance or time interval or the entire road section (Shen 1993).

To design a feasible horizontal curve, the designer considers the minimum curve radius, acceptable road grade on horizontal curve, and minimum safe stopping distance. The design speed for the truck is the minimum of the maximum speed limited by road grade, stopping sight distance (SSD), sliding, overturning, dust and road roughness (Sessions 2007). The model proposed is developed based on the maximum limiting speeds on each road segment as limited by road grade, stopping sight distance (SSD) and road alignment. The model is a simplified approach to simulating vehicle performance that uses equations from the literature for limiting speeds from road gradient, SSD and road alignment and does not simulate performances based power train properties such as engine rpm, torque, and transmission and rear end ratios. The input data for this model is, therefore, the length, gradient and radius of each road curve. The model assumes that all road characteristics are constant for each curve length of the road and also predicts the chip van travel time in two simulation passes. Like BNG, the chip van simulation model first calculates the maximum speeds limited by road grade, stopping sight distance (SSD), and road alignment (sliding or overturning) on each road segment based on the input data and takes the lowest limiting speed. Unlike the UWTRUCK backward procedure, the CHIP-VAN simulation considers the effect of vertical alignment on the truck's speed in the first pass. UWTRUCK also does not simulate sight distance quantitatively; this model does.

The second pass calculates the allowable speeds by looking at one or two curves ahead and accelerating and decelerating accordingly just as a driver would. The second pass is built with a "look ahead and behind feature" that simulates the driver's actions based on the limit speeds on previous curves and curves ahead. The model development has taken advantage of the available empirical data collected to find the acceleration and deceleration rates by minimizing the sum of deviations between the observed time taken and the predicted time to give the best fit to the data and give the best travel time prediction. The total travel time is calculated as the sum of time taken during acceleration and deceleration, and time taken while traveling at allowable speeds. The formulas and logic used by the model simulation to predict the travel time is described in the following sections

Maximum Speed Limited by Road Alignment (Sliding or Overturning)

The limiting speed of the vehicle around the horizontal curve, ft/sec, can be formulated by considering vehicle weight, side friction force, centrifugal force, curve radius, side friction coefficient, and superelevation (Sessions 2007). The model assumes zero super elevation and uses the rollover criterion that determines the maximum speed on a horizontal curve based on the maximum lateral acceleration to prevent rollover (overturning). Douglas (1999) recommends maximum lateral acceleration to prevent rollover to be limited to a design value of 0.15g based on roll over tests by El-Gindy and Woodrooffe (1990). The 0.15g rollover criterion provides almost identical results as the Byrne et al. (1960) recommendations to use a side skid factor of 0.16g (Sessions 2009).

$$F = ma = \frac{mV^2}{R},\ a = \frac{V^2}{R} = \ 0.15\text{g} \quad (3)$$

Where, F is the force, lbs, m is the mass, a is acceleration rate, ft/sec^2, V is the velocity, ft/sec, R is the curve radius, ft and g is the standard gravity, ft/sec^2. Therefore, these rollover criteria would limit maximum truck velocity for a loaded truck on a road with zero superelevation to

$$V = \sqrt{0.15\mathrm{Rg}}, \mathrm{ft/sec} \quad (4)$$

Where, R is the radius of the horizontal curve in feet and g is the standard gravity 32.174 ft/sec^2 (Sessions 2009).

Maximum Speed Limited by Road Gradient

The power required to move a vehicle along a road is the total power required to overcome grade resistance, rolling resistance and air resistance (Byrne et al. 1960). The model assumes that air resistance is negligible since the chip vans move at low speeds on forest roads at which air resistance is low. Therefore, to get the maximum speed limited by road gradient the model simulation first calculates the total force the chip van has to overcome due to rolling and grade resistance using Equations 5 and 6.

$$Grade\ Resistance = \mathrm{g}vw * \ Sin\ \theta \quad (5)$$

$$Rolling\ \ Resistance\ = k * \mathrm{g}vw * Cos\ \theta \quad (6)$$

Where, *gvw* is the gross vehicle weight, lbs, θ is the road gradient, degrees, and *k* is the coefficient of rolling resistance, lb/lb of normal force. Rolling resistance depends on road surface type, type and condition of tires, and friction of wheel bearings (Byrne et al. 1960). Byrne et al. determined the coefficients of rolling resistance for different adverse grades and recommended constant coefficients of rolling resistance of 0.020 lb/lb and 0.015 lb/lb for gravel and paved roads respectively. Douglas (1999) estimated typical unit rolling resistances as a function of the road structure type and surface conditions and found rolling resistances for crushed gravel, gravel and sandy clay to be between 0.015 lb/lb to 0.025 lb/lb of the gross vehicle weight. Although the coefficient of rolling resistance of radial truck tires has been shown to increase slightly with speed (Wong 2001) we have assumed it constant at speeds typical of forest roads. All forest roads that were traversed during data collection were gravel and this model assumes a constant coefficient rolling resistance of 0.02 lb/lb for the all the roads. The total force required by a vehicle to overcome resistive forces uphill is calculated by adding the grade resistance and the rolling resistance since both forces are opposing the moving direction of the vehicle. The total force required for a vehicle to overcome resistive forces downhill is calculated by subtracting the rolling resistance from the grade resistance because the grade resistance is supporting the vehicle's moving direction and the rolling resistance is opposing this movement.

Another component used to calculate the speed limited by grade is effective (wheel) horse power (EHP) which is calculated using efficiencies of the gear transmissions. Sessions (1991) gives the common values of manual gear transmissions efficiencies: 0.90 for direct gears, 0.80 for other gears and 0.75-0.85 for very high reduction gears. Douglas (1999) also gives a guide to drive train efficiencies based on the pulling vehicle configuration (number of wheels on pulling tractor by number of drive wheels) and gear type. For a 6 x 4 vehicle Douglas (1999) indicates an efficiency of 0.85 for direct drives and 0.80 for other gears. The maximum net horsepower at the wheels depends on the operating conditions. Uphill travel depends on engine power output to the drive train to overcome power train energy losses, grade, rolling and air resistances, safe downhill travel depends on the power dissipation ability of the engine brake and power train energy losses to maintain a constant speed by dissipating the difference between grade assistance and the sum of rolling resistance and air resistances. During downhill movement, the rolling resistance, air resistance, and internal efficiencies support engine braking therefore the needed energy (EHP) supplied by the engine to the wheels will generally be less than that delivered during uphill movement, all other things equal. To determine the EHP for uphill and downhill movement in the model, Equation 8 was solved for EHP using the average fastest speed at the steepest grade and the vehicle weight from the data collected during the study. Based on the findings, the model assumes that the effective horse power (EHP) to be 400 HP and 300 HP for uphill and downhill chip van movement respectively (Appendix G). These EHPs also represent 80% and 60% of the gross horse power of the chip vans used in the study respectively, which was generally 500 HP. These percentages compare well with gear transmission efficiencies given by Sessions (1991) and Douglas (1999). Since we have the EHP and the force, the grade limited speed on the curve is calculated using Equation 8.

$$Velocity = \frac{EHP}{Force} \tag{8}$$

Maximum Speed Limited by Stopping Sight Distance (SSD)

AASHTO (1984) defines sight distance as the length of the roadway ahead that is visible to the driver. The objective is to provide a sufficient sight distance for the drivers to safely stop their vehicles before reaching objects obstructing their forward motion (Sessions 2007). The safe speed on single lane roads, for which this model is developed, is limited by the sight distance that permits two trucks approaching each other to stop without colliding or one truck to stop without hitting an obstruction in the road (Byrne et al. 1960). The model simulation calculates SSD as a function of the curve radius (R) and the middle ordinate (M) as developed by Byrne et al (Figure 4, Appendix A).

$$SSD = \sqrt{(8MR - 4M^2)} \quad (9)$$

The curve radius is used in the equation based on the assumption that the vehicle speeds depend on the radius of the curve (Byrne et al. 1960, Jackson 1986). The middle ordinate is calculated using the height above the road at which the line of sight is tangent to the back slope. It is assumed that sight distance is limited by back slope (Byrne et al. 1960) and the sight distance is the distance from the driver's eye to another vehicle or an obstacle in front. Byrne et al. (as cited in Jackson 1986) used a drivers eye height of approximately 7.5 feet and a sighting point at which all braking reactions from the driver are triggered of 4.5 feet with a back slope ratio of 1 to 1. It is also assumed that the point of tangency between the back slope and the line of sight is also the intersection point between the eye height and the sighting point. The driver's eye height used by Byrne et al. (1960) is similar to the truck driver's eye heights found by a study done by the Oregon State University Transportation Research Institute (1997) that found truck eye heights ranging from 6 feet to 9.4 feet with an average height of 7.7 feet. This model uses the same eye height, the sighting point and back slope ratio as in Byrne et al to calculate the middle ordinate. A ditch of 2 feet and road width of 12 ft is used as determined from the field (Figure 3.4b). After the SSD is determined, the Velocity for two vehicles approaching each other is derived from Equation 10.

$$SSD = 2V_0T + \frac{{V_0}^2}{(\mu + f)} \quad (10)$$

Where,

V_0 = Vehicle speed, ft/sec

f = coefficient of friction

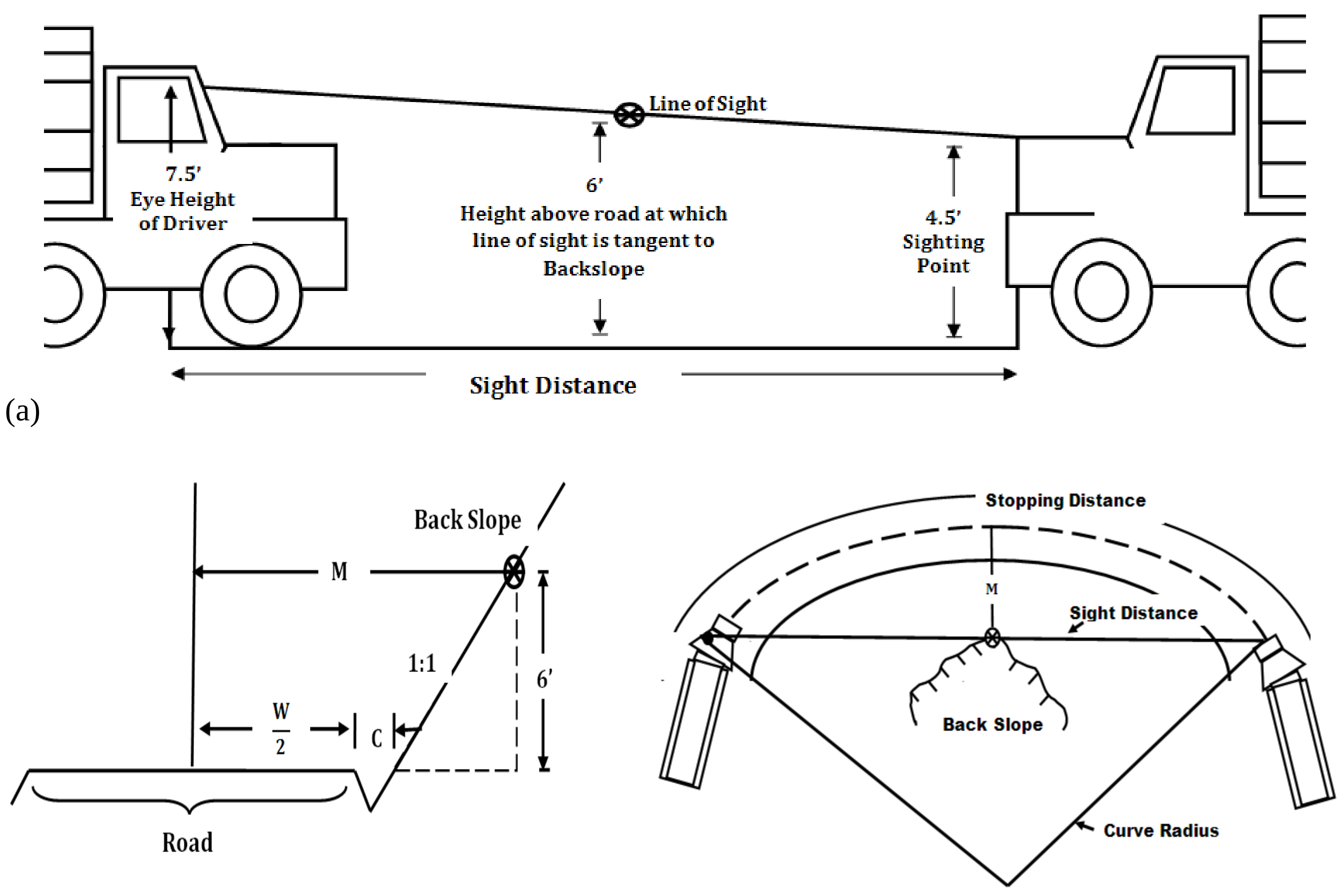
μ = coefficient of rolling resistance lb/lb

T = Reaction time

Solving for V (in miles per hour) gives quadratic Equation 11 (Appendix B)

$$V = -26.4 + \sqrt{77.44 + 0.67SSD}, \text{ miles/hour} \quad (11)$$

The derivation of Equation 12 assumes 3 seconds as the driver's reaction time and a combined coefficient of traction and friction of 0.4.



(b) Side view of road (c) Overhead view of road

Figure 3.4. Stopping Sight Distance Geometry (Byrne et al. 1960, Jackson 1986)

Modeling driver's behavior and travel time

Modeling driver's behavior is one of the most difficult steps in vehicle simulation models. Drivers have considerably varying operation patterns and their responses to changing road conditions are dependent on the driver's experience and other factors. In a truck performance simulation program OTTO, Jalinier et al. (1993) carried out tests on more than 60 drivers and used the empirical results to derive five driving techniques: fastest driver (A), slowest driver (B), highest consumption (C), lowest consumption (D), and reference driver (E). A driver technique is selected as one of the inputs to the model to incorporate driver behavior simulation in the model. Other models have emulated driver's behaviors through simulating gear shifting in relation to engine RPMs, engine torque, engine horsepower and road conditions. Truck simulations need detailed control logic to emulate the more important aspects of this highly discretionary driver behavior and the two most important functions are gear shifting and precautionary braking (McCormack and Canberra 1990). In a log truck performance simulator TRUCKSIM, McCormack and Canberra (1990) modeled the driver's behavior using gear shifting (upshift or downshift) during simulation that was initiated whenever engine RPM changed based on user-defined limits. UWTRUCK models the driver's behavior through an inference mechanism and several sub-models that find the resistive forces (air, grade, rolling), normal force at the wheels and simulate the cruising up and down, gear shifting, braking, and accelerating. The acceleration or deceleration rates are calculated based on the engine horsepower, traction of the distance interval, current speed and the engine RPM (Shen 1993).

This model uses a conceptually similar method in emulating the driver's behavior but does not use the engine properties (horsepower and rpm) and gear shifting approach. It is considered in this model that the driver of the chip van will not reach maximum speed on all curves based on the limiting speeds on the road curves before and ahead. The driver will either accelerate or decelerate to ensure that he reaches the next curve at a slower or maximum limiting speed. To determine whether a driver will reach the maximum speed or not, four cases are assumed and checked (Figure 5). Table 1 contains the nomenclature for the chip van speeds and curve distances covered as used in the Figure 5 and equations for all the cases. All Equations used to calculate the velocities, time taken, acceleration (or deceleration) and distances are derived from Equations 12 and 13. Before any case is applied, a 'look ahead feature' is also added in the model simulation. This feature looks at the cases that apply on one or two curves ahead to ensure that there is a correct transition from V_{fn} to V_{in} from one curve to the next. The acceleration and deceleration rates used in the model were determined through a least squares method that searched for the combination of a_1 and a_2 that gave the best fit to the GPS data collected and gave the model the best travel time prediction

$$V_{fn}^2 = V_{in}^2 + 2aS \tag{12}$$

$$V_{max} = V_{in} + aT \tag{13}$$

Table 3.1. Nomenclature for the chip van speeds, time and curve distances covered as used in Figure 4.5 and equations for all the four cases. The four cases determine whether the driver will accelerate, decelerate or continue at the current speeds.

Symbol	Description
V_{max}	Maximum limiting speed on curve, ft/sec
V_{min}	Highest non-limiting speed a vehicle can accelerate to or highest non-limiting speed allowing enough distance to decelerate to limit speed on next curve, ft/sec
V_{in}	Initial velocity or final velocity on previous curve, ft/sec
V_{fn}	Final velocity or maximum limiting speed(V_{max}) on next curve, ft/sec
V_{back}	Velocity calculated backwards from V_{fn}, ft/sec
S_1	Acceleration distance, ft
S_2	Deceleration distance, ft
S	Total curve distance, ft
T_1	Acceleration time, minutes
T_2	Deceleration time, minutes
T_{Vmax}	Time taken while moving at V_{max}, minutes
a_1	Acceleration rate with a positive value, ft/sec^2
a_2	Deceleration rate with a negative value, ft/sec^2

Case I.

Case I applies when V_{max} is greater than V_{in} and V_{fn}. In this case, it is assumed that the chip van will either accelerate for a distance S_1 to V_{max} and move at the same limiting speed for some time before it decelerates for a distance S_2 to V_{fn} (Case I(a)) or it will accelerate for a distance S_1 to V_{min} and immediately decelerate for a distance S_2 to V_{fn} (Case I (b)). The curve distance determines whether the chip van will accelerate to V_{max} or V_{min}. To check which situation applies S_1 and S_2 for Case I (a) are calculated using Equations 14 and 15.

$$S_1 = \frac{V_{max}^2 - V_{in}^2}{2a_1} \tag{14}$$

$$S_2 = \frac{V_{fn}^2 - V_{max}^2}{2a_1} \tag{15}$$

Since $S_1 + S_2$ in Case I (a) are less than S, it assumed that if the sum of S_1 and S_2 is greater than S then Case I(b) applies otherwise Case I(a) applies. If the Case I(a) applies travel time on the curve is calculated as the sum of T_1, T_2 and T_{Vmax}. T_1, T_2 and T_{Vmax} for case I(a) are calculated through Equations 16, 17 and 18.

$$T_1 = \frac{V_{max} - V_{in}}{a_1} \tag{16}$$

$$T_2 = \frac{V_{fn} - V_{max}}{a_2} \tag{17}$$

$$T_{Vmax} = \frac{S - (S_1 + S_2)}{V_{max}} \tag{18}$$

If Case I(b) applies then V_{min} is calculated through Equation 20 and the total time on the curve is calculated as the sum of T_1 and T_2. For Case I(b), S_1, S_2, T_1 and T_2, are calculated by replacing V_{max} with V_{min} in Equations 14, 15, 16 and 17 respectively. Equation 19 is derived from sum of S_1 and S_2. Since, $S = S1 + S2$, therefore;

$$S = \frac{V_{min}^2 - V_{in}^2}{2a_1} + \frac{V_{fn}^2 - V_{min}^2}{2a_2} \tag{19}$$

Solving for V_{min} gives Equation 20 (Appendix C.)

$$V_{min} = \sqrt{\frac{(2Sa_1a_2) + (a_2\ V_{in}^2) - (a_1V_{fn}^2)}{(a_1 - a_2)}} \tag{20}$$

Case II.

Case II is a case where the chip van reaches a curve at V_{max} but has to decelerate at some point because V_{fn} is less than V_{max}. In this case, it is assumed that in Case II (a) the chip van will move at Vmax for the distance S_1 and then decelerate for a distance S_2 or as in Case II (b), it will immediately start decelerating as soon as it reaches the curve for the entire distance *S*. To check which situation applies, S_2 is calculated through Equation 15 and if it is greater than S then Case II (b) applies otherwise Case II (a) applies. If Case II (a) applies the total time taken on the curve is calculated as the sum of T_2 (Equation 17) and T_{Vmax} calculated using Equation 18 without S_2. If Case II (b) applies, it means the Chip van should have entered the curve with a slower speed than $V_{max.}$ Thus in the model simulation, V_{in} is recalculated backwards (Equation 21) using V_{fn} to determine the speed the chip van should have started with given the available *S* for deceleration. The total time taken on the curve is calculated using Equation 16 by replacing $V_{max.}$ with V_{back}.

$$V_{back} = \sqrt{V_{fn}^2 - (2a_2S)} \tag{21}$$

Case III

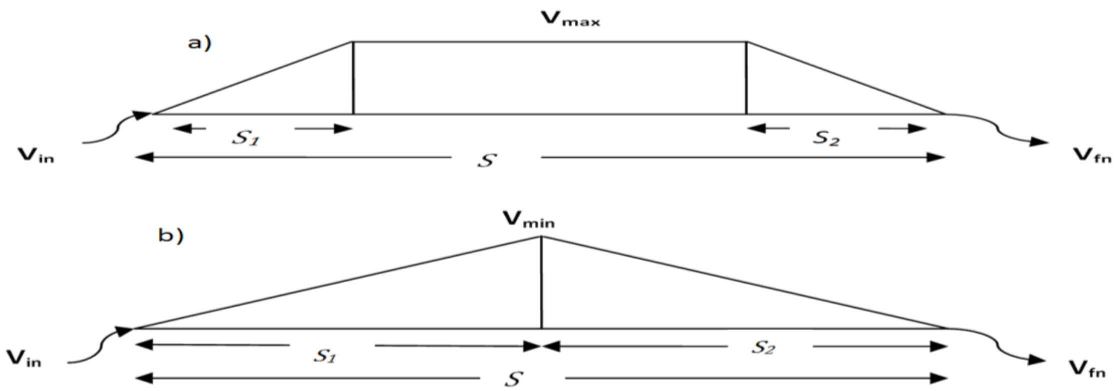
Case III applies when the chip van enters a curve with Vin less than V_{max} and V_{fn} equal or greater than V_{max} . The assumption in this case is that, the chip van will both accelerate to V_{max} for a distance S_1 and move at V_{max} for a distance S_2 Case III(a) before the next curve or it will accelerate for the entire distance *S* until it enters the next curve Case III(b). To check which case applies, S_1 is calculated through Equation 13 and if it is greater than S then Case II (b) applies otherwise Case II(a) applies. If Case II(a) applies the total time taken on the curve is calculated as the sum of T_1(Equation 16) and T_{Vmax} calculated using Equation 18 without S_1. If Case II(b) applies, it means the chip van cannot accelerate to V_{max} given the available distance *S* and therefore, the model simulation, calculates the speed (V_{front}) that the chip van will be able to accelerate to through the distance S using V_{in}(Equation 22). The total time taken on the curve is calculated using Equation 17 by replacing $V_{max.}$ with V_{front}.

$$V_{front} = \sqrt{V_{in}^2 - (2a_1 S)} \quad (22)$$

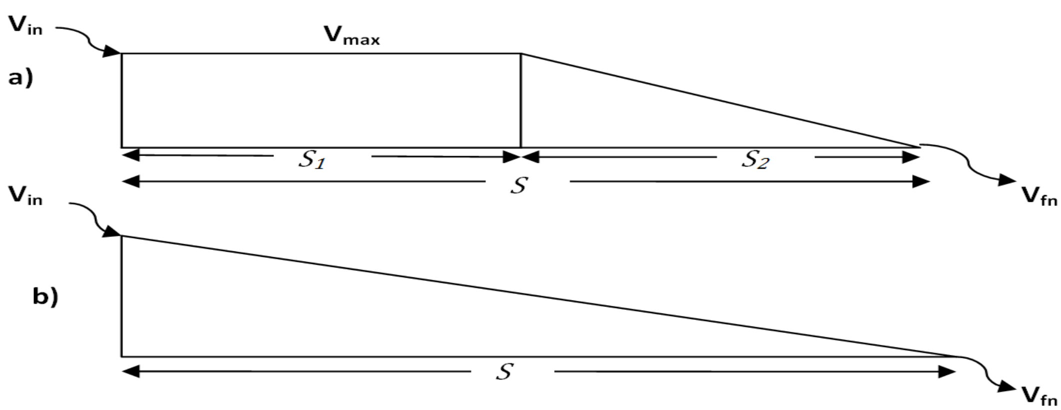
Case IV.

Case IV applies assumes the Chip van enters a curve with V_{in} equal to V_{max} and V_{fn} Equal or greater than V_{max}. The assumption under this case is that the chip van driver can maintain the speed at V_{max} but cannot accelerate until he enters the next curve. Therefore, the model simulation assumes the chip van driver maintains the speed at V_{max}. The total time taken on the curve is calculated by dividing S by V_{max}.

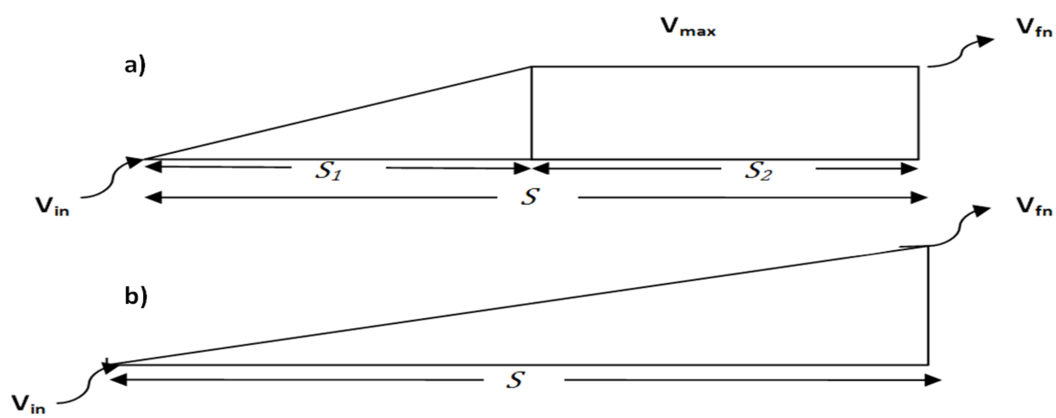
Case I



Case II



Case III.



Case IV.

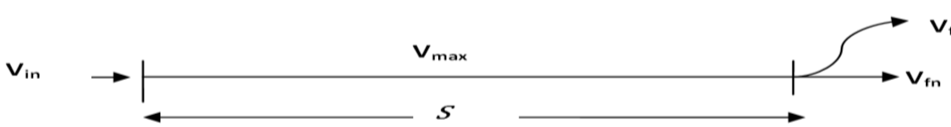


Figure 3.5. Cases determining the conditions for accelerating and decelerating of a chip vans on a road curve. The four cases are applied in the model to determine whether the driver will accelerate, decelerate or continue at the current speeds.

Implementation and Testing of the Model

The model (CHIP-VAN) was implemented in the Visual Basic programming language in Windows Microsoft Excel 2007. The data collected for this study was separated into two parts for development and, testing and validation purposes. One part of the data was used to develop and implement the model and the other was used for testing and validation. The data was also separated into the respective roads trips made by the chip vans; loaded travel and unloaded travel. This was done to take into account differences in loaded and unloaded truck properties that the model considers during simulation. A total of 88 road trips were available from the data collected which included 44 loaded travel road trips and 44 unloaded travel road trips. From both, unloaded and loaded travel trip data, 27% (12 road trips) of the data was used to implement and test the model and 73% (32 road trips) was used for validation. The division of road trip data (27% for testing and 73% for validation) was chosen based on the principles of statistical data mining. Statistical data mining uses small sample data sets to find patterns in large data sets but requires that validation be carried out on other data sets to check if the patterns found are generally representative of the entire data set (Fayyad et al. 1996). The total length of forest roads on which the model tests and validations were carried on summed up to a total of 190 miles of road that ranged from 1.3 miles to 6.5 miles. The model was also compared to BNG by applying the BNG method on the 88 road trips data and comparing the BNG predicted times to the travel times predicted by the model. The BNG predicted travel times were also compared to the observed travel times. The features, testing and validation, and BNG comparison results of CHIP-VAN are described in the sections below. A flowchart showing the CHIP-VAN simulation is also given in Figure 6.

Data Input Requirements

The input data required include both road conditions and truck specifications. An effort was made in this model to reduce the amount of input data required from the user. The road condition parameters required are: total number of curves, length of each curve, curve radius, road gradient on each road curve, road surface type, road width and the ditch size on the road. The input data is the same for both loaded trucks and unloaded truck except that for unloaded trucks the user is required to input the probable number of stops that the truck will make before reaching the loading point. This is because in forest operations, the loaded truck is given the right of way on a single lane road. The unloaded trucks stop in a turnout. This feature is added to take into account the delay time taken from stoppages. This is discussed in detail later in the paper. The truck specifications include; the engine horsepower, gross vehicle weight and tare vehicle weight.

CHIP-VAN Simulation Features

As indicated in the previous sections, CHIP-VAN follows a two simulation pass procedure (Figure 5). The CHIP-VAN First Pass Simulation calculates the maximum limit speeds on each road segment based on the input data (grade, curve radius, and curve length). The simulation also has a 25 mph maximum speed limit set for all forest roads as established from the GPS data collected for this study. The simulation looks at the three possible limit speed values and takes the lowest as the maximum limiting speed (in Mph) on each road curve. In cases were, all the three possible maximum speed values are greater than set limit, the simulation takes the set limit (25 mph) as the maximum limit speed on that curve. The second pass models the driver's behavior and tries to mimic that behavior through the four cases described earlier and decides to accelerate and decelerate accordingly just as an observed driver would. The second pass also calculates the time taken on each road curve and gives the total predicted time as output. After the data is fed to the model, the user is provided with two run options for each pass simulation. The first option runs the CHIP-VAN First Pass Simulation and gives the total time taken at maximum limit speeds. The second option runs the CHIP-VAN Second Pass Simulation and gives the allowable speeds and time taken on each curve or road section and the total predicted travel time on the entire forest road traversed.

Acceleration and Deceleration rates

An important step in the development of this model was to determine the acceleration and deceleration rates. The accuracy, with which the model would predict travel time through the four different applicable cases, was highly dependent on these rates. A least squares method was used to find the minimum sum of squared deviations between the observed time taken and the predicted travel time for different combinations of acceleration and deceleration rates. The least squares method is a common statistical method used for finding the best fit between observed and expected sets of data. A range of acceleration rates from 1 ft/sec^2 to 5 ft/sec^2 and deceleration rates from 1ft/sec^2 to 10ft/sec^2 were evaluated. Maximum suggested comfortable deceleration rates for logging trucks based on travel speed ranged from 12 ft/sec^2 at 10 mph to 9 ft/sec^2 at 30 mph (Botha et al. 1977).

A check to determine whether the acceleration rates were possible was also performed using an example of a truck moving on level ground. If

F = Force required for truck to move, lb
m = Mass of the vehicle, lb/ft/sec^2
a = Acceleration or deceleration rate, ft/sec^2
W = weight of the truck, lb
γ = Equivalent mass factor for energy in rotating parts
g = Standard gravity (nominal acceleration due to gravity, 32.174 ft/s^2).
N = Normal force at the drivers, lb
μ = Coefficient of traction, lb/lb of normal force
f = Coefficient of rolling resistance, lb/lb of normal force

and, $F = \gamma m a \quad and \quad a = \frac{\mu N + f N}{\gamma m} \quad and \quad m = \frac{W}{g} \quad and\ N = W$ on level ground. Solving for a gives Equation 23 (Appendix B).

$$a = \frac{(\mu + f)g}{\gamma} \tag{23}$$

Equivalent mass factors (γ) for trucks in lower gears can be 2.0 or greater (Taborek 1957). Assuming $\gamma = 2.0$, μ = 0.4 and f = 0.02 as in the model and solving for the acceleration (a) gives 6.8 ft/sec^2. It was therefore, assumed that conservative rates of acceleration n(up to 5 ft/sec$^{2)}$ and deceleration (up to 10 ft/sec^2) would be possible on the forest roads with varying vertical alignment.

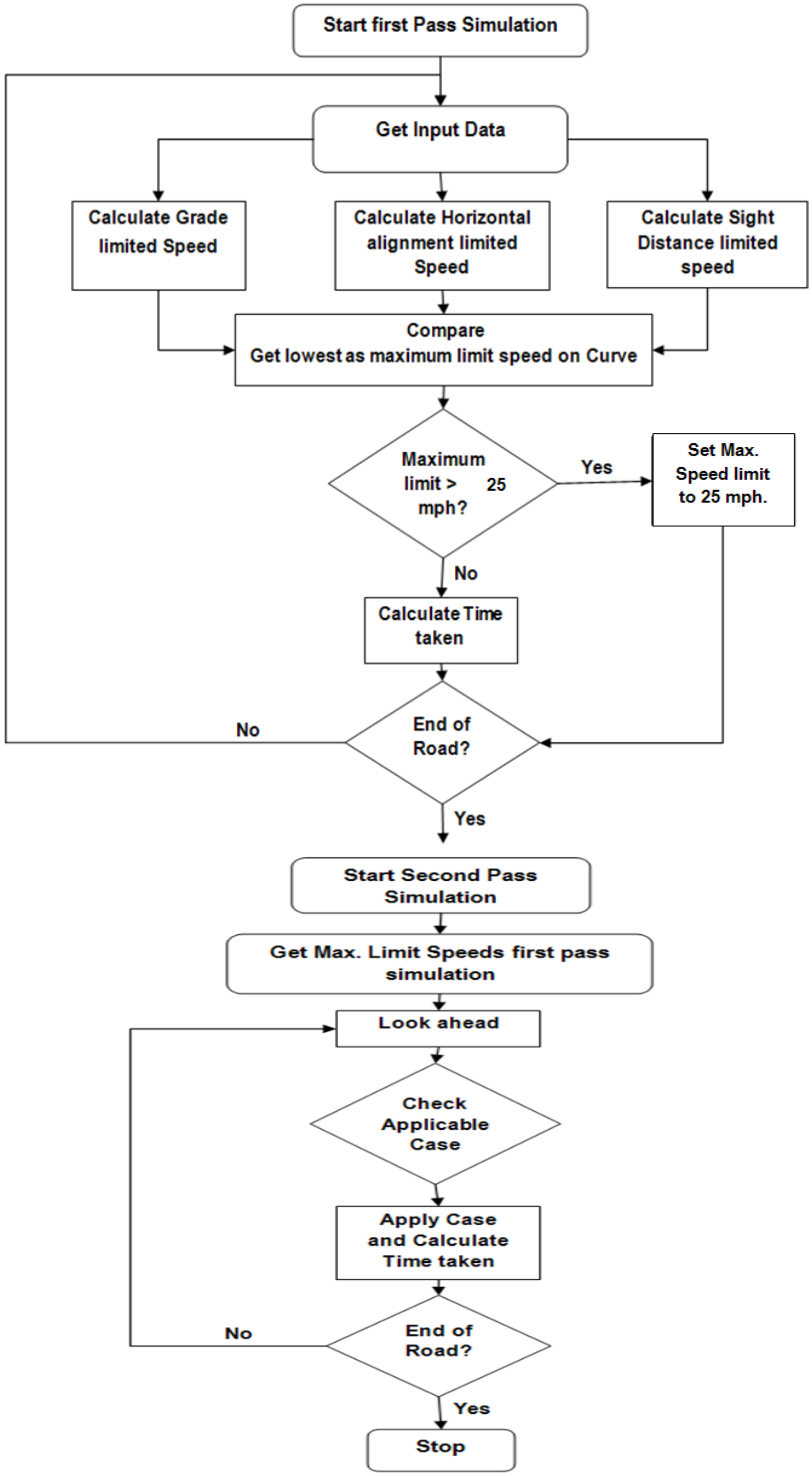


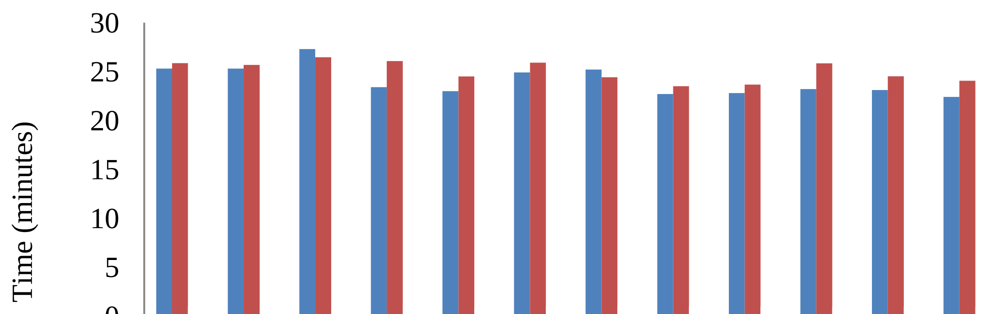
Figure 3.6. Flowcharts showing the CHIP-VAN first and second pass simulations.

Model Tests and Validation Results

The model testing and validation results for the predicted loaded and unloaded chip vans travel time (in minutes) are presented. In the presentation of the results, the roads leading to the four operations are referred to as road 1 to 4 respectively.

Loaded Chip Vans

The model was first implemented and tested on data from loaded chip van trips taken on Road 1, which was approximately 6.5 miles of forest road. The least squares algorithm that was developed to find the minimum sum of squared deviations that gave the best fit of the predicted times to the observed times taken by the chip vans was run on 12 loaded road trips on Road 1 using random combinations of acceleration and deceleration rates. The minimum sum of deviations indicated that the chip vans decelerated at a high rate but did not accelerate as fast. A loaded chip van acceleration rate of 1.5 ft/sec^2 and deceleration rate 9.5 ft/sec^2 gave the best fit. The minimum sum of deviations was 25.3 and the differences between the predicted times and the observed times ranged from 0.4 to 1.7 minutes. The percentages of the predicted time from the observed time that the chip vans took on the 12 road trips ranged from 90% to 99% indicating a significant time prediction (Figure 3.7). As the loaded trucks had the right-of-way, there was no observed delay time in turnouts.

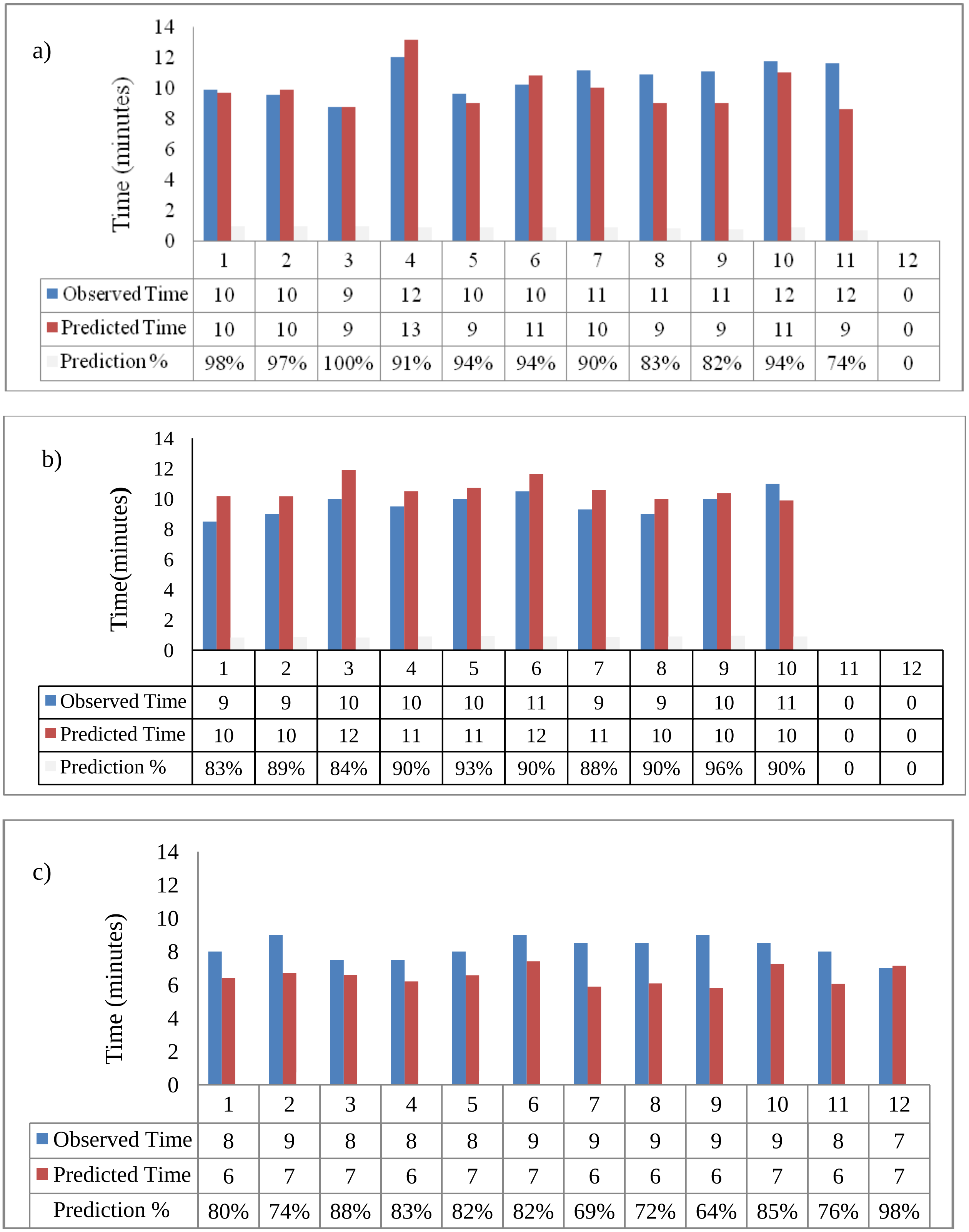


	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	25	25	27	23	23	25	25	23	23	23	23	22
Predicted Time	26	26	26	26	25	26	24	23	24	26	25	24
prediction %	98%	99%	97%	90%	94%	96%	97%	97%	96%	90%	94%	93%

Figure 3.7. Results from the Least Squares Algorithm program showing the best fit of CHIP-VAN predicted travel times and the observed time taken by the loaded chip vans.

After determining acceleration and deceleration rates, the model was then tested on the remaing 28 loaded trips made by the chip vans on three other roads for validation (Figure 3.8). The model tests on Road 2 which was approximately 2.5 miles gave significantly accurate prediction of the observed travel time taken by the chip vans on this road. The differences between the predicted times and the observed times generally ranged from 0 to 1.2 minutes representing a range of percentages of the predicted time from the observed time from 90% to 100% indicating a significantly accurate prediction in time. However, on three of the trips tested, less accurate travel time predictions were observed. The differences in the predicted time in relation to the observed time were 1.8 minutes, 2.1 minutes and 3 minutes representing percentage of prediction, 83%, 82% and 74% respectively. These could probably be caused by changes in the drivers' general operation behavior in these trips.

The model tests carried out on Road 3, which was approximately 3.5 miles, also gave significantly accurate prediction of the observed travel time taken by the chip vans on this road. The differences between the predicted times and the observed times generally ranged from 0.4 to 1.9 minutes representing a range of percentages of the predicted time from the observed time from 83% to 96%. This was also significantly accurate prediction of the travel time. The tests results were generally from 89% to 90% except for two road trips in which the least predictions were observed. The two trips had differences between the times predicted and observed time of 1.7 minutes (84% prediction) and 1.9 minutes (83% prediction). Model tests were also carried out on 12 loaded travel trips on Road 4 that had the least mileage (1.4 miles) as compared to the other roads. The observed predicted times versus the observed time taken by the chip vans on all trips on this road were not as accurate as in the tests carried out on the other two roads (Road 2 and 3). The percentage predictions of the observed time were generally between 80% to 88% for six trips, 64% to 76% for five trips and only one trip had a 98% prediction of the observed time. The differences between the predicted times and the observed times generally ranged from 1 minute to 3.2 minutes.



a)

	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	10	10	9	12	10	10	11	11	11	12	12	0
Predicted Time	10	10	9	13	9	11	10	9	9	11	9	0
Prediction %	98%	97%	100%	91%	94%	94%	90%	83%	82%	94%	74%	0

b)

	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	9	9	10	10	10	11	9	9	10	11	0	0
Predicted Time	10	10	12	11	11	12	11	10	10	10	0	0
Prediction %	83%	89%	84%	90%	93%	90%	88%	90%	96%	90%	0	0

c)

	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	8	9	8	8	8	9	9	9	9	9	8	7
Predicted Time	6	7	7	6	7	7	6	6	6	7	6	7
Prediction %	80%	74%	88%	83%	82%	82%	69%	72%	64%	85%	76%	98%

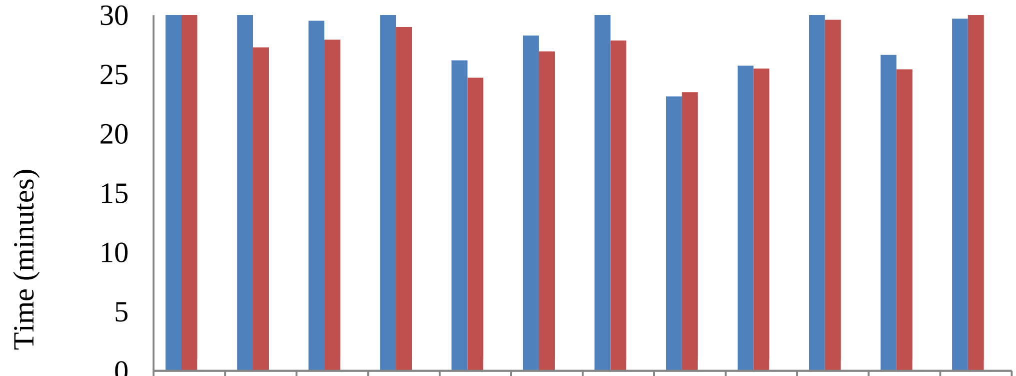
Figure 3.8. Model (CHIP-VAN) validation test results showing the predicted travel times compared to observed travel time for each loaded chip van road trip. Charts a, b and c represent results from tests on roads 2, 3 and 4 respectively.

Unloaded Chip Vans

To predict the travel times for unloaded chip vans, the model was also first implemented and tested on Road 1. Twelve unloaded chip van trips were used to run the least squares algorithm to find the minimum sum of squared deviations between the predicted and the observed travel time taken by the chip vans using random combinations of acceleration and deceleration rates. The minimum sum of deviations indicated that the unloaded chip vans did not decelerate as quickly as the loaded chip vans but accelerated at the same rate. The unloaded chip van acceleration rate of 1.5 ft/sec^2 and deceleration rate of 6.5 ft/sec^2 gave the best fit. Unlike the loaded trucks, the unloaded trucks used the turnouts. The number of stops the unloaded chips vans made on each trip to give way to the loaded chip vans was also incorporated in the algorithm to take into account the delay in the travel time caused by these stoppages.

The data analysis carried out throughout the entire unloaded trips database for all the roads indicated that the chip van delay time when decelerating to stop and when beginning to accelerate from a stop to normal speed ranged from 5 to 30 seconds. The observed delay time was verified using the fastest speed observed (25 mph) and the acceleration and deceleration rates determined by the least squares algorithm. It was found that at an acceleration rate of 1.5 ft/sec^2 and a deceleration rate of 6.5 ft/sec^2 it would take 25 seconds to accelerate from a stop to the fastest speed and 6 seconds to decelerate to a stop respectively. The verification indicated that the delay times found using the observed fastest speed and the rates of acceleration and deceleration were within the observed 5 to 30 seconds. It was therefore assumed that the longest delay time for each stoppage is 1 minute comprised of 30 seconds delay when decelerating to stop and 30 seconds delay when starting to accelerate from a stoppage to normal speed.

The minimum sum of squared deviations was 38.0 and the differences between the predicted times and the observed times generally ranged from 0.2 to 2.2 minutes. The percentages of the predicted time from the observed travel times on the 12 road trips ranged from 90% to 99% indicating a significant prediction in time (Figure 3.9). However, two road trips were observed to give 3.1 minutes and 2.8 differences between the predicted time and the observed time although they were in the same percentage prediction range as all the other trips.



	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	32	30	30	30	26	28	30	23	26	32	27	30
Predicted Time	32	27	28	29	25	27	28	24	26	30	25	32
Prediction %	99%	90%	95%	97%	94%	95%	93%	98%	99%	91%	95%	92%

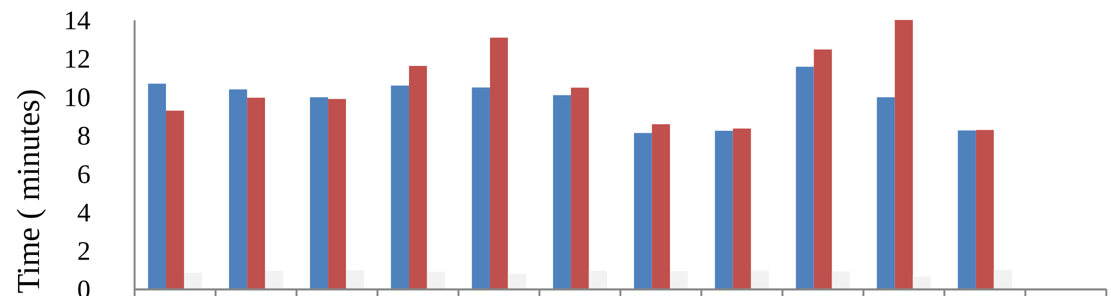
Figure 3.9. Results from the Least Squares Algorithm program showing the best fit of CHIP-VAN predicted travel times and the observed time taken by unloaded chip vans.

The remaining 28 trips taken by the unloaded chipvans were also used to test the model on the other three roads for validation (Figure 10). Just as in the loaded chips van trips, the model tests on Road 2 also gave significantly close prediction of the observed travel time taken by the chip vans on this road. The differences between the predicted times and the observed times generally ranged from 0 to 1.4 minutes representing a range of percentages of the predicted time from the observed time from 87% to 100%. This also was an indication of a significant accurate prediction of travel time. Two of the road trips tested, however, gave lesser accurate travel time predictions with differences between the predicted time and the observed time of 2.6 minutes (80% prediction) in one of the trips and 5 minutes (67% prediction) in the other. The model tests carried out on Road 3 from the 10 unloaded trips gave differences between the predicted times and the observed times that generally ranged from 0.1 to 2.5 minutes. Generally, the time difference ranged from 0.1 to 0.8 minutes representing prediction percentages ranging from 92% to 99%. Three trips, however, had differences between the times predicted and observed time of 2.2 minutes (81% prediction), 2.3 minutes (79% prediction), and 2.5 minutes

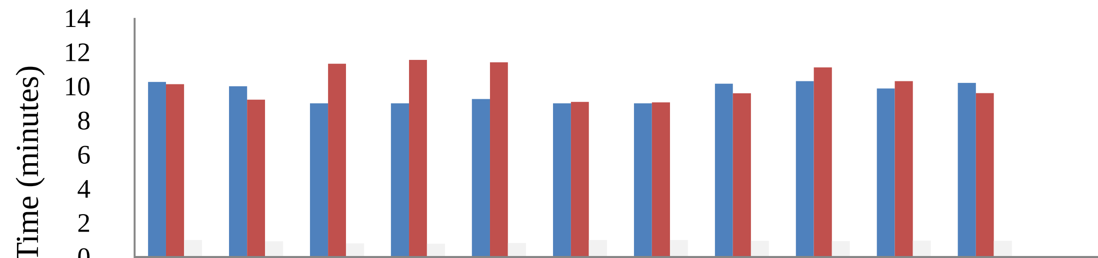
(78% prediction). Model tests were also carried out on 12 unloaded trips on Road 4. The observed predicted times were also not as accurate as in the tests carried out on the other two roads (Road 2 and 3). The percentage predictions of the observed time generally ranged from 85% to 89%, although three trips were observed with better prediction percentages of 96%, 98%, and 100%. The differences between the predicted times and the observed times generally ranged from zero to 1.4 minutes.

Comparison with BNG

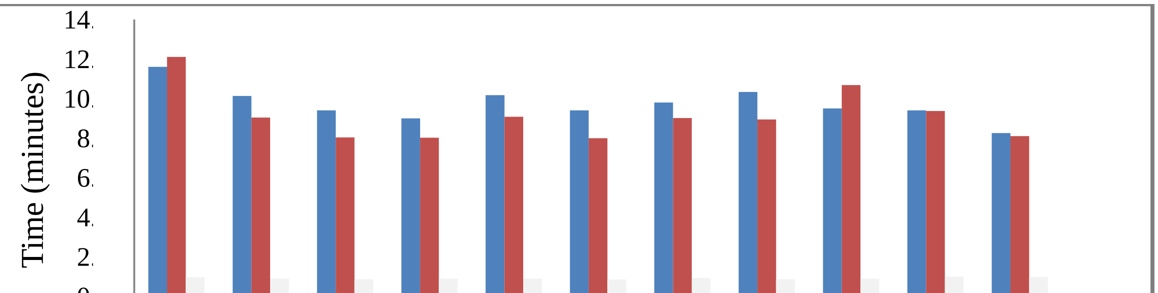
Comparison of BNG travel time prediction to the model (CHIP-VAN) and observed predicted times was done by applying the BNG method on the data for both loaded and unloaded chip van trips on all the roads. The BNG method assumes that vehicle speeds on single lane roads are limited by either alignment or grade. Since vehicle speed is inversely proportional to the travel time of the vehicle, alignment and grade will therefore determine the time taken for the vehicle to travel over a given distance. The model applies the same equations as the ones used in the BNG method to calculate speeds limited by alignment (sight distance) and speeds limited by adverse grades during uphill movement. The equations used in the model were thus used to apply the BNG method for alignment and adverse grade limited speeds. The speeds limited by downhill (favorable) grades were determined by an empirical equation that was set up by BNG based on field observations (Appendix D). The speeds calculated from this equation are assumed to be the safe speeds at which a vehicle can descend a grade. However for favorable grades exceeding 16%, the same method used to calculate speeds and travel times on adverse grades was used. This was established from a study by Jackson (1986) that found that favorable grades exceeding 16% had significant differences between predicted and observed travel times. The BNG method was implemented on each curve or segment with distinct road conditions (grade, radius, distance) to calculate the travel time on each curve, which was then summed for the entire road section to get the total predicted travel time. To find the limiting road condition on each curve, the calculated times (in minutes per mile) limited by either grade or alignment, were compared and the one with the longer time per mile was taken as the limiting road condition.



	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	10.7	10.4	10.0	10.6	10.5	10.1	8.1	8.3	11.6	10.0	8.3	0
Predicted Time	9.3	10.0	9.9	11.6	13.1	10.5	8.6	8.4	12.5	15.0	8.3	0
Prediction %	87%	96%	99%	91%	80%	96%	95%	99%	93%	67%	100%	0



	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	10.3	10.0	9.0	9.0	9.3	9.0	9.0	10.2	10.3	9.9	10.2	0
Predicted Time	10.1	9.2	11.3	11.5	11.4	9.1	9.1	9.6	11.1	10.3	9.6	0
Prediction %	99%	92%	79%	78%	81%	99%	99%	94%	93%	96%	94%	0



	1	2	3	4	5	6	7	8	9	10	11	12
Observed Time	11.6	10.1	9.4	9.0	10.2	9.4	9.8	10.3	9.5	9.4	8.3	0
Predicted Time	12.1	9.0	8.0	8.0	9.1	8.0	9.0	8.9	10.7	9.4	8.1	0
Prediction %	96%	89%	85%	89%	89%	85%	92%	87%	89%	100%	98%	0

Figure 3.10. Model (CHIP-VAN) validation test results showing the predicted travel times compared to observed travel time for each unloaded chip van road trip. Charts a, b and c represent results from tests on roads 2, 3 and 4 respectively.

The BNG method also classifies the alignment into four different categories: poor, fair, good and excellent (Appendix F). The alignment classes for each road are determined by an alignment rating (or factor) established by BNG that relates to the average curve radius and the number of curves per mile. The alignment factor is calculated by dividing the average curve radius by the number of curves per mile. The BNG method requires that, for all travel times limited by alignment, the average curve radius and the number of curves per mile should be obtained for each road section and the alignment should be classified. When calculating the average curve radius and the number of curves per mile, all the curves with radii greater than four times the minimum curve radius are not included in the computations (BNG). This method used to compare the BNG to the model was also used by Jackson (1986) and Moll and Copstead (1996). A summary of the alignment classification results are shown in Table 3.2 for both loaded and unloaded trips as determined from the data. Appendix F shows the alignment classification results for each of the 88 road trips.

The effect of the recommendation that only curves less than four times the minimum radius be included was tested by comparing the alignment classification results with and without the "four times recommendation" being included. Before applying the BNG "four times recommendation" the road alignment classification was generally "poor" on all roads for the tests on all 88 road trips. After applying the BNG "four times recommendation" a significant difference was observed and the average alignment classification on all roads ranged from "good" to "excellent" (Table 3.2). However, it should be noted that the general alignment classification ratings from all the road trips ranged from poor to excellent (Appendix F). BNG also recommends that unloaded travel times should be adjusted for the lost time during stoppages at turnouts based on the density of traffic and turnout spacing. A 3.2% increase was determined from the BNG method and applied to the BNG unloaded travel time prediction (Appendix D).

Table 3.2. Average BNG Alignment Classification results for each road from loaded and unloaded road trips taken by Chip-Van 1line

Loaded Chip Van	Average Curve Radius	Number of Curves Per Mile	Average Alignment factor	BNG Alignment Class
Road 1	459	5	159	Excellent
Road 2	186	6	144	Excellent
Road 3	174	5	232	Excellent
Road 4	95	13	61	Good
Unloaded Chip Van				
Road 1	506	5	205	Excellent
Road 2	154	5	58	Good
Road 3	210	2	294	Excellent
Road 4	122	8	56	Good

The BNG predicted travel time was first compared to the CHIP-VAN First Pass Simulation that predicts travel times from the maximum limit speeds on each curve and assumes instantaneous acceleration and deceleration from one curve to the next. The second comparison was done with the CHIP-VAN Second Pass Simulation that predicted travel times through a smooth transition of speeds from one curve to the next by accelerating and decelerating based on the maximum limit speeds from the CHIP-VAN First Pass Simulation. In the comparison results of the BNG to the model (CHIP-VAN), the two simulations are referred to as the CHIP-VAN First Pass Simulation and CHIP-VAN Second Pass Simulation respectively. It should be noted that the CHIP-VAN Second Pass Simulation represents the final results of the travel time prediction by the model, CHIP-VAN as observed in the comparison results between CHIP-VAN predicted travel times and observed travel times in the previous sections.

The results show that BNG predicted shorter travel times than the observed travel times and the CHIP-VAN Second Pass Simulation predicted travel times. However, the BNG predicted travel times closely matched with the CHIP-VAN First Pass Simulation for both loaded and unloaded trips taken by the chip vans. The distribution of percentage differences of the BNG predicted time in comparison to the CHIP-VAN First Pass Simulation, CHIP-VAN Second Pass Simulation and the observed travel times are also shown in the histograms in Appendix E.

The percentage differences between the BNG and the CHIP-VAN First Pass Simulation predicted travel times from the loaded chip van trips ranged from 0% to 2.5%. The highest frequencies of observed differences were below 1%. Larger differences were observed between the BNG predicted travel times and the CHIP-VAN Second Pass Simulation with most percentage differences generally ranging from 40% to 80%. A significant distribution of percentage differences ranging from 0% to 20% were also observed between the BNG and CHIP-VAN Second Pass Simulation predicted travel times. The highest frequency of observed percentage differences fell within the range of 40% to 60%. Similar large differences were observed between BNG predicted travel times and the observed travel times that generally ranged from 40% to 80%. A significant distribution of percentage differences less than 20% was also observed.

The percentage differences between the BNG predicted travel times and the CHIP-VAN First Pass Simulation from the unloaded chip van road trips ranged from 0 % to 25%. The highest frequency of observed differences was between 0 and 5%, followed by differences ranging 5% to 15%. A considerable frequency of percentage differences were also observed on ranges from 15% to 25%. Larger differences were observed between the BNG predicted travel times and the CHIP-VAN Second Pass Simulation with percentage differences ranging from 5% to 75%. The highest frequency of observed percentage differences fell within the range of 40% to 60%. Just as observed between the BNG and the CHIP-VAN Second Pass Simulation, large differences that ranged from 7% to 70% were observed between BNG predicted travel times and the observed travel times. The highest frequencies of observed percentage differences, however, were within the range of 40% to 60%.

Discussion of Results

The error frequency distribution of the predicted travel times for both loaded and unloaded chip vans indicate that the model was able to predict the travel time with error less than 0.1 for most the road trips on which the model was tested for validation (Figure 3.11). The distribution also indicates that a considerable number of trips predicted the travel time with error greater than 0.1 but less than 0.2. A few errors greater than 0.2 and up to a maximum of 0.36 were also observed. This is also indicated in the percentage wise error frequency distribution of all the results: 61% error less than or equal to 0.1, 27% error greater than 0.1 but less or equal to 0.2 and 12% error greater than 0.2. It was also observed that most errors greater than two were on Road 4 that had the shortest mileage (1.4 miles) as compared to the others roads.

The most probable explanation for this observation, is that, since the model predicts travel time based on changing road conditions and simulates the driver's behavior based on those changing conditions, the model tends to predict simulate high speeds and shorter travel times on short roads with almost the same road conditions. This is also shown on longer roads where the model simulation predicted the travel time with less error. The results showing prediction errors greater than 0.2 could also possibly be attributed to the varying operation patterns of the different drivers on those particular trips. It might be that on these trips the drivers did not react to the changing road conditions and might have been driving faster or slower than they usually do due to factors that cannot be simulated by the model. These factors may include human factors such the psychological status of the drivers at any moment in time. For example, if the driver knows that he still has to wait for other chip vans to load at the landing, he may drive slower than normal. The results show that 88% of differences between the predicted time and the observed time are less than 2 minutes. These suggest that the model is valid for predicting travel time of the chip vans on forest roads with acceptable accuracy.

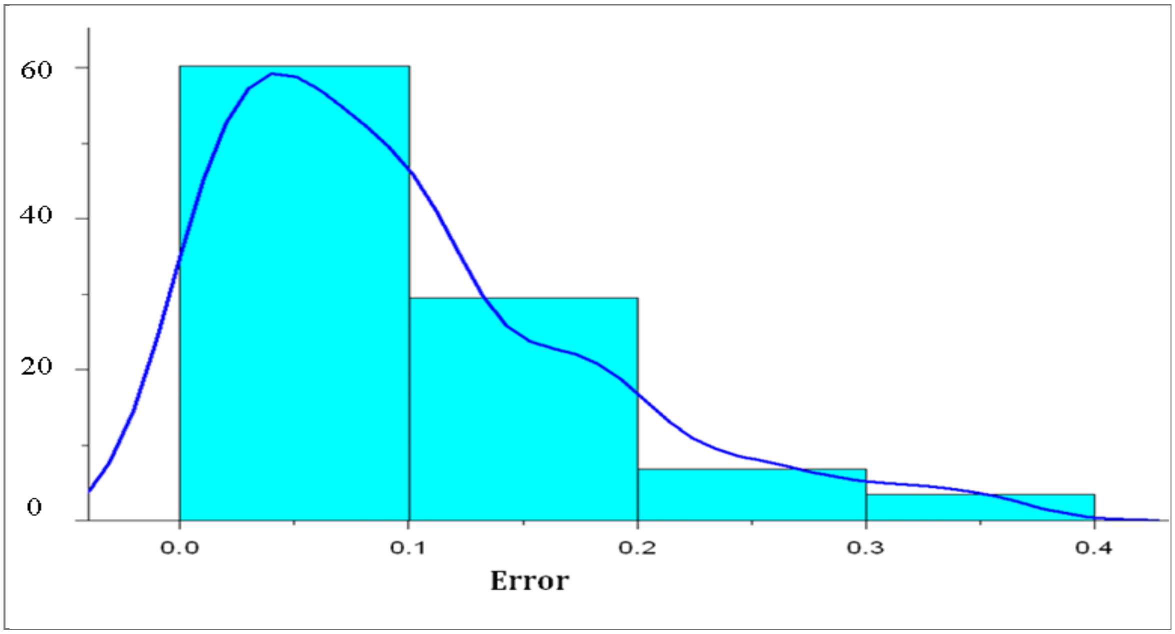


Figure 3.11. Error frequency distribution of the CHIP-VAN predicted travel times from the model tests as compared to the observed travel times. The y-axis represents the percentage frequency of observed errors.

The results show that the prediction of the travel times for chip vans on forest roads can be simulated using equations in the literature that determine the maximum limit speeds on road curves or sections based road grade, horizontal alignment and vertical alignment, and modeling the drivers behavior by accelerating or decelerating based the limit speeds ahead. This might imply that chip vans are not different from other forest vehicles such as log trucks on which the equations in the literature were developed. The results, however, also show that the unloaded and loaded chips vans were accelerating at the same slow rate but were decelerating at higher rate although the loaded chip vans are able to decelerate faster than the unloaded chip vans. This might be expected to be influenced by the different weights of the loaded and unloaded chip vans. The loaded chip van with more weight will have more traction and gradeability than the unloaded chip van, thus the loaded chip van can decelerate faster than the unloaded chip van without easily losing its traction.

Another factor observed to play an important part in predicting the travel time for unloaded chip vans was the number of stops on turnouts and the delays in time resulting from the stoppages. The differences between the predicted travel time and the observed travel time were observed to be larger without adding the time lost from stopping at turnouts in the simulation. The assumption that the total delay time is equal to the time required for the unloaded chip van to decelerate and stop plus the time required for the unloaded chip van to start and accelerate to normal speed gave the best-fit for predicting the travel time. There is no standard method in the literature that defines how to estimate turnout delay times for unloaded truck are derived. Past research has, however, attempted to model the delay time based on turnout spacing (Bryne et al. 1960; Anderson 1980). In reality, the deceleration time would normally be less than the acceleration time because the deceleration rate is usually higher than the acceleration rate. Bryne et al. (1960) assumed that the delay time on a turnout is equivalent to, the time required for the loaded truck to approach and pass the unloaded truck; the unloaded truck driver reaction time to start his vehicle after the loaded truck passes; the unloaded truck acceleration time to normal speed less the time it would take to cover the same distance at normal speed and they suggested that it is not necessary to consider deceleration time because the time will normally be less than the time for the loaded truck to travel one-half the distance between turnouts. This is also observed in the deceleration rate determined by the best-fit between predicted and observed travel times.

The BNG comparison results also added to the understanding of chip vans travel time simulation and prediction. The BNG and the CHIP-VAN First Pass Simulation predicted travel times which were generally shorter than the observed travel times are an indication that the assumption of instantaneous change in speeds from one curve to the next is not valid for predicting travel times of chip vans and probably other forest vehicles such as log trucks. These BNG comparison results indicating similar results between the BNG and the CHIP-VAN First Pass Simulation predicted travel times and large differences with the CHIP-VAN Second Pass Simulation and observed travel times, confirm the importance of modeling the drivers reactions to changing road conditions. This also suggests that methods that ensure a smooth transition of speeds from one curve to the next are an important component that should be included in simulation models such as the method proposed in CHIP-VAN using the four cases described that determine the conditions for accelerating and decelerating.

Conclusion

A model simulation program called CHIP-VAN that predicts the travel time of chip vans on forest roads has been presented. The model was developed from empirical data that was collected using GPS technology to record location and speed information on chip vans that were exclusively transporting forest biomass on forest roads. The model is developed based on the maximum limiting speeds on each road segment as limited by road grade, stopping sight distance (SSD) and road alignment as well as modeling the driver's behaviors as these road conditions change. A two pass simulation was built in the model; a CHIP-VAN First Pass Simulation that calculates the maximum limit speeds on each road segment and a CHIP-VAN Second Pass Simulation that simulates the driver's behavior and calculates the travel time. To emulate the driver's behavior four cases that determine whether a driver will accelerate, decelerate or continue at their current speed, were developed. Acceleration and deceleration rates were also determined using an algorithm developed to minimize the sum of squared deviations between the predicted and observed travel time and give the best fit for different combinations of acceleration and deceleration rates.

The model has been tested for validation using the data collected for the study. The tests carried out on the model indicate minor differences between the predicted time and the observed time with most of them reporting errors less than 0.1(10%). These suggest that the model is valid for predicting travel time of the chip vans on forest roads with acceptable accuracy. The model tests were carried out on data from forest roads not longer than 6.5 miles. The model can be applied over longer distances, but further validation should be carried out to verify if the driver behavior is the same on longer roads as on shorter ones.

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CHAPTER 4. MONITORING GPS ACCURACY FOR VEHICLE TRACKING UNDER DIFFERENT FOREST CANOPY CONDITIONS

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Introduction

Ground Positioning Systems (GPS) technology applications for collecting resource measurements and managing forestry operations have been increasing over the past ten years. Several recent technological and economical developments have increased accessibility to GPS technology for natural resource professionals and have expanded potential applications (Wing 2008). High precision GPS receivers are capable of providing coordinate locations of objects to within a cm of their actual location in ideal conditions but are often limited in forested settings due to canopy cover and topographic conditions (Wing and Kellogg 2004). The accuracy and performance of GPS under different forest conditions have been investigated in several studies (Deckert and Bolstad 1996, Karsky et al. 2001, Yoshimura and Hasegawa 2003, Hasegawa and Yoshimura 2007, Wing et al. 2005, Rodríguez-Pérez et al. 2007, Wing and Eklund 2007, Wing et al. 2008, Wing 2009). These studies have determined that GPS receivers are capable of recording positions to within several meters of true location under forest canopy with certain GPS receiver configurations. However, the reliability of GPS receiver measurements for moving vehicles under forest canopy and in mountainous terrain has not been examined.

A GPS receiver operating within a moving vehicle can record location, heading, and speed information derived from satellite signals. Using GPS receivers for monitoring and tracking mobile machines has significant potential for monitoring and increasing the efficiency of forestry operations including harvesting and transportation processes (Codero et al. 2004). According to Veal et al. (2001), researchers and practitioners are beginning to use GPS more frequently for vehicle tracking, but little information is available concerning GPS accuracy in dynamic vehicle tracking applications in forest operations. Few studies that have investigated the accuracy of GPS receiver measurements placed in moving vehicles within a forest and to our knowledge, no study has tried to compare the consistency in measurement of identical GPS receivers placed within a vehicle under different forest conditions.

This study investigates the accuracy of data recorded through GPS technology to track and monitor chip trucks that were exclusively used for transporting chipped biomass from forest operation sites in Dillard, Oregon. The primary objective of this study was to determine the accuracy and reliability of GPS for vehicle tracking in forested terrain and, if inconsistencies were found between measurements, to investigate whether forest canopy or other operational characteristics influenced inconsistencies. Although our GPS testing focused on the transportation of biomass from forest supply locations to distribution and processing centers, study results are applicable to any transportation process that involves vehicles operating in steep, forested terrain.

Background

GPS data collection throughout North America and in many other parts of the world relies on the Navigation Signal Timing and Ranging (NAVSTAR) GPS. NAVSTAR is operated by the US Department of Defense and is a collection of satellites and terrestrial-based monitoring stations that provide measurement information to GPS receivers (Wing 2009). All GPS receiver position measurements are derived from communications with satellite systems to calculate positions and are subject to several potential error sources. Errors can come from a number of factors including imprecision in accounting for time, satellite orbits, atmospheric conditions, and other factors (Wing 2008). In a forest setting, the major sources of error have been reported to be the forest canopy cover and terrain which may obstruct GPS receivers from capturing satellite signals since GPS signal reception is dependent upon a line-of-sight between satellites and a receiver. The accuracy of data recorded using GPS under forest canopy has therefore been of interest to a number of researchers and practitioners. However, most research in the literature, has concentrated on GPS accuracy based on stationary (Deckert and Bolstad 1996, Karsky et al. 2001, Yoshimura and Hasegawa 2003, Hasegawa and Yoshimura 2007, Wing et al. 2005, Rodríguez-Pérez et al. 2007, Wing and Eklund 2007, Wing et al. 2008, Wing 2009). In these studies, GPS accuracy has generally been reported to decrease as one moves from open to dense forest canopies.

Research on GPS accuracy under different forest conditions related to mobile machines has also been carried out on mobile harvesting Equipment and forest vehicles. Spruce et al. (as cited in Devlin and McDonnell 2009) used a typical mapping-grade GPS receiver and reported degraded GPS accuracies under forest canopy as compared to open sky.

Jalinier and Courteau (1993), examined the ability of a GPS receiver (SERCEL NR 101) that was attached to a vehicle traversing forest roads to develop a rapid, accurate and economical means of surveying forest roads and produce input data for a truck performance simulation program called OTTO. The study indicated that under the right conditions, GPS in differential mode had full potential to survey roads in three dimensions and positions them with great accuracy. The accuracy was also not affected by vehicle speed and acceleration. However, the study also indicated that surveys in proximity to dense forest cover yielded questionable results. Veal et al. (2001) quantified errors in GPS positions recorded during operation of wheeled skidders in three different canopy conditions and at two different ground speeds using two different commercially available GPS receivers. The study reported significant differences in the accuracy of positions recorded by the two receivers with accuracy decreasing as canopy conditions changed from open to dense canopy. However, the machine speeds tested did not appear to affect accuracy of GPS positions. Recent research by Devlin et al. (2007), evaluated the positional accuracy of a dynamic non-differential global positioning system (non-DGPS) for tracking an articulated truck across the Irish road network. The study was carried out using a Trimble GeoXT handheld mapping-grade GPS receiver in non-differential mode meaning that no differential corrections were applied to the collected data. The GPS receiver was operated in conjunction with an external magnetic antenna that was fitted to the cab of the articulated truck. The level of positional accuracy (expressed as a horizontal root mean square (HRMS) error measured at 63% confidence level) observed in this study ranged from 6.9 m to 3.2 m. The results showed that dynamic non-differential GPS could be successfully implemented to track the position and movement of an articulated truck across the Irish public road network. Devlin et al. (2007) determined that the level of accuracy provided by the relatively low-cost, non-differential GPS was well suited to track positions and movement of timber trucks.

Devlin and McDonnell (2009) studied the GPS performance accuracy (at 63% HRMS confidence level) of real-time vehicle tracking systems for timber transport trucks travelling on both the internal forest road network and the public road network of Ireland. The objective of the study was to quantify GPS performance under varying forest environments. The study involved the installation of Bluetree GPS asset tracking systems onto two timber transport trucks. The HRMS accuracy values for this study ranged from 2.47 m to 2.55 m for public roads. The HRMS accuracy of the recorded values on the internal forest road network differed as much as 27 m in one of the two trucks and as much as 41 m in the other. These differences were attributed to forest canopy. Devlin and McDonnell (2009) believed that vehicle tracking systems worked well for monitoring purposes given that GPS positions could be recorded throughout forested areas.

Materials and Methods

Study Site

Our study was conducted on chip trucks that were exclusively transporting biomass from three harvesting operations on forest lands owned by Roseburg Forest Products Company in Dillard, Oregon, USA. All the operations were situated about 12 miles south of Dillard. For identification and analysis purposes, the operation sites were separated into three components which we refer to as Operation 1, 2, and 3. Each of these operations occurred in a different portion of the landscape and was selected based on the varying forest canopy conditions that each exhibited. The forest road system associated with Operation 1 was characterized by a forest canopy cover mixture of mature and young stands, and open areas. The forest roads in Operation 2 were characterized by more mature canopy cover than open areas and almost no young forest canopy conditions. The forest roads in Operation 3 had more open areas, very few young stands, and almost no mature forest canopy cover. The forest roads leading to all the operation sites were single lane with turnouts and curve widening, included both paved and unpaved sections, and had a range of gradients from relatively level to 19%.

Data Collection

The GPS receivers that recorded location and speed information on the chip trucks werea consumer-grade Visiontac VGPS-900 receivers (Figure 1) and have a 51 channel MTK chipset with enhanced positioning system technology (up to 1.5 m accuracy with DGPS reception according to manufacturer specifications). The Visiontac VGPS-900 also comes with a MicroSD Slot with support for up to 2GB of storage capacity (about

25,000,000 locations, also referred to as waypoints in the GPS literature). The measurement parameters recorded by this GPS receiver include date, time, latitude, longitude, altitude, speed, heading, fix mode, Percent Dilution of Position (PDOP), Horizontal Dilution of Precision (HDOP)**,** and Vertical Dilution of Precision (VDOP) (www.visiontac.com/v900_feature.htm).

Figure 4.1. The Visiontac VGPS-900 GPS receiver.

Each operation had two chip trucks transporting biomass from the operation sites. The chip trucks a tandem axle 2009 Kenworth truck (Model T800) with a 525 HP Cummins ISX engine (Figure 2, top) and a tandem axle 2007 Peterbilt truck (Model 378SB) with a 500 HP Cummins ISX engine (Figure 2, bottom). The Kenworth truck pulled tandem axle 45 feet live floor chip truck trailers and the Peterbilt truck pulled a tri- axle 48-foot chip van trailer with a drop center. Six GPS receivers divided into two sets (Set 1 and Set 2) of three were placed in the two chip trucks. The GPS receivers were identified by numbers from 1 to 6 for tracking and analysis purposes. The first set (GPS receivers 1, 2, and 3) was placed in the Peterbilt truck and the second set (GPS receivers 4, 5, and 6) was placed in the Kenworth truck. The GPS receivers were firmly mounted on the truck's dashboards to avoid excessive movement and other disturbance. The GPS receivers were configured to record a location every second during chip hauling activities.

Data were recorded on four separate days in 2009. Operation 1 spanned two days (July 30 and 31), whereas Operation 2 (August 7) and Operation 3 (August 12) each took place during a single day. The chip trucks made three round trips (three trips in and three trips out) on each day. During Operation 1, receiver Set 1 recorded data on July 30th and Set 2 recorded data on July 31st. The GPS receivers in Operation 1 recorded an average of 15,000 data points each at one second intervals during each day, creating 45,000 data points for each set and a total of 90,000 data points for the entire operation. Both sets were used to record data on the same day during Operation 2 and Operation 3. Each GPS receiver in Operation 2 and Operation 3 recorded an average of 8,000 data points. The total number of data points for each set was nearly 24,000, (missing a number here) creating about 48,000 points for each operation. Approximately 186,000 GPS measurements were recorded for the entire study.

Figure 4.2. Chip trucks used in the study. A tandem driving axle 20-foot tractor, drop axle in raised position, with a tandem axle 45 feet live floor chip van trailer (top); and a tandem 18-foot tractor with a tri- axle 48-foot chip van trailer with a drop center (bottom).

Data Management and Analysis

The GPS receiver measurements were managed and prepared for analysis using ESRI's ArcGIS desktop 9.3.1 software. The main ArcGIS tools used were ArcMap, ArcCatalog, ArcToolBox, ArcEditor and XTools Pro. The data were downloaded from the GPS receivers and uploaded into ArcMap using the default World Geodetic System of 1984 (WGS 84) map projection. The data were then reprojected to the North American Datum of 1983 **(**NAD 83**)** Oregon Statewide Lambert (international foot) projection and Xtools Pro was used to add the x and y coordinates. The re-projection was necessary to get the default longitude and latitude coordinates into a projected coordinate system that could support horizontal distance calculations. The GPS measurements were than sieved so that all periods when the chip trucks were not in motion were removed from the analysis databases. After these non-moving GPS measurements were removed, the total number of data points available for GPS accuracy analysis for this study was 34,585 points. Table 1 shows the total number of points left after sieving for Operation, Set and GPS unit.

Table 4.1. Number of GPS data points available for Analysis from each Operation, Set and GPS receiver.

	Set-1				Set-2				
Operation	GPS-1	GPS-2	GPS-3	Total	GPS-4	GPS-5	GPS-6	Total	Total Overall
1	10,330	10,397	10,357	31,084	10,617	10,886	10,779	32,282	63,366
2	5,091	5,110	5,120	15,321	5,164	5,234	5,144	15,542	30,863
3	6,737	6,734	6,744	20,215	4,730	4,896	4,744	14,370	34,585

To analyze the data based on different forest canopy cover types, a digital orthophotograph image of the study area taken in October 2009 was downloaded from the Oregon Image Explorer website. The Oregon Imagery Explorer is a natural resources digital library that serves Oregon's half-meter resolution orthoimagery and other imagery, including satellite data that can be downloaded online (www.oregonexplorer.info/imagery). The orthophotograph was projected to the same map coordinate system as the GPS data points. Using the orthophotograph image and ArcEditor, a line was created in the center of the forest roads traversed by the chip trucks. The line was then buffered by 15 feet (4.6 m) on both sides, thereby creating a buffer roads polygon layer with a total 30 foot (9.1 m) width. This 30-ft buffer size was based on the road width needed for a chip van with an 18 foot (5.5 m) tractor and a 36 foot (11.0 m) trailer, traveling on a 50 foot (15.2 m) radius curve with 180 degree central angle (BLM 1984). Field measurements were also collected to ensure that the recommended maximum lane width was also applicable to the chip trucks used in this study. It was assumed that if the data points recorded by the GPS receivers were relatively accurate (+/- 15 ft) in tracking the chip trucks, they should fall within the 30-foot roads polygon layer. The roads polygon layer created was then divided into sub-polygons based on the forest canopy cover type and road type (paved or unpaved) as observed on the digital orthophotograph. The forest canopy cover types were categorized as mature, mature/open, young, young/open and open. The parts of the forest road polygon layer where both sides were covered by mature stands were placed in the mature category and those that had one side covered by a mature stand and the other side open, were placed in the mature/open category. The forest road polygon parts with both sides covered by young stands were placed in the young category and those that had one side covered by a young stand and the other side open, were placed in the young/open category. Parts of the forest road polygon that were open on either side were placed in the open category.

Using geoprocessing tools from the Arc Toolbox, the data points from each Set (Set 1 and Set 2) of three GPS receivers for each chip truck on each day were appended into single databases in order to support data manipulation and analysis. A spatial join was carried out to associate the appended databases to the road polygon layer based on spatial location. Through the spatial join, each GPS data point was given all the canopy cover and road type attributes of the sub-polygon that it was located within or, if located outside of all sub-polygons, the attributes of sub-polygon that was closest to it and the distance to the closest sub-polygon.

The data was analyzed using Windows Microsoft EXCEL and the S-Plus statistical software package. ArcGIS was used to calculate the straight-line distance from the GPS measurement points to the nearest road polygon and Microsoft EXCEL was then used to create pivot tables and get the average distances and standard deviations for each GPS receiver and trip in each forest canopy cover category (table1). We describe this distance as a mean measurement distance (MMD) in reporting average distances and also include a standard deviation (SD). These descriptive statistics were calculated for each GPS receiver and trip for all forest canopy cover categories. We initially intended to perform an Analysis of Variance (ANOVA) for statistical assessment but data distribution normality assumptions were not met. Therefore, we applied the Kruskal Wallis non-parametric test for our statistical analyses (Kruskal and Wallis 1952). The Kruskal Wallis non-parametric test compares three or more groups of data without assuming normal data distributions, and can accept numeric data in interval or ordinal form. The Kruskal Wallis test has two hypotheses: a null hypothesis that assumes that there is no difference between population group medians being compared and an alternative hypothesis that assumes that there is difference between population group medians. McDonald (2009) simplifies how the Kruskal Wallis test works: it starts by putting all the values from a data set in ranks from low to high and calculates the sum of the ranks for each group. The test statistic, H, representing the variance of the ranks among groups is then calculated. H is approximately chi-square distributed; meaning that the probability of getting a particular value of H by chance, if the null hypothesis is true, is the P value corresponding to a chi-square equal to H and the degrees of freedom is the number of groups minus 1 (McDonald 2009). The commonly used threshold for H is 5; values larger than 5 mean that the null hypothesis is rejected and vice versa.

Results and Discussion

Since the roads polygon layer was divided into sub-polygons that had attributes of forest canopy cover type, we were able to establish the road distances and the associated percentage of each canopy cover type for each operation (Table 2). We found that the forest roads in Operation 1 had a mixture of canopy cover types:. 35% mature, 14% mature/open, 15% young, 14% young/open and 21% open. Although there was slightly higher percentage of the mature forest canopy cover type, the percentage distribution satisfied our intent that the environmental setting of Operation 1 have a relatively balanced mixture of canopy cover types. Operation 2 exhibited mature canopy cover (35%), followed by young/open (27%) , open (21%), mature/open (15%) and almost no young canopy cover (2%). Operation 3 exhibited more open canopy cover (47%), followed by young/open (33%), very little mature/open (11%) and young (10%) canopy cover types and mature canopy cover (0%). The environmental settings for Operation 2 and Operation 3 supported our intention to have increased variability in forest cover types within our three study areas

Table 4.2. Distance (kms) and percentage of forest canopy cover types in each operation.

	Operation					
	One		Two		Three	
Cover	Km	%	Km	%	Km	%
Mature	4.8	35%	2.5	35%	0.0	0%
Mature/Open	1.9	14%	1.0	15%	0.7	10%
Young	2.1	15%	0.2	2%	0.7	11%
Young/Open	1.8	14%	1.9	27%	2.1	33%
Open	2.8	21%	1.5	21%	3.1	47%
Total	13.4	100%	7.1	100%	6.6	100%

The results of the mean measurement distances (MMDs) and standard deviations (SDs) from the 30 foot roads polygon in each forest canopy cover category for each set of GPS receivers used in each operation are shown in Table 2. A side by side comparison of the performance of GPS receivers in all the operations and for each set in the different forest canopy cover types is also shown in Figure 3. We found that, in general, there was a loss in positional accuracy as the chip trucks moved from open to mature forest canopy cover categories. The MMDs from open to mature canopy cover types generally varied from 0.3 m to 8.1 m and SDs varied from 1.1 m to 15.3 m respectively. The MMDs (and SDs) were consistently lower in the open canopy cover types when compared to the mature canopy cover type for all operations and GPS sets. The trend in MMDs between cover types fluctuated for some operations and receiver sets but the average MMDs for each set demonstrated an increase from the open, to young, to mature cover types. The overall MMDs for Operation 1, ranged from 2.3 m (6.5 m SD) to 5.9 m (12.8 m SD). The MMDs for Operation 2 ranged from 0.8 m (2.4 m SD) to 8.1 m (15.3 m SD) and for Operation 3, MMDs ranged from 0.4 m (1.2 m SD) to 1.6m (2.3 m SD). In a few cases, however, the GPS receiver measurements were less accurate in the young forest canopy cover as compared to the mature/open cover. This can likely be attributed to the open side of the mature/open cover type which could positively influence measurement accuracy if satellite signals are captured on that side. The overall MMDs and SDs observed in Operation 2 were better than those observed in Operation 1 except in the mature canopy cover. This was also probably expected, because the mature cover on forest roads in Operation 2 was heavier than that of Operation 1. Expectedly, also the lowest MMDs and SDs were in Operation 3 where forest roads had more open areas, very few young stands, and almost no mature forest canopy cover. Operation 1 with a relatively balanced mixture of mature, young stands, and open areas on forest roads had larger MMDs and SDs than Operation 3 but lower MMDs and SDs than Operation 1.

We observed a reduced measurement performance for the GPS receivers in Set 1 when compared to Set 2 for Operations 1 and 2 (Table 3). The total MMDs, which take the average of all three receiver measurements in each Set, for Set 1 ranged from 3.9 m (8.8 m SD) to 10.0 m (16.5 m SD) in Operation 1 and from 1.1 m (3.0 m SD) to 14.3 (19.7 m SD) in Operation 2 in comparing the open to mature canopy cover types. The Set 1 GPS receivers, however, were more accurate in Operation 3 with MMDs ranging from 0.5 m (1.3 m SD) to 1.4 m (2.2 m SD). The strong measurement performance of Set 1 receivers in Operation 3 provided some assurance that the large MMDs witnessed in Operations 1 and 2 were not due to mechanical or configuration issues within the receivers. GPS receivers in Set 2, were consistently more accurate in Operation 1 and Operation 2 with total MMDs ranging from 0.7 m (1.6 m SD) to 1.4 m (2.9 m SD) and from 0.5 m (1.6 m SD) to 2.0 m (3.6 m SD), respectively. GPS receivers in Set 2 of Operation 3 were as accurate as in Set 1 with MMDs ranging from 0.3 m (1.1 m SD) to 1.8 (2.5 m SD. These minimum and maximum amounts were associated with the open and mature canopy cover types, respectively.

Our findings demonstrate that the potential GPS tracking accuracy of vehicles on forested roads are clearly influenced by the composition of the surrounding canopy, with the strongest influence being from mature forests. These results have also been observed in previous research that has examined GPS accuracy related to tracking forest vehicles and harvesting machines under different forest conditions (Jalinier and Courteau 1993, Veal et al. 2001, Devlin et al. 2007, Devlin and McDonnell 2009). The observed reduced MMD accuracy in locations where forest cover was more dominant could have come from several potential error sources including satellite orbits and atmospheric conditions. The most likely sources are communication with a reduced number of satellites and multipathing influences. A GPS receiver requires communication with at least three satellites to determine location and at least four satellites to calculate a location and associated elevation. As signals from more satellites reach a receiver, position determination becomes enhanced leading to greater positional accuracies and reduced variation. We are not able to derive information about the number of satellites that the GPS receivers in this study were able to communicate with in looking at the information recorded by the receivers. Doubtlessly, however, as canopy conditions become more prevalent, we would expect that fewer satellite signals are attainable by a GPS receiver, leading to a decrease in the relative accuracy of positional measurements.

Multipathing occurs when a satellite signal is reflected from another object before reaching a GPS receiver. Shiny, smooth objects such as roof tops or water bodies have high potential for contributing to multipathing but forest canopy can also provide a multipath source. Multipathing causes a delay of the actual time that it takes a signal to reach a GPS receiver, thus introducing error into location calculations by the receiver since the delay is not addressed within satellite signal information (Wing 2008). We would expect that our results contain measurements that were influenced by multipathing but are unable to quantify to what extent. A consistent method of quantifying the occurrence of multipath under varying forest canopy conditions is not available (Veal et al. 2001)

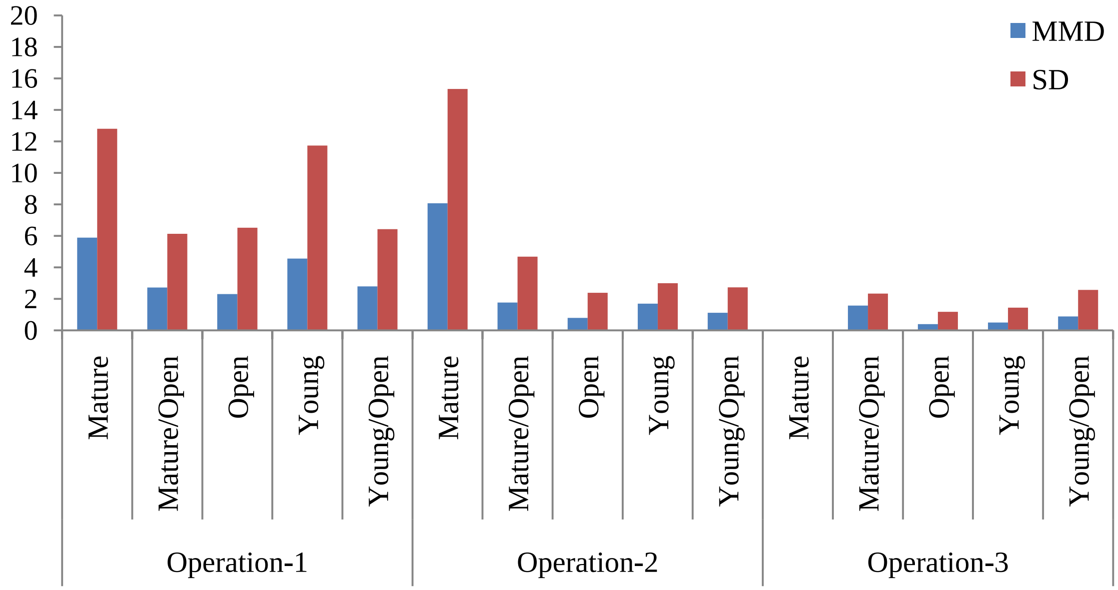
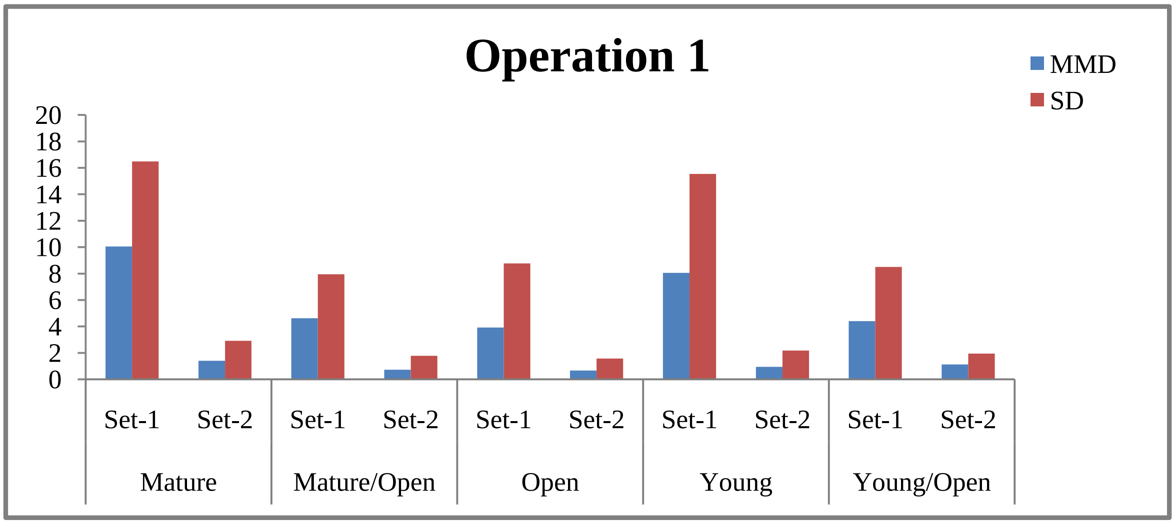


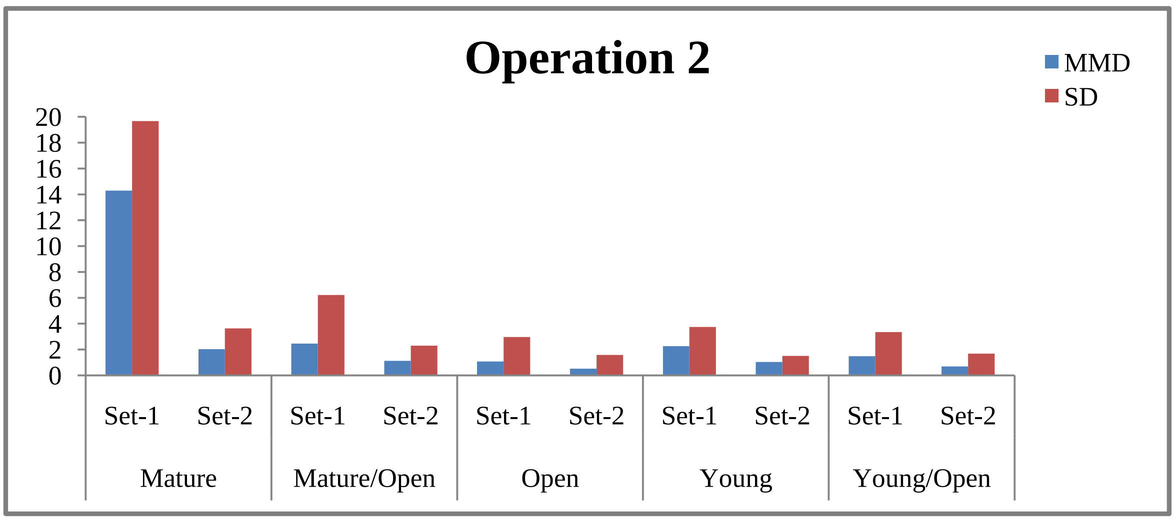
Figure 4.3. Sum Mean Measurement Distance (MMD) and Standard Deviation (SD) by forest cover category for all operations combined (units are meters).

One of the objectives of this study was to assess the consistency of GPS receiver measurements that were collected simultaneously in a moving vehicle. The assumption was that there should be no difference in the measurements from identical receivers operating simultaneously and placed in the same relative location within the same chip truck. We also expected to find minimal measurement differences between receivers that were placed in separate chip trucks and operating in similar environmental settings. As demonstrated by the SDs in some of the operation results (Table 3) and subsequent Kruskal Wallis statistical test results, there was high variance among ranks in the measurement databases. The Krukal Wallis variance tests were first carried out on each operation database by combining the receiver measurements from both Set1 and Set 2. We then tested the variance within each of the three GPS receivers from each set. The variance in the measurements was also tested separately for individual receivers in each operation. In all the tests, measurements were compared based on the road type (paved and unpaved), the speed of the chip trucks and the trips that the chip trucks made (inbound or outbound. The tests were carried out to check whether measurements were different in each forest canopy cover category within individual receivers, between receivers placed within the same chip truck and between receivers placed within separate chip trucks.

Table 4.3. Mean Measurement Distances (MMD) and Standard Deviations (SD)by forest canopy cover for GPS receivers Sets (Units are meters).

	GPS-Set 1								GPS-Set 2									
Operation No. 1	GPS-1		GPS-2		GPS-3		Total		GPS-4		GPS-5		GPS-6		Total		Overall	
Cover	MMD	SD	MMD	SD	MMD	SD	MMD	SD	MMD	SD	MMD	SD	MMD	SD	MMD	SD	MMD	SD
Mature	11.8	20.9	8.8	13.1	9.6	14.5	10.0	16.5	1.3	2.5	1.5	3.2	1.4	3.0	1.4	2.9	5.9	12.8
Mature/Open	6.1	10.3	3.4	5.0	4.4	7.4	4.6	7.9	0.7	1.9	0.7	1.7	0.7	1.7	0.7	1.8	2.7	6.1
Young	11.5	20.3	6.4	13.2	6.2	11.0	8.1	15.5	1.3	2.5	1.2	2.5	0.4	1.1	0.9	2.2	4.6	11.7
Young/Open	6.4	12.2	3.4	5.5	3.5	5.6	4.4	8.5	1.7	2.3	0.9	1.7	0.8	1.7	1.1	2.0	2.8	6.4
Open	6.4	13.2	2.8	5.2	2.6	4.5	3.9	8.8	0.9	1.8	0.7	1.7	0.4	1.2	0.7	1.6	2.3	6.5
Grand Total	9.4	17.8	6.0	10.9	6.5	11.4	7.3	13.8	1.2	2.3	1.1	2.6	0.9	2.2	1.1	2.4	4.2	10.5
Operation No. 2																		
Mature	15.0	21.0	16.0	18.9	11.9	18.8	14.3	19.7	2.7	4.8	1.9	3.2	1.4	2.3	2.0	3.6	8.1	15.3
Mature/Open	4.2	8.5	2.3	5.9	0.8	1.6	2.5	6.2	0.5	1.0	2.2	3.3	0.7	1.4	1.1	2.3	1.8	4.7
Young	2.0	3.2	1.3	2.2	3.4	5.0	2.3	3.7	1.2	1.6	1.2	1.5	0.7	1.3	1.0	1.5	1.7	3.0
Young/Open	1.7	2.9	1.4	3.9	1.3	3.1	1.5	3.3	0.3	0.9	1.3	2.4	0.5	1.2	0.7	1.7	1.1	2.7
Open	1.3	3.3	1.2	3.4	0.7	2.0	1.1	3.0	0.3	0.8	1.0	2.3	0.3	1.1	0.5	1.6	0.8	2.4
Grand Total	5.5	13.1	5.5	12.4	4.0	11.4	5.0	12.3	1.0	2.9	1.5	2.8	0.7	1.7	1.1	2.5	3.0	9.1
Operation No. 3																		
Mature	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mature/Open	1.3	1.7	1.7	2.6	1.2	2.2	1.4	2.2	0.8	1.4	2.7	3.1	1.8	2.3	1.8	2.5	1.6	2.3
Young	0.6	1.8	0.5	1.4	0.8	1.9	0.6	1.7	0.2	0.7	0.6	1.3	0.2	0.6	0.3	0.9	0.5	1.4
Young/Open	1.0	2.7	1.1	2.0	0.9	2.3	1.0	2.4	0.6	2.2	1.1	3.9	0.5	1.6	0.7	2.8	0.9	2.6
Open	0.4	1.2	0.6	1.4	0.3	1.1	0.5	1.3	0.3	0.9	0.5	1.4	0.2	0.8	0.3	1.1	0.4	1.2
Grand Total	0.6	1.9	0.8	1.7	0.6	1.7	0.7	1.8	0.4	1.4	0.8	2.5	0.4	1.2	0.5	1.8	0.6	1.8





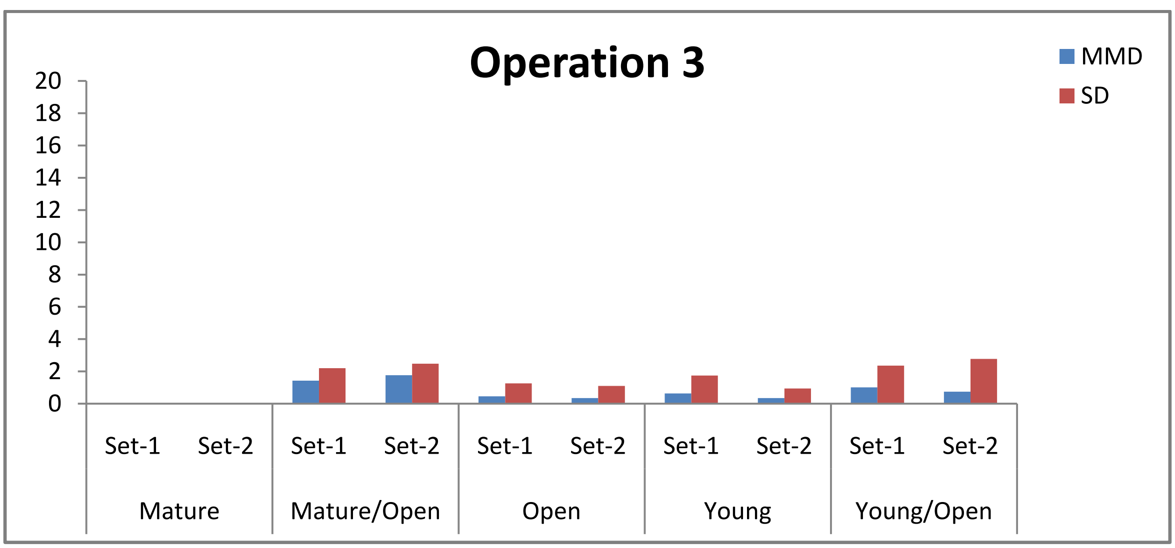


Figure 4.4. Mean Measurement Distance (MMD) and Standard Deviation (SD) by forest cover category for GPS receiver sets (units are meters).

All Krukal Wallis statistical test results gave very high values (> 5) of the test statistic, H, corresponding to significantly small P values (< 0.0001) indicating very high variance in the measurements from all the receivers. The low P values indicated that there were statistically significant differences between grouped GPS receiver measurements as well as between individual receivers that were within the same set of receivers placed in the same chip van. The low P values also infer that forest cover type, road type (paved or unpaved) and speed have a statistically significant effect on the GPS receiver measurement accuracy. Further research might consider more precisely quantifying the effect of truck speed and forest road environmental conditions on the MMD. These subsequent efforts might help increase understanding of the limitations of GPS receiver performance when applied in moving vehicles operating within different forest conditions.

Conclusion

We examined the accuracy and reliability of consumer-grade GPS receivers used for vehicle tracking on forest roads under varying forest canopy within mountainous terrain. The accuracies we measured varied depending on cover type and among receiver sets. The least desirable accuracies were found in mature forest cover conditions with average mean measurements distances reaching a maximum of 14.3 m for one of the sets of GPS receivers that we tested. The best average accuracy in mature forest cover was 5.9 m for a different receiver set. Accuracies were generally improved, and in some cases considerably improved, in areas that featured less forest canopy. We found that the consumer-grade GPS measurements we determined are acceptable for tracking and improving biomass transport from forest supply locations to distribution and processing centers. This range of accuracies that we found for vehicles operating within mature cover types is probably acceptable for many forest transportation monitoring and planning applications, including the mapping of forest road locations and other forest transportation operations. Forest operations where positional accuracy requirements are greater than those that resulted from the GPS receivers that we examined may want to consider alternative receivers or approaches to vehicle movement measurements.

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CHAPTER 5. SUMMARY AND CONCLUSIONS

This dissertation has presented two manuscripts from two studies aimed at improving biomass transportation planning decisions and potentially reducing biomass transportation costs. The high costs involved in the transportation of wood and biomass resources from landing and other collection locations to processing and distribution sites provided a basis for this dissertation as they have been identified as a major contributing factor to the delivered costs. The two studies were developed from data collected using GPS technology to track and monitor chip vans that were exclusively used for transporting chipped (ground) biomass from forest operation sites in western Oregon. Chip vans have been identified to be the most cost-efficient mode of transporting biomass chips provided the roads are suitable for the trucks carrying the vans which are generally built for highway use.

The ability of GPS receivers to record information such as location (longitude, latitude and elevation), movement (speed, heading) and travel times, made them very attractive for data collection to develop a chip van travel time prediction simulation model. The accuracy and performance of GPS under different forest conditions have been investigated in several studies but the reliability of GPS receiver measurements for moving vehicles under forest canopy and in mountainous terrain has not been examined. The first study in chapter 4 presents a travel time prediction simulation model (CHIP-VAN) that predicts the travel time of chip vans on forest roads and chapter 5 presents the second study that examines the accuracy and reliability of GPS for vehicle tracking under different forest canopy conditions and mountainous terrain.

The model, CHIP-VAN, is developed based on the maximum limiting speeds on each road segment as limited by road grade, stopping sight distance (SSD) and road alignment as well as modeling the driver's behaviors as these road conditions change. A two pass simulation was built in the model; a CHIP-VAN First Pass Simulation that calculates the maximum limit speeds on each road segment and a CHIP-VAN Second Pass Simulation that simulates the driver's behavior and calculates the travel time. To emulate the driver's behaviors four cases that determine whether a driver will accelerate, decelerate or continue at their current speed, were developed. Acceleration and deceleration rates were also determined using a least squares algorithm developed to minimize the deviations and give the best fit between the predicted time and the observed travel time for different combinations of acceleration and deceleration rates.

The model has been tested for validation using the data collected for the study. The tests carried out on the model indicate minor differences between the predicted time and the observed time with most of them reporting errors less than 0.1(10%). These suggest that the model is valid for predicting travel time of the chip vans on single lane forest roads with acceptable accuracy. The model tests were carried out on data from forest roads not longer than 6.5 miles. However, the model is designed so that chip vans travel time can be predicted even for very long forest road distances. It is, therefore, recommended that further validation is carried out on other forest roads with longer distances.

The findings in the second study demonstrate that the potential GPS tracking accuracy of vehicles on forested roads are clearly influenced by the composition of the surrounding canopy, with the strongest influence being from heavy forest canopy cover. Accuracies were generally improved, and in some cases considerably improved, in areas that featured less forest canopy. The study concludes that the consumer-grade GPS receiver measurements determined are acceptable for tracking and improving biomass transport from forest supply locations to distribution and processing centers. The analysis of the range of accuracies found for vehicles operating within heavy forest canopy cover indicated that the accuracies are probably acceptable for many forest transportation monitoring and planning applications, including the mapping of forest road locations and other forest transportation operations. Forest operations where positional accuracy requirements are greater than those that resulted from the GPS receivers examined may want to consider alternative receivers or approaches to vehicle movement measurements.

Due to lack of travel time prediction models for chip vans and limited studies that have documented GPS tracking accuracy of vehicles on forested roads, it is expected that the result of these studies will be used by forest transportation managers in decision making and transportation planning in biomass operations. Most importantly it is hoped that the results of this research will increase transportation management planning efficiency for biomass and lead to improved methods for developing biomass cost assessments. It is also important to note that, although the GPS testing focused on the transportation of biomass from forest supply locations to distribution and processing centers, study results are applicable to any transportation process that involves vehicles operating in steep, forested terrain.

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Appendix A. Derivation of the stopping sight distance approximation formula from Bryne et al (1960) and Jackson (1986).

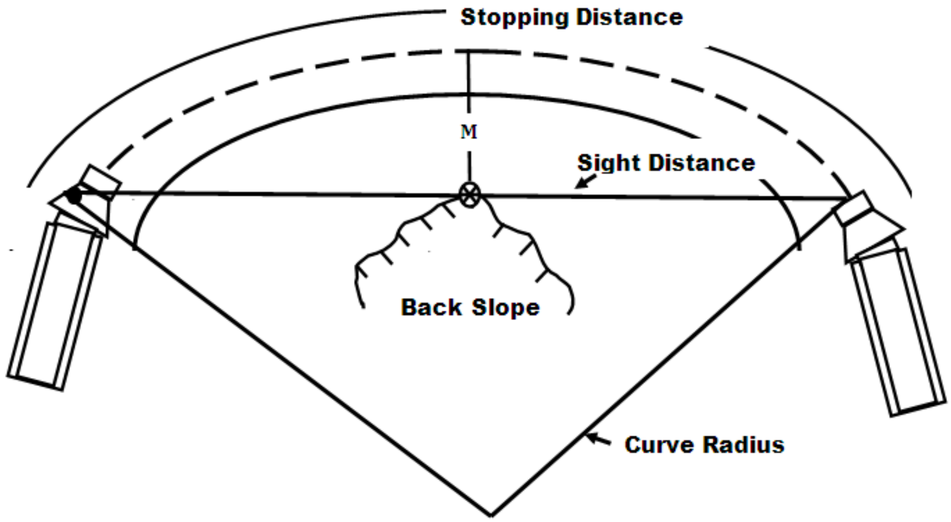

Figure A.1. Overhead view of road showing sight distance and stopping distance.

1. $M = R - (R - M)$

2. $(SD/2)^{\,2} + (R - M)^{\,2} = R^2$

3. $(SSD^2/4) + -2MR + = R^2$

4. $SSD^2 = (4\,R^2 - 4\,R^2 + 8MR - 4M^2)$

5. $SSD = \sqrt{(8MR - 4M^2)}$

If the value of *R* is large compared to *M*, the term $-4M^2$can be dropped with little error.

6. $SSD = \sqrt{(8MR)}$

Also, for large curve radii, the difference between straight-line sight distance and observed stopping distance available on the roadway is small.

$$Sight\ Distance = Stopping\ Distance = \sqrt{(8MR)}$$

This assumption was used by BNG.

Appendix B. Derivation of equation for calculating the Velocity for two vehicles approaching each other on single lane roads

Using sight distance and the resistive forces that a vehicle moving on a level ground road has to overcome, the formula for calculating velocity for two vehicles approaching each other can be derived. The total forces required for the vehicle to move is the sum of the all the resistive forces which include forces required to overcome rolling resistance, friction and air resistance. Assuming the vehicle moves at speeds were air resistance is negligible, the formula can be derived from the following variables.

$F =$	Force required for truck to move, lb
$m =$	Mass of the vehicle, lb/ft/sec^2
$a =$	Acceleration or deceleration rate, ft/sec^2
$W =$	Weight of the truck, lb
$\gamma =$	Equivalent mass factor for energy in rotating parts
$g =$	Standard gravity (nominal acceleration due to gravity, 32.174 ft/sec^2).
$N =$	Normal force at the drivers, lb
$\mu =$	Coefficient of traction, lb/lb of normal force
$f =$	Coefficient of rolling resistance
$V_0 =$	Initial Velocity, ft/sec
$S =$	Distance covered by vehicle, ft
$SD =$	Sight Distance, ft
$t =$	Reaction time, sec
$\theta =$	Slope Angle, deg

From these variables the following equations are available

1. $$F = \gamma m a$$

2. $$m = \frac{W}{g}$$

3. $$a = \frac{\mu N + fN}{\gamma m} \quad but \qquad N = W \quad \text{if } \theta = 0$$

$$therefore;\ a = \frac{\mu W + fW}{\gamma \frac{W}{g}} \qquad = \frac{(\mu + f)g}{\gamma} \quad but\ \gamma\ \approx 1 \text{ in high gear}$$

4. $$S = V_0 t + \frac{at^2}{2}$$

We can now derive the formula. For two vehicles approaching each other at V_0

5. $$\text{SD} = 2S = 2[V_0 t + \frac{at^2}{2}] = 2V_0 t + at^2$$

$$Note: \quad t = \frac{V_0}{a}$$

Therefore if we want to stop

6. $$\text{SD} = 2V_0 t + a(\frac{V_0}{a})^2 = 2V_0 t + \frac{{V_0}^2}{(\mu + f)}$$

If V_0 is in ft/sec and we want in miles per hour (mph); using 1.47, the conversion factor from mph to ft/sec, the equation becomes.

7. $$\text{SD} = (2)(1.47)V_0 t + \frac{(1.47){V_0}^2}{(\mu + f)32.174}$$

$$= (2.94)\ V_0 t + \frac{(0.067){V_0}^2}{(\mu + f)}$$

Assuming μ = 0.4 and f = 0.02 and t = 3 seconds, Equation 7 becomes.

$$\text{SD} = (2.94)V_0(3) + \frac{(0.067){V_0}^2}{(0.4 + 0.02)}$$

$$\text{SD} = (8.8){V_0}^2 + (0.168){V_0}^2$$

Solving for V (in miles per hour) gives quadratic Equation 8

8. $$V = \frac{-8.8 \pm \sqrt{8.8^2 - 4(0.168)(-SD)}}{2(0.168)}$$

Simplifying Equation 8 gives Equation 9.

9. $$V \cong -26.4 + 3\sqrt{77.4 + (0.67)\ SD}$$

The above derivation approach is taken from Sessions (2009). A similar approach was also used by Bryne et al. (1960).

Appendix C. Derivation of equation for calculation of the highest non limiting speed a vehicle can accelerate to (V_{min}). The equation is used if Case I (b) applies and is derived from the following Variables.

V_{max} Maximum limiting speed on curve, ft/sec

V_{min} Highest non-limiting speed a vehicle can accelerate to or highest non-limiting speed allowing enough distance to decelerate to limit speed on next curve, ft/sec

V_{in} Initial velocity or final velocity on previous curve, ft/sec

V_{fn} Final velocity or maximum limiting speed(V_{max}) on next curve, ft/sec

S_1 Acceleration distance, ft

S_2 Deceleration distance, ft

S Total curve distance, ft

a_1 Acceleration rate with a positive value, ft/sec^2

a_2 Deceleration rate with a negative value, ft/sec^2

To derive the Equation follow the steps below.

1. $$S = S_1 + S_2$$

2. $$S_1 = \frac{V_{max}^2 - V_{in}^2}{2a_1} \quad \text{and} \quad S_2 = \frac{V_{fn}^2 - V_{max}^2}{2a_1}$$

3. $$S = \frac{V_{min}^2 - V_{in}^2}{2a_1} + \frac{V_{fn}^2 - V_{min}^2}{2a_2}$$

Solving Equation 3 for V_{min},

4. $$S = \frac{a_2 V_{min}^2 - a_2 V_{in}^2 + a_1 V_{fn}^2 - a_1 V_{min}^2}{2a_1 a_2}$$

5. $$S = \frac{V_{min}^2 (a_2 - a_2) - a_2 V_{in}^2 + a_1 V_{fn}^2}{2a_1 a_2}$$

6. $$S2a_1a_2 = V_{min}^2\,(a_2 - a_2) - a_2V_{in}^2 \quad + a_1V_{fn}^2$$

7. $$V_{min}^2\,(a_2 - a_2) \;= S2a_1a_2 + a_2V_{in}^2 \quad - a_1V_{fn}^2$$

8. $$V_{min}^2 \;=\; \frac{S2a_1a_2 + a_2V_{in}^2 \quad - a_1V_{fn}^2}{(a_2 - a_1)}$$

Finally get Equation 9.

9. $$V_{min} \;=\; \sqrt{\frac{(2Sa_1a_2\,) + (\,a_2\;V_{in}^2\,) - (a_1V_{fn}^2\,)}{(a_1 - a_2)}}$$

Appendix D. Determination of the percentage increase in BNG predicted travel times for unloaded chip vans from stoppages on turnouts and BNG empirical equation for determining vehicle speeds on favorable grades.

Percentage increase of BNG predicted travel times

BNG assumes that the delay time or lost time on a turnout is equivalent to. the time required for the loaded truck to approach and pass the unloaded truck; the reaction time for the driver of the unloaded truck to start his vehicle after the loaded truck passes and the time for the unloaded truck to accelerate to normal speed less the time it would take to cover the same distance at normal speed. The main variables considered in determining the lost time are the traffic density and turnout spacing.

Traffic Density.

The traffic density was determined as follows: approximately 10 loads per day were hauled from 4 am to 2 pm and at least 3 dump trucks and 2 pick up truck were used on the road daily.

Therefore,

$$\text{Chip van density per hour} = \frac{10 \text{ loads} \times 2}{10 \text{ hours}} = \underline{2 \text{ chip vans / hour}}$$

$$\text{Dump truck and Pick up density per hour} = \frac{5 \text{ Vehicles}}{10 \text{ loads}} = \underline{0.5 \text{ vehicles/ hour}}$$

0.5 vehicles per hour was rounded off to <u>1 vehicle/ hour</u>

<u>Total Vehicle per hour = 3 vehicles/ hour</u>

Turnout Spacing.

A turnout spacing of 500 feet was assumed based on observations from the field.

BNG uses a round-trip travel time multiplier to adjust for the increase in round trip time due to the empty vehicle stopping in turnouts during the empty travel segment of the round trip. For example, using the above traffic level and turnout spacing, the percentage increase in the predicted round trip travel times was determined from a table (Byrne et al. 1960, page 33) showing the percent increase in travel time, by turnout spacing and traffic density of 5, 10, 15 and 20 vehicles per hour.

According to BNG, for 500-foot turnout Spacing.

5 vehicles/hour = 2.6% increase in round trip travel time

In our case we have 3 vehicles per hour. Therefore, the estimated increase in round trip time is taken as a proportion of the 5 vehicle increase:

$$3 \text{ vehicles/hour} = \frac{3 \text{ vehicles/ hour x } 2.6\%}{5 \text{ vehicles/ hour}} = \underline{1.6\% \text{ increase per round trip.}}$$

Since this study keeps travel time for loaded and unloaded trucks separately, we must adjust the BNG turnout delay multiplier to apply only to the empty segment in order to do our travel time comparison. Based on observation from data collected from the study, an assumption was made that loaded and unloaded chip vans traveled at approximately the same speed. Therefore, if the 1.6% increase was to be applied to the round trip time (loaded plus unloaded), it meant that the unloaded chip van predicted travel times would increase by twice the round trip percentage increase. Therefore a 3.2% increase was determined and applied to determine the BNG predicted travel times for unloaded chip vans.

BNG empirical equation for vehicle speeds on favorable grades.

According to BNG, the speed at which a vehicle can safely descend a grade is dependent upon.

a) Steepness of grade
b) Ratio of brake capacity to gross load

c) Sight distance

d) Roughness of road surface

e) Height of center of gravity with relation to with between outside tires

f) Personal element of the driver

BNG justifies the derivation of an equation for vehicle speeds on favorable grades from empirical data by indicating that an equation that would include all the above listed items and be practical to use would be difficult to find. Instead BNG uses an empirical equation based on field observations:

$$V = \frac{2.4}{(0.03 - G)}$$

Where, V is the velocity in miles per hour and G is the decimal percent of grade. For example, the speed on a -5 percent grade would be 30 miles per hour.

Appendix E. Histograms showing the frequency of Percentage Differences between BNG predicted travel times, CHIP-VAN First and Second Pass Simulation Predicted Travel Times, and Observed Travel Times for loaded and unloaded chip van road trips.

The x-axis represents the percentage differnce and the y- represnets the observation percentage frequency in all the charts.

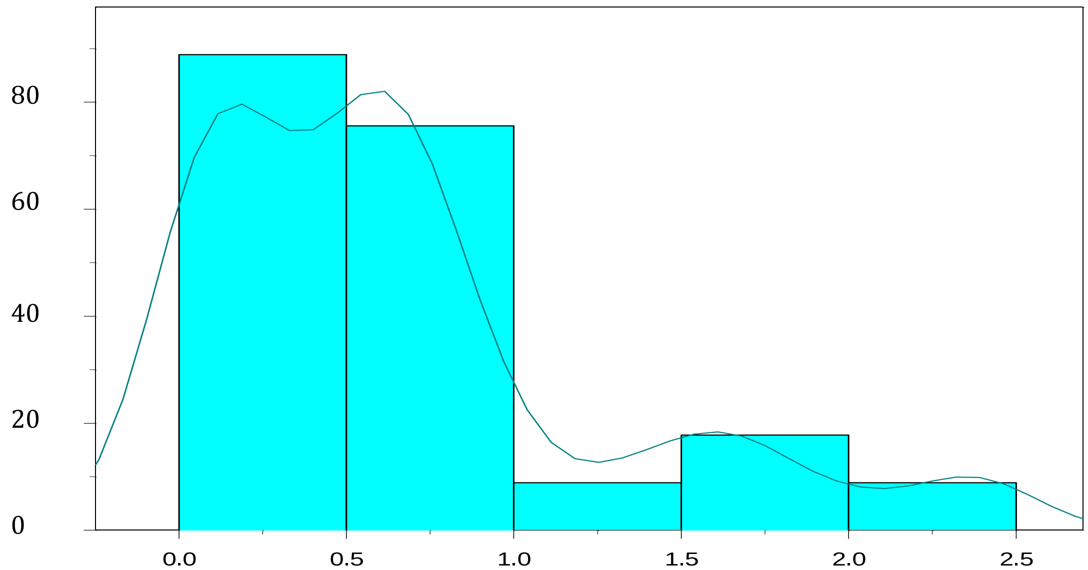

Figure E.1. Unloaded Percentage Difference between BNG and CHIP-VAN First Pass Simulation.

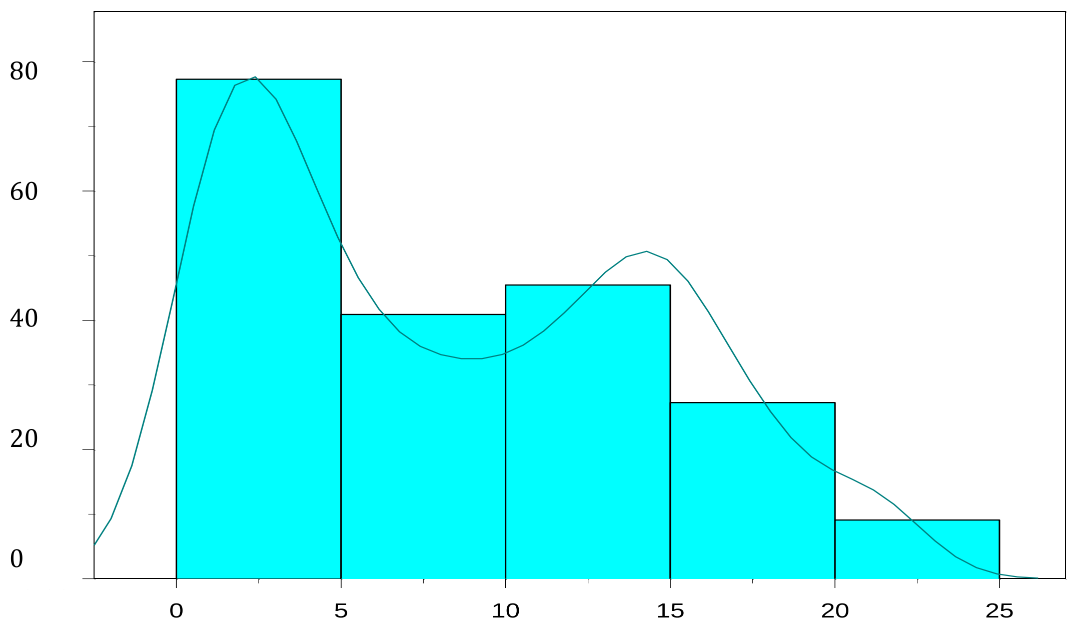

Figure E.2. Loaded Percentage Difference between BNG and CHIP-VAN First Pass Simulation.

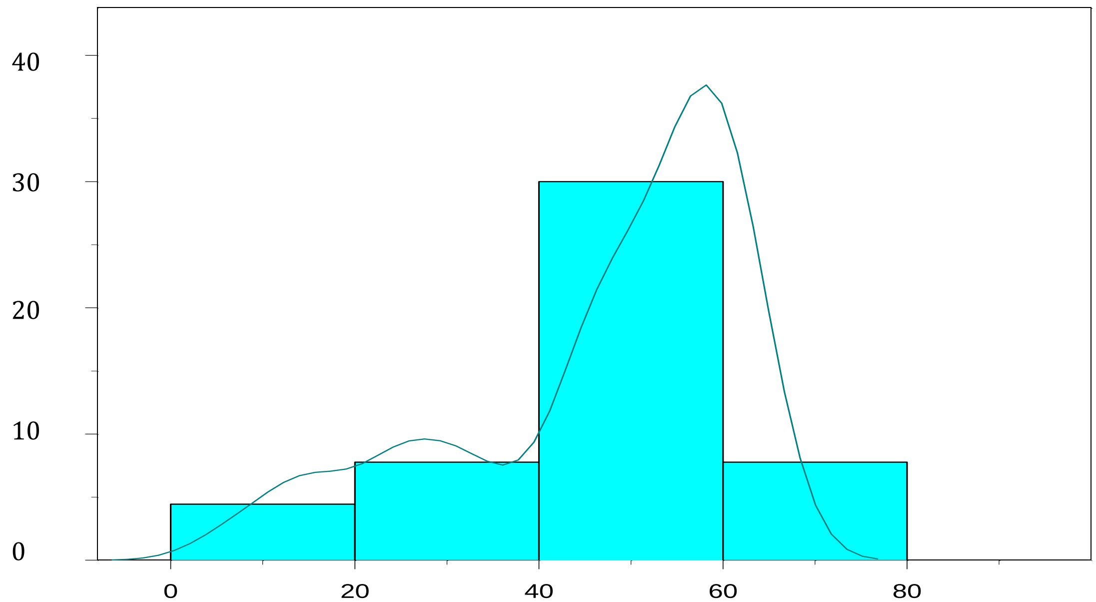

Figure E.3. Unloaded Percentage Difference between BNG and CHIP-VAN Second Pass Simulation.

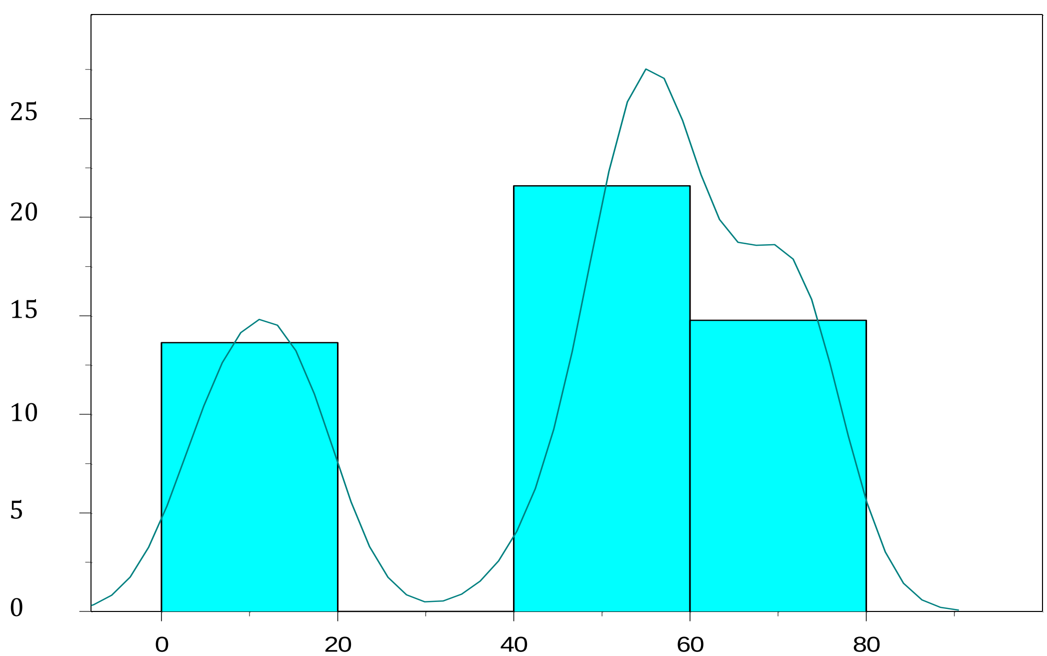

Figure E.4. Loaded Percentage Difference between BNG and CHIP-VAN Second Pass Simulation.

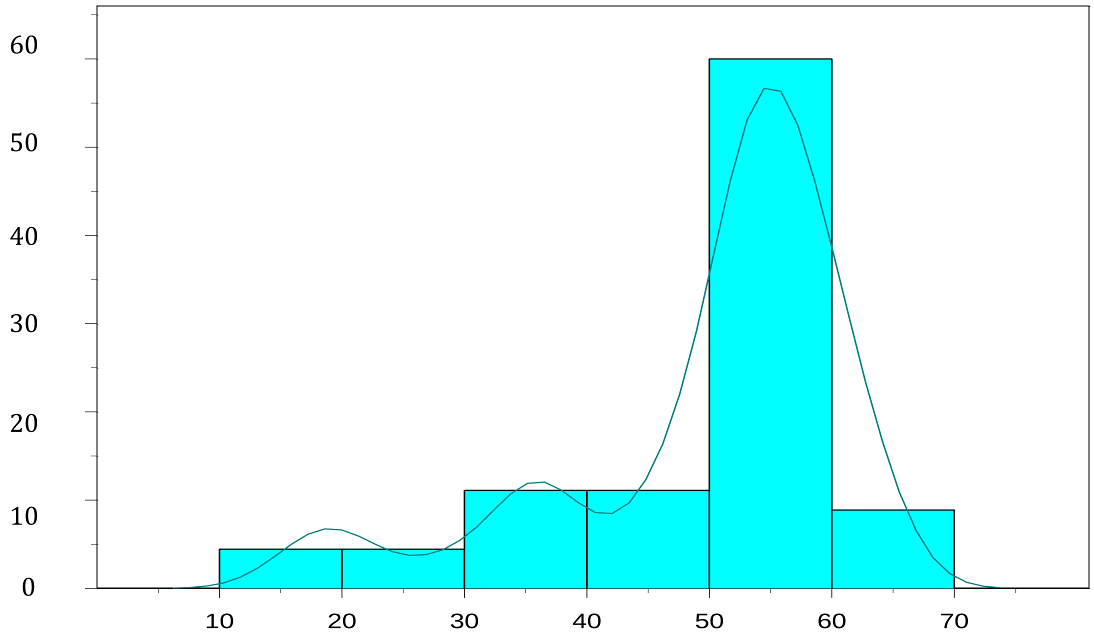

Figure E.5. Unloaded Percentage Difference between BNG and Observed Travel Times.

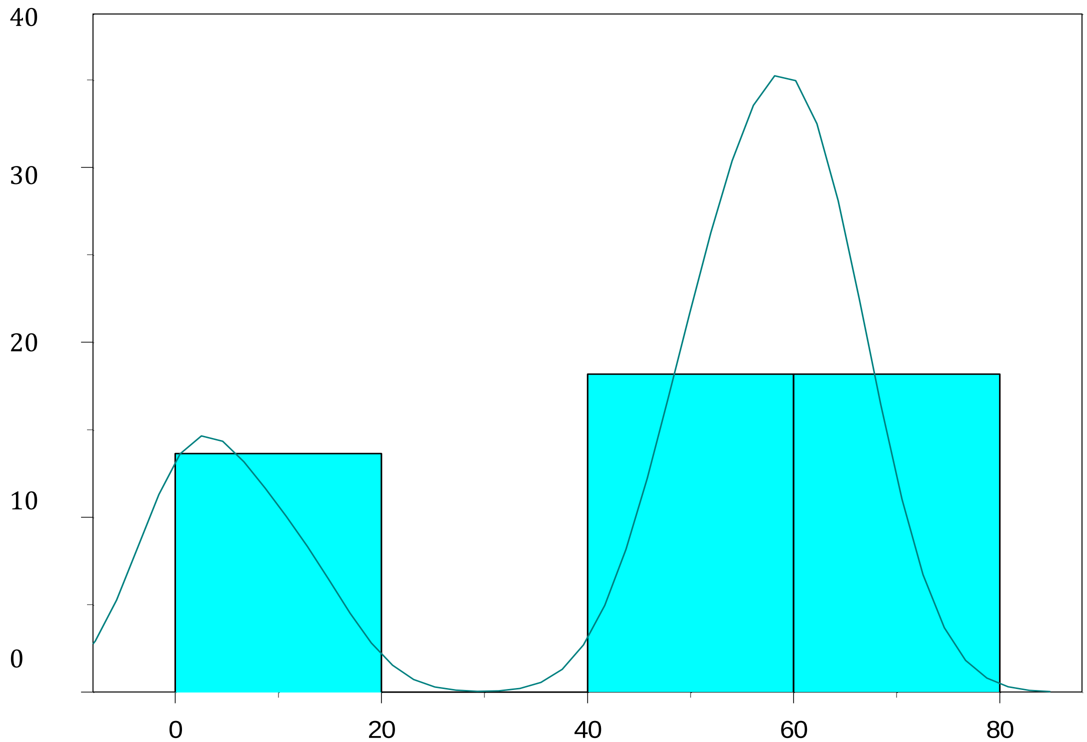

Figure E.6. Unloaded Percentage Difference between BNG and Observed Travel Times.

Appendix F. BNG predicted travel times, CHIP-VAN First and Second Pass Simulation Predicted Travel Times, Observed Travel Times for loaded and unloaded chip van road trips and road alignment classification results.

The CHIP-VAN First Pass Simulation represents the CHIP-VAN model's predicted travel time as the maximum limiting speed on each curve and assumes an instantaneous acceleration and deceleration from one curve to the next. The CHIP-VAN Second Pass Simulation represents the CHIP-VAN model's predicted travel times through a smooth transition of speeds from one curve to the next by accelerating and decelerating based on the maximum limiting speeds from the CHIP-VAN First Pass Simulation. Table F.1 shows the description of the road alignment classification used according to the criteria developed by BNG. The abbreviations for the columns in the Tables F.3 and F.4 showing BNG comparison results are given in Table F.2

Table F.1. Description of Road Alignment Classification Criteria by BNG.

Alignment Classification	Road Alignment Factor [1]
Poor	Less the 20
Fair	20 to 50
Good	50 to 100
Excellent	Over 100

Table F.2. Nomenclature for abbreviations used in table columns (Table F.3 and Table F.4) showing BNG comparison Results.

Abbreviation	Description
BNG	BNG predicted travel times, minutes
FSP	CHIP-VAN First Pass Simulation, minutes
SPS	CHIP-VAN Second Pass Simulation, minutes
OBTT	Observed Travel Times, minutes
ACR	Average Curve Radius, ft
NCPM	Number of Curves Per Mile
AF	Alignment Factor
AC	Alignment Class

[1] Alignment Factor = Average curve radius (feet)/ Number of curves per mile

Table F. 3. Predicted travel times from BNG and CHIP-VAN First and Second Pass Simulations, observed travel times and road alignment classification results for all unloaded chip van road trips.

Trip	Road	BNG	FPS	SPS	OBTT	ACR	NCPM	AF	AC
1	Road 1	21.4	22.5	25.9	25.3	519	7	72	Good
2	Road 1	20.9	22.2	25.7	25.3	493	9	52	Good
3	Road 1	21.8	22.1	26.5	27.3	575	3	184	Excellent
4	Road 1	20.8	22.0	26.1	23.4	503	9	57	Good
5	Road 1	20.9	21.9	24.5	23.0	467	5	136	Excellent
6	Road 1	20.9	22.1	25.9	24.9	502	5	136	Excellent
7	Road 1	20.8	22.0	24.4	25.2	467	3	186	Excellent
8	Road 1	20.4	21.9	23.5	22.7	434	1	496	Excellent
9	Road 1	20.6	22.2	23.7	22.8	540	1	437	Excellent
10	Road 1	20.0	21.5	25.8	23.2	484	1	439	Excellent
11	Road 1	20.3	21.5	24.5	23.1	503	4	160	Excellent
12	Road 1	21.2	22.5	24.1	22.4	579	6	92	Good
13	Road 2	6.1	7.0	9.7	9.9	155	16	25	Fair
14	Road 2	6.2	7.3	9.9	9.6	193	13	36	Fair
15	Road 2	5.9	6.8	8.8	8.8	176	8	60	Good
16	Road 2	8.5	12.7	13.2	12.1	162	5	86	Good
17	Road 2	6.4	7.6	9.1	9.7	171	3	62	Excellent
18	Road 2	6.2	6.7	10.9	10.3	180	15	33	Fair
19	Road 2	6.8	8.2	10.0	11.2	167	12	51	Good
20	Road 2	6.8	7.8	9.1	10.9	164	12	54	Good

Table F. 3 continued

Trip	Road	BNG	FPS	SPS	OBTT	ACR	NCPM	AF	AC
21	Road 2	6.3	7.5	9.1	11.1	138	11	34	Fair
22	Road 2	6.9	7.9	11.1	11.8	140	11	42	Fair
23	Road 2	6.6	8.1	8.7	11.7	173	12	58	Good
24	Road 2	4.8	5.4	6.4	8.0	172	7	65	Good
25	Road 2	4.9	5.2	6.6	7.5	126	10	48	Fair
26	Road 3	8.0	9.0	10.2	8.5	163	4	146	Excellent
27	Road 3	8.5	9.2	10.2	9.0	115	6	95	Good
28	Road 3	6.9	8.4	11.9	10.0	173	5	180	Excellent
29	Road 3	8.0	9.0	10.5	9.5	162	4	167	Excellent
30	Road 3	8.3	9.8	10.7	10.0	201	1	700	Excellent
31	Road 3	9.1	11.0	11.6	10.5	207	8	103	Excellent
32	Road 3	5.8	9.5	10.6	9.3	189	2	425	Excellent
33	Road 3	8.5	9.7	10.0	9.0	160	1	538	Excellent
34	Road 3	8.8	9.0	10.3	9.9	178	1	297	Excellent
35	Road 3	9.0	10.0	9.6	10.2	163	1	191	Excellent
36	Road4	5.1	5.4	6.2	7.5	93	11	35	Fair
37	Road 4	5.0	5.3	6.6	8.0	122	6	63	Good
38	Road4	4.7	5.2	7.4	9.0	136	9	46	Fair
39	Road4	5.0	5.3	5.9	8.5	146	11	52	Good
40	Road4	3.5	4.8	6.1	8.5	120	7	71	Good
41	Road4	4.3	5.0	5.8	9.0	106	6	63	Good
42	Road4	4.7	5.3	7.2	8.5	118	7	65	Good
43	Road4	4.6	5.1	6.1	8.0	92	8	44	Fair
44	Road4	4.5	5.4	7.1	7.0	110	8	60	Good

Table F. 4. Predicted travel times from BNG and CHIP-VAN First and Second Pass Simulations, observed travel times and road alignment classification results for all loaded chip van road trips.

Trip	Road	BNG	FPS	SPS	OBTT	ACR	NCPM	AF	AC
1	Road 1	21.4	22.5	25.9	25.3	519	7	72	Good
2	Road 1	20.9	22.2	25.7	25.3	493	9	52	Good
3	Road 1	21.8	22.1	26.5	27.3	575	3	184	Excellent
4	Road 1	20.8	22.0	26.1	23.4	503	9	57	Good
5	Road 1	20.9	21.9	24.5	23.0	467	5	136	Excellent
6	Road 1	20.9	22.1	25.9	24.9	502	5	136	Excellent
7	Road 1	20.8	22.0	24.4	25.2	467	3	186	Excellent
8	Road 1	20.4	21.9	23.5	22.7	434	1	496	Excellent
9	Road 1	20.6	22.2	23.7	22.8	540	1	437	Excellent
10	Road 1	20.0	21.5	25.8	23.2	484	1	439	Excellent
11	Road 1	20.3	21.5	24.5	23.1	503	4	160	Excellent
12	Road 1	21.2	22.5	24.1	22.4	579	6	92	Good
13	Road 2	6.1	7.0	9.7	9.9	155	16	25	Fair
14	Road 2	6.2	7.3	9.9	9.6	193	13	36	Fair
15	Road 2	5.9	6.8	8.8	8.8	176	8	60	Good
16	Road 2	8.5	12.7	13.2	12.1	162	5	86	Good
17	Road 2	6.4	7.6	9.1	9.7	171	3	62	Excellent
18	Road 2	6.2	6.7	10.9	10.3	180	15	33	Fair
19	Road 2	6.8	8.2	10.0	11.2	167	12	51	Good
20	Road 2	6.8	7.8	9.1	10.9	164	12	54	Good
21	Road 2	6.3	7.5	9.1	11.1	138	11	34	Fair
22	Road 2	6.9	7.9	11.1	11.8	140	11	42	Fair
23	Road 2	6.6	8.1	8.7	11.7	173	12	58	Good
24	Road 2	4.8	5.4	6.4	8.0	172	7	65	Good

Table F. 5 continued

Trip	Road	BNG	FPS	SPS	OBTT	ACR	NCPM	AF	AC
25	Road 2	4.9	5.2	6.6	7.5	126	10	48	Fair
26	Road 3	8.0	9.0	10.2	8.5	163	4	146	Excellent
27	Road 3	8.5	9.2	10.2	9.0	115	6	95	Good
28	Road 3	6.9	8.4	11.9	10.0	173	5	180	Excellent
29	Road 3	8.0	9.0	10.5	9.5	162	4	167	Excellent
30	Road 3	8.3	9.8	10.7	10.0	201	1	700	Excellent
31	Road 3	9.1	11.0	11.6	10.5	207	8	103	Excellent
32	Road 3	5.8	9.5	10.6	9.3	189	2	425	Excellent
33	Road 3	8.5	9.7	10.0	9.0	160	1	538	Excellent
34	Road 3	8.8	9.0	10.3	9.9	178	1	297	Excellent
35	Road 3	9.0	10.0	9.6	10.2	163	1	191	Excellent
36	Road4	5.1	5.4	6.2	7.5	93	11	35	Fair
37	Road 4	5.0	5.3	6.6	8.0	122	6	63	Good
38	Road4	4.7	5.2	7.4	9.0	136	9	46	Fair
39	Road4	5.0	5.3	5.9	8.5	146	11	52	Good
40	Road4	3.5	4.8	6.1	8.5	120	7	71	Good
41	Road4	4.3	5.0	5.8	9.0	106	6	63	Good
42	Road4	4.7	5.3	7.2	8.5	118	7	65	Good
43	Road4	4.6	5.1	6.1	8.0	92	8	44	Fair
44	Road4	4.5	5.4	7.1	7.0	110	8	60	Good

Appendix G. Determination of the Effective Horse Power (EHP) for downhill and uphill movement of chip Vans

To determine EHP to use in the following observed information was used.

Gross Vehicle Weight (GVW) = 70, 000 lbs

Coefficient of Rolling Resistance (k) = 0.02 lb/lb of normal force

Steepest Grade = 15%

Velocity (V) = 18.3 ft / sec

Since,

EHP = Force x Velocity

Force (F) = Grade Resistance (GR) + Rolling Resistance (RR) for going uphill

Force (F) = Grade Resistance (GR) + Rolling Resistance (RR) for going downhill

Slope angle (theta) = Arctangent (grade)

GR = GVW * Sine (theta)

RR = GVW * k * Cosine (theta)

The steps taken were as follows.

1. **Determine Theta, GR and RR**

Theta = Arctangent (15%) = $\underline{8.53^{0}}$

GR = 70,000 * Sine (8.53) = <u>10, 382.90 lbs</u>

RR = 70, 000 * 0.02 * Cosine (8.53) = <u>1384.51lbs</u>

2. **Determine Force uphill and downhill**

Force Uphill = 10, 382.90 lbs + 1384.51lbs = <u>11767.41 lbs</u>

Force Downhill = 10, 382.90 lbs - 1384.51lbs = <u>8998.39 lbs</u>

3. Determine EHP Uphill

$$EHP = \frac{11767.41 \text{ lbs} * 18.3 \text{ ft/sec}}{550 \text{ lb-ft/sec}}$$

Note. $1Hp = \underline{550 \text{ lb-ft/sec}}$

EHP = **392.33 Hp**

4. Determine EHP Downhill

$$EHP = \frac{8998.39 \text{ lbs} * 18.3 \text{ ft/sec}}{550 \text{ lb-ft/sec}}$$

EHP **= 300.01 Hp**

Therefore, 400 HP and 300 HP at the wheels was used for uphill and downhill chip van movement in the model.

Appendix H: Visual Basic Programming Code used to process GPS data points into separate road curves.

This programming code shows the first step used to process GPS data points to determine the road geometry of the roads traversed by the chip vans. The algorithm shown below was developed to separate GPS data points into separate road curves based on the change (difference) between the heading values of one GPS point and the immediate previous point, count and assign a number to each road curve, and indicate the turn direction for that road curve. The programming code was developed using the Visual Basic programming language in Windows Microsoft Excel 2007.

```
''*********************************************************************
                                  '' Start Process
''*********************************************************************

Sub Count_Curves()

Dim Turn(100000)        'Indicates the turning direction at the begining of each curve
Extent = 498            'Extent is the number of points in the data set

n = 1                   '' n = curve counter

Range("P" & (1)).Value = " Curve No"       '' Define the curve number column in work
                                            sheet

Range("Q" & (1)).Value = " Turn Direction" '' Define the turn direct column in work
                                            sheet

''Import heading information from work sheet

For i = 3 To Extent

' H1 is the difference in heading change  at current point
' H2 is the difference in heading at previous point

  H2 = Range("M" & (i)).Value
  H1 = Range("M" & (i - 1)).Value

  curveN = n                              '' Count the first  curve
```

Programming Code used to process GPS points into road curves (Continued)

```
''************************ Start Algorithm*********************************

 If H1 = H2 Then                    'If Heading change is equal to previous Heading change
      curveN = n                         'Count as same curve
      If H1 > 0 And H2 > 0 Then          'If Heading change change is positve
        Turn(i) = "Right"                'Then turn right
     Else
        Turn(i) = "left"                  'Else,then  turn left
     End If
   ElseIf H1 < 0 And H2 >= 0 Then         'If Heading change is Positive or equal to Zero
                                           and previous Heading change is negative
     curveN = n + 1                       'Then Count as different curve
     Turn(i) = "right"                    'and turn right
   ElseIf H1 >= 0 And H2 < 0 Then          'If Heading change is Negative and previous
                                             Heading change is Positive or equal to  Zero
     curveN = n + 1                        'Then Count as different curve
     Turn(i) = "left"                       'and turn left
   ElseIf H1 >= 0 And H2 >= 0 Then        'If Heading change is continuously positive
     curveN = n                             'Count as same curve
     Turn(i) = "right"                       'Then keep turning right

   ElseIf H1 < 0 And H2 < 0 Then         'If Heading change is continuously negative
     curveN = n                           'Count as same curve
     Turn(i) = "left"                    'Then keep turning Left
  ElseIf H1 * H2 < 0 Then          'If Heading change is negative to positive or vise versa
      curveN = n + 1                 'Then Count as different curve
      If H2 >= 0 Then                'If Heading is Positive or equal to Zero
         Turn(i) = "right"           'Then turn right
     Else                          'Else
        Turn(i) = "left"            'Then turn left
      End If
```

Programming Code used to process GPS points into road curves (Continued)

```
 ElseIf H1 = 0 And H2 <> 0 Then        'If Heading change is not equal to Zero and
                                          previous Heading change is equal to  Zero
        curveN = n + 1               'Then Count as different curve
        If  H2 >= 0 Then              'If Heading is Positive or equal to  Zero
           Turn(i) = "right"          'Then turn right
        Else                         'Else
           Turn(i) = "left"           'Then turn left
        End If
  End If

         n = curveN       ' keep  the curve count at each point

  ''*********************** Print Results ******************************
          Range("P" & (i)).Value = curveN        'Export curve number to work sheet
          Range("Q" & (i)).Value = Turn(i)       'Export t turn direction  to work sheet
Next i
End Sub
```

Appendix I: Visual Basic Programming Code for the Travel Time Prediction Simulation Model (CHIP-VAN)

The model, CHIP-VAN, is developed based on the maximum limiting speeds on each road segment as limited by road grade, stopping sight distance (SSD) and road alignment as well as modeling the driver's behavior as these road conditions change. A two pass simulation was built in the model; the first pass simulation that calculates the maximum limiting speeds on each road segment and the second pass simulates the driver's behavior and calculates the travel time. To emulate the driver's behavior, four cases that determine whether a driver will accelerate, decelerate or continue at current speed, were developed. The simulation procedure was implemented through the following programming code developed using the Visual Basic programming language in Windows Microsoft Excel 2007.

1. First Pass Simulation Programming Code

```
Sub First_Pass_Simulation()
'**********************************************************************
                              'Declare Variables
'**********************************************************************

Dim V_Alin_limited(1000)       '' Maximum Velocity limited by Road Alignment ( mph)
Dim V_Grade_limited(1000)      '' Maximum Velocity limited by Road Grade (mph)
Dim V_SD_limited(1000)         '' Maximum Velocity limited by Sight Distance(mph)
Dim Radius(1000)               '' Curve Radius in ft
Dim Arclength(1000)            '' Curve distance on current curve in ft
Dim Arclength2(1000)           '' Curve distance on next curve in ft
Dim T_taken_Alin(1000)         '' Time taken at road alignment limited velocity ( min)
Dim T_taken_Grade(1000)        '' Time taken at road Grade limited velocity ( min)
Dim T_taken_SD(1000)           '' Time taken at road stopping sight distance limited
                               velocity( min)
Dim T_Alin_limited(1000)       '' Time (minutes) per mile at road alignment limited
                               velocity
Dim T_Grade_limited(1000)      '' Time (minutes)per mile  at road Grade limited velocity
```

First Pass Simulation Programming Code (continued)

```
Dim T_SD_limited(1000)        '' Time (minutes) per mile at stopping sight distance
                               limited velocity in
Dim Theta(1000)               '' Slope Angle in degrees
Dim Rr(1000)                  '' Rolling Resistance in lb
Dim Gr(1000)                  '' Grade Resistance  in lb
Dim Force(1000)               '' Sum of Resistive forces in lb
Dim SD(1000)                  '' Sight Distance in ft

'' Name columns in excel sheet where results will be exported.
    Range("F" & (2)).Value = "Alignment limited"
    Range("G" & (2)).Value = " Grade limited"
    Range("H" & (2)).Value = "Sight Distance limited"
    Range("J" & (2)).Value = " Velocity (Mph)"
    Range("K" & (2)).Value = " Time (Mins)"

'*******************************************************************
                 ''Get Input Data from excel Sheet
'*******************************************************************
''Model control parameters
Extent = Range("f" & (3)).Value                  '' Number of of curves in the data set
Hp_Uphill = (Range("f" & (8)).Value * 0.8)       '' Effective horsepower uphill
Hp_Downhill = (Range("f" & (8)).Value * 0.6)     '' Effective horsepower Downhill
GVW_Empty = Range("f" & (9)).Value               '' Gross Vehicle Weight in lb
GVW_Loaded = Range("f" & (10)).Value             '' Empty Vehicle Weight in lb
g = 32.174                                       '' standard gravity in ft/ sec^2
K = 0.02                                 '' Coefficient of Rolling Resistance in lb/lb
RW = Range("f" & (5)).Value                      '' Road width in ft
d = Range("f" & (6)).Value                       '' ditch in ft
sd_ht = 6                  '' Height at which driver sees the other approaching vehicle
M = RW / 2 + d + sd_ht                           '' Middle Ordinate
Max_spd = 25                    '' Set maximum Limit speed on  single lane forest road
```

First Pass Simulation Programming Code (continued)

```
For CurveNo = 3 To Extent
" Import road geometry parameters
     Radius(CurveNo) = Range("B" & (CurveNo)).Value        " Radius of Curve
    Arclength(CurveNo) = Range("C" & (CurveNo)).Value     " Curve distance
    Grade = Range("D" & (CurveNo)).Value                   " Grade on Curve
    Theta(CurveNo) = Atn(Grade)                            " Slope angle

'***********************************************************************
        ''Calculate Maximum Limit Velocity on each Curve and Time Taken
'***********************************************************************

  '' Maximum Road Alignment Limited Velocity and Time

   If  Radius(CurveNo) <> 0 Then

      Spd_Alin_1 = Sqr(0.15 * Radius(CurveNo) * g)              '' speed in  ft/s

      V_Alin_limited(CurveNo) = Spd_Alin_1 * 0.681818182   '' Speed in Mph

      Spd_Alin_2 = V_Alin_limited(CurveNo) / 60          " Speed in miles per minute

      T_Alin_limited(CurveNo) = 1 / Spd_Alin_2           ''Time in minutes per mile

      T_taken_Alin(CurveNo) = Arclength(CurveNo) / (Spd_Alin_1 * 60)  " minutes

   Else

      V_Alin_limited(CurveNo) = 0

      T_Alin_limited(CurveNo) = 0

      T_taken_Alin(CurveNo) = 0

  End If

'' Maximum Road Grade Limited Velocity and Time

 Gr(CurveNo) = GVW * Sin(Theta(CurveNo))                  '' Grade Resistance
 Rr(CurveNo) = K * GVW * Cos(Theta(CurveNo))              '' Rolling  resistance
```

First Pass Simulation Programming Code (continued)

```
If Grade >= 0 Then "( if going up hill)
    Force(CurveNo) = Gr(CurveNo) + Rr(CurveNo)        "Sum of resistive forces uphill
    Spd_grade_1 = (Hp_Uphill / Force(CurveNo)) * 33000        " Velocity in ft/min
    V_Grade_limited(CurveNo) = Spd_grade_1 * 0.0113636364      "Velocity in mph
    Spd_grade_2 = V_Grade_limited(CurveNo) / 60        " Velocity in mph
    T_Grade_limited(CurveNo) = 1 / Spd_grade_2        " Minutes per mile
    T_taken_Grade(CurveNo) = Arclength(CurveNo) / Spd_grade_1   " in minutes

ElseIf Grade < 0 Then       "( if going down hill)
    Force(CurveNo) = Rr(CurveNo) + (Gr(CurveNo))     " Total resistive force down hill
    If Force(CurveNo) < 0 Then        " If force is negative
        Force(CurveNo) = Force(CurveNo) * -1
    ElseIf Force(CurveNo) = 0 Then        " Avoid Division by Zero
        Force(CurveNo) = Force(CurveNo) + 1
    Else        " If force is positive
        Force(CurveNo) = Force(CurveNo)
    End If

    Spd_grade_1 = (Hp_Downhill / Force(CurveNo)) * 33000        " Velocity in ft/min
    V_Grade_limited(CurveNo) = Spd_grade_1 * 0.0113636364        " Velocity in mph
    Spd_grade_2 = V_Grade_limited(CurveNo) / 60        " Velocity in miles/min
    T_Grade_limited(CurveNo) = 1 / Spd_grade_2        " Time in Minutes per mile
    T_taken_Grade(CurveNo) = Arclength(CurveNo) / Spd_grade_1        " in minutes

End If
```

First Pass Simulation Programming Code (continued)

```
" Maximum Stopping Sight Distance Limited Velocity and Time
 If Radius(CurveNo) <> 0 Then                                    ''if radius is not equal to Zero
   R = Radius(CurveNo)                                          " Radius
   SD(CurveNo) = Sqr((8 * R * M) - (4 * M ^ 2))         ''Sight distance in ft
   V_SD_limited(CurveNo) = (-26.4 + 3 * Sqr(77.4 + 0.67 * SD(CurveNo)))  '' in mph
   Spd_SD_1 = V_SD_limited(CurveNo) / 60                  " speed in Miles per min
   T_SD_limited(CurveNo) = 1 / Spd_SD_1                   '' Time in Minutes per mile
   T_taken_SD(CurveNo) = (Arclength(CurveNo) * 0.000189393939) *  _
   T_SD_limited(CurveNo)                                          '' in minutes
 Else
   V_SD_limited(CurveNo) = 0
   T_SD_limited(CurveNo) = 0
   T_taken_SD(CurveNo) = 0
End If

'*******************************************************************
        '' Select the slowest  velocity as the Maximum limit velocity on Curve
'*******************************************************************
        '' If Alignment is limiting then do the following

 If T_Alin_limited(CurveNo) > T_Grade_limited(CurveNo) And _
   T_Alin_limited(CurveNo) > T_SD_limited(CurveNo) And _
   V_Alin_limited(CurveNo) < Max_spd Then

       Speed = V_Alin_limited(CurveNo)             '' speed in Mph
       T = T_Alin_limited(CurveNo)                 " Time in min per mile
       TimeTaken = T_taken_Alin(CurveNo)           " Time in minutes
```

First Pass Simulation Programming Code (continued)

```
    " If Grade is limiting then do the following
 ElseIf T_Grade_limited(CurveNo) > T_Alin_limited(CurveNo) And _
        T_Grade_limited(CurveNo) > T_SD_limited(CurveNo) And _
        (V_SD_limited(CurveNo) <> 0) And (V_SD_limited(CurveNo) <> 0) And _
        V_Grade_limited(CurveNo) < Max_spd Then

             Speed = V_Grade_limited(CurveNo)          " speed in Mph
             T = T_Grade_limited(CurveNo)              " Time in min per mile
             TimeTaken = T_taken_Grade(CurveNo)        " Time in minutes

    '' If Stopping Sight Distance is limiting then do the following

ElseIf T_SD_limited(CurveNo) > T_Alin_limited(CurveNo) And _
        T_SD_limited(CurveNo) > T_Grade_limited(CurveNo) And _
        V_SD_limited(CurveNo) < Max_spd Then

             Speed = V_SD_limited(CurveNo)       '' speed in Mph
             T = T_SD_limited(CurveNo)           " Time in min per mile
             TimeTaken = T_taken_SD(CurveNo)     " Time in minutes

    '' if all speed are greater than the set limit then set to limit speed

  ElseIf V_Alin_limited(CurveNo) > Max_spd And V_Grade_limited(CurveNo) _
        > Max_spd And V_SD_limited(CurveNo) > Max_spd Then

          Speed = Max_spd                                '" in  mph
          T = 1 / (Max_spd / 60)                         '"  Time in mile per minute
          TimeTaken = Arclength(CurveNo) / (Speed * 88)      '" Time in Minutes
```

First Pass Simulation Programming Code (continued)

```
    '' if curve radius is Zero and Grade speed is less than limit
 ElseIf V_Alin_limited(CurveNo) = 0 And V_Grade_limited(CurveNo) _
     < Max_spd And V_SD_limited(CurveNo) = 0 Then

        Speed = V_Grade_limited(CurveNo)          '' Speed in Mph
        T = T_Grade_limited(CurveNo)              '' Time in min per mile
        TimeTaken = T_taken_Grade(CurveNo)        '' Time in minutes

  ''if curve radius is Zero and Grade speed is more than limit then get set limit

 ElseIf V_Alin_limited(CurveNo) = 0 And V_Grade_limited(CurveNo) _
     > Max_spd And V_SD_limited(CurveNo) = 0 Then

        Speed = Max_spd        ''' Miles per hour
        T = 1 / (Max_spd / 60)    '''  mile per minute
        TimeTaken = Arclength(CurveNo) / (Speed * 88)  ''' Time in Minutes
 End If
'***********************************************************************
                  ''Export results to the work sheet
'***********************************************************************
   Range("F" & (CurveNo)).Value = V_Alin_limited(CurveNo)

   Range("G" & (CurveNo)).Value = V_Grade_limited(CurveNo)

   Range("H" & (CurveNo)).Value = V_SD_limited(CurveNo)

   Range("j" & (CurveNo)).Value = Speed            '' Maximum limit velocity on curve

   Range("k" & (CurveNo)).Value = TimeTaken        '' Time taken on Curve

   TimeTMAX = TimeTMAX + TimeTaken

Next CurveNo
Range("p" & (13)).Value = TimeTMAX            '' Total predicted travel time
End Sub
'******************  END FIRST PASS SIMULATION*******************
```

2. Second Pass Simulation Programming Code

```
Sub Second_Pass_Simulation ()
'*******************************************************************
                              Declare Variables
'*******************************************************************

Dim V0 (1000000)            Initial Velocity (Vin)
Dim V1 (1000000)            Maximum Limit velocity on curve or maximum velocity
                            that vehicle can   accelerate to before beginning to
                            decelerate (Vmax or Vmin)
Dim V2 (100000)             Final velocity or maximum limit velocity on the next curve
                            (Vfn)
Dim V3 (100000)             Maximum limit velocity on the second next curve (Vfront)
Dim S (1000000)             Curve Distance
Dim S1 (100000)             Acceleration Distance
 Dim S2 (10000)             Deceleration Distance
Dim Acc (10000)             Acceleration rate
Dim Dec (10000)             Deceleration rate
Dim Dist1 (100000)          Curve distance on current curve
Dim Dist2 (100000)          Curve distance on next curve
Dim Dist3 (100000)          Curve distance on second next curve
Dim Spd (100000)            Speed
Dim T1 (1000000)            Acceleration Time
Dim T2 (1000000)            Deceleration Time
Dim T3 (1000000)            Time taken while vehicle is moving at maximum velocity
Dim TT(1000000)             Total Time Taken on curve (T1+T2+T3)
Dim Dclrtn_Dist (10000)     Deceleration Distance
Dim Aclrtn_Dist (10000)     Acceleration Distance
```

Second Pass Simulation Programming Code (continued)

```
'*************************************************************************
                    '' Get Input Data from excel sheet
*************************************************************************

Extent = (Range("p" & (3)).Value)              '' Number of curves from excel sheet

No_of_Stops = Range("p" & (7)).Value           '' Number of Stops on turnouts for empty
                                                  trucks

 a1 = (Range("p" & (4)).Value)                 '' Acceleration rate

 a2 = (Range("p" & (5)).Value) * -1            '' Deceleration rate

 Spd(1) = 0                                    '' Set Initial speed to zero

V0(2) = Spd(1)


'' Name columns in excel sheet where results will be exported.
  Range("M" & (2)).Value = "Velocity (Mph)"

  Range("N" & (2)).Value = "Time (minutes)"


'' Get velocities and Curve distances from first Pass simulation
For i = 3 To Extent

     V1(i) = (Range("J" & (i)).Value)

    V2(i) = (Range("J" & (i + 1)).Value)

    V3(i) = (Range("J" & (i + 2)).Value)

    Dist1(i) = Range("C" & (i)).Value

    Dist2(i) = Range("C" & (i + 1)).Value

    Dist3(i) = Range("C" & (i + 2)).Value
```

Second Pass Simulation Programming Code (continued)

```
************************************************************************
            '' Apply the four cases modeling the driver's Behavior
************************************************************************

'******************************* Case I *******************************
 (a) Vmax  is greater than Vin and Vfn. with adjustment for Case II ahead

 If  V1(i) > V0(i) And V1(i) > V2(i) And V2(i) > V3(i) Then

     '' look ahead on the next two curves

   Dclrtn_Dist(i) = (V3(i) ^ 2 - V2(i) ^ 2) / (2 * a2)     '' Calculate deceleration distance

   If  Dclrtn_Dist(i) > Dist2(i) Then          '' if deceleration distance > curve distance

   V2(i) = Sqr((V3(i) ^ 2 - (2 * a2 * Dist2(i))))     '' Calculate initial next curve velocity

 End If

 '' Check if maximum speed on curve was reached
        S1(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)              '''Acceleration distance

        S2(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)              '''Deceleration distance

        S(i) = S1(i) + S2(i)                                    '''Total Distance

 ''' compare Acceleration and Deceleration distances with curve distance to check if
maxamum speed was reached.

      If  S(i) > Dist1(i) Then  '' if yes

            '' calculate velocity

          Spd(i) = Sqr((((2 * Dist1(i) * a1 * a2) + (a2 * V0(i) ^ 2) - (a1 * V2(i) ^ 2)) _
          / (a2 - a1)))

         T1(i) = (Spd(i) - V0(i)) / a1          '''Acceleration Time

         T2(i) = (V2(i) - Spd(i)) / a2          '''Deceleration Time

         TT(i) = (T1(i) + T2(i)) / 60           '' Total Time on curve in minutes

         V0(i + 1) = V2(i)              '' Set final velocity as initial velocity for next curve
```

Second Pass Simulation Programming Code (continued)

```
ElseIf S(i) < Dist1(i) Then   '' if not

    Spd(i) = V1(i)

    T1(i) = (Spd(i) - V0(i)) / a1            '''Acceleration Time

    T2(i) = (V2(i) - Spd(i)) / a2            '''Deceleration Time

    T3(i) = (Dist1(i) - S(i)) / Spd(i)       '' Time at maximum velocity

    TT(i) = (T1(i) + T2(i) + T3(i)) / 60     '' Total Time on curve in minutes

    V0(i + 1) = V2(i)            '' Set final velocity as initial velocity for next curve

End If
```

********************************** Case I **********************************

(b)Vmax is greater than Vin and Vfn.) with no need for adjustments for cases ahead

```
ElseIf V1(i) > V0(i) And V1(i) > V2(i) And V2(i) < V3(i) _

Or V1(i) > V0(i) And V1(i) > V2(i) And V2(i) = V3(i) Then


    '' Check if maximum speed on curve was reached

    S1(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)          '''Acceleration distance

    S2(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)          '''Deceleration distance

    S(i) = S1(i) + S2(i)                                '''Total Distance


''' compare Acceleration and Deceleration distances with curve distance to check if
    max speed was reached.

    If  S(i) > Dist1(i) Then  '' if yes

        '' calculate velocity

        Spd(i) = Sqr(((2 * Dist1(i) * a1 * a2) + (a2 * V0(i) ^ 2) - (a1 * V2(i) ^ 2)) / (a2 -
        a1))

        T1(i) = (Spd(i) - V0(i)) / a1        '''Acceleration Time
```

Second Pass Simulation Programming Code (continued)

```
        T2(i) = (V2(i) - Spd(i)) / a2          '''Deceleration Time
        TT(i) = (T1(i) + T2(i)) / 60           '' Total Time on curve in minutes
        V0(i + 1) = V2(i)                      '' Set final velocity as initial velocity for next curve

ElseIf S(i) < Dist1(i) Then   '' if not
          Spd(i) = V1(i)
         T1(i) = (Spd(i) - V0(i)) / a1              '''Acceleration Time
         T2(i) = (V2(i) - Spd(i)) / a2              '''Deceleration Time
         T3(i) = (Dist1(i) - S(i)) / Spd(i)          '' Time at maximum velocity
         TT(i) = (T1(i) + T2(i) + T3(i)) / 60    '' Total Time on curve in minutes
         V0(i + 1) = V2(i)                  '' Set final velocity as initial velocity for next curve
 End If
```

*********************************** Case II **********************************

'' Vin is equal to Vmax but Vmax is greater than Vfn

```
ElseIf V0(i) > V1(i) And V1(i) > V2(i) Or V0(i) = V1(i) And V1(i) > V2(i) Then
    Dclrtn_Dist(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)     ''deceleration distance
    If Dclrtn_Dist(i) > Dist1(i) Then             '' if deceleration distance > curve distance
        Spd(i) = Sqr((V2(i) ^ 2 - (2 * a2 * Dist1(i))))      '' calculate velocity
        TT(i) = (V2(i) - Spd(i)) / a2                        '' Total Time on curve in minutes
        V0(i + 1) = V2(i)                  '' Set final velocity as initial velocity for next curve
```

Second Pass Simulation Programming Code (continued)

```
ElseIf Dclrtn_Dist(i) < Dist1(i) Then
        Spd(i) = V1(i)
        T1(i) = (Dist1(i) - Dclrtn_Dist(i)) / Spd(i)    ''time at constant Speed
        T2(i) = (V2(i) - Spd(i)) / a2                   ''deceleration time
        TT(i) = (T1(i) + T2(i)) / 60                    '' Total Time on curve in minutes
        V0(i + 1) = V2(i)            '' Set final velocity as initial velocity for next curve
End If
```

********************************** Case III ***********************************

Vin is less than Vmax but Vmax is less than Vfn

```
 ElseIf V0(i) < V1(i) And V1(i) < V2(i) Or V0(i) < V1(i) And V1(i) = V2(i) Then
     Aclrtn_Dist(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)     '''Acceleration distance
     If Aclrtn_Dist(i) < Dist1(i) Then          '' if deceleration distance < curve distance
        Spd(i) = V1(i)
        T1(i) = (V1(i) - V0(i)) / a1                    ''time at constant Speed
        T2(i) = (Dist1(i) - Aclrtn_Dist(i)) / Spd(i)    ''deceleration time
        TT(i) = (T1(i) + T2(i)) / 60                    '' Total Time on curve in minutes
        V0(i + 1) = Spd(i)           '' Set final velocity as initial velocity for next curve
    ElseIf Aclrtn_Dist(i) > Dist1(i) Then       '' if deceleration distance < curve distance
         Spd(i) = Sqr((V0(i) ^ 2 + (2 * a1 * Dist1(i))))    '' Actual speed on curve
         TT(i) = ((Spd(i) - V0(i)) / a1) / 60      '' Total Time on Curve = distance / speed
         V0(i + 1) = Spd(i)          '' Set final velocity as initial velocity for next curve
    End If
```

Second Pass Simulation Programming Code (continued)

************************************ Case IV ************************************

Vin is equal to Vmax and Vmax is equal Vfn or Vfn is greater than Vmax

```
 ElseIf V0(i) = V1(i) And V1(i) < V2(i) Or V0(i) = V1(i) And V1(i) = V2(i) Then
        Spd(i) = V1(i)
        TT(i) = (Dist1(i) / V1(i)) / 60        " Total Time on Curve in minutes
        V0(i + 1) = V1(i)              " Set final velocity as initial velocity for next curve
End If

    Range("N" & (i)).Value = TT(i)      '' export total time on each curve to excel
    TimeT = TimeT + TT(i)     '' Calculate total time on entire road section cumulatively
Next i

"  *********************Apply all cases to the last curve *********************

If V0(Extent) < V1(Extent) And V1(Extent) > V2(Extent) Then
        Spd(Extent) = Sqr((((2 * Dist1(Extent) * a1 * a2) + (a2 * V0(Extent) ^ 2) - (a1 *
       V2(Extent) ^  2)) / (a2 - a1)))
       TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60


ElseIf V0(Extent) > V1(Extent) And V1(Extent) < V2(Extent) Then
        Spd(Extent) = Sqr((((2 * Dist1(Extent) * a1 * a2) + (a2 * V0(Extent) ^ 2) - (a1 *
       V2(Extent) ^  2)) / (a2 - a1)))
        TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60


ElseIf V0(Extent) > V1(Extent) And V1(Extent) > V2(Extent) Then
       Spd(Extent) = Sqr((V2(Extent) ^ 2 - (2 * a2 * Dist1(Extent))))
       TT(Extent) = (V2(Extent) - Spd(Extent)) / a2
```

Second Pass Simulation Programming Code (continued)

```
ElseIf  V0(Extent) < V1(Extent) And V1(Extent) < V2(Extent) Or V0(Extent) <
V1(Extent) And      V1(Extent) = V2(Extent) Then
        Spd(Extent) = V1(Extent)
        TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60
End If
      TimeT = TimeT + TT(Extent)       " Calculate total time on entire road section
                                         cumulatively
       TimeT = TimeT + No_of_Stops        " Add empty chip van delay time on turnouts

 'TimeT is the total predicted travel time
End Sub

'********************* END MODEL SIMULATION *********************
```

Appendix J. Visual Basic Programming Code for the Least squares algorithm used to find the minimum sum of squared deviations between the observed travel times and the predicted travel times all possible combinations of acceleration and deceleration rates.

The programming code for the least squares method was implemented through the following steps:

‘***
Declare Variables
‘***

Global V0 (1000000)	*Initial Velocity (Vin)*
Global V1 (1000000)	*Maximum Limit velocity on curve or maximum velocity that vehicle can accelerate to before beginning to decelerate (Vmax or Vmin)*
Global V2 (100000)	*Final velocity or maximum limit velocity on the next curve (Vfn)*
Global V3 (100000)	*Maximum limit velocity on the second next curve (Vfront)*
Global S (1000000)	*Curve Distance*
Global S1 (100000)	*Acceleration Distance*
Global S2 (10000)	*Deceleration Distance*
Global Acc (10000)	*Acceleration rate*
Global Dec (10000)	*Deceleration rate*
Global Dist1 (100000)	*Curve distance on current curve*
Global Dist2 (100000)	*Curve distance on next curve*
Global Dist3 (100000)	*Curve distance on second next curve*
Global Spd (100000)	*Speed*
Global T1 (1000000)	*Acceleration Time*
Global T2 (1000000)	*Deceleration Time*
Global T3 (1000000)	*Time taken while vehicle is moving at maximum velocity*
Global TT(1000000)	*Total Time Taken on curve (T1+T2+T3)*
Global Dclrtn_Dist (10000)	*Deceleration Distance*
Global Aclrtn_Dist (10000)	*Acceleration Distance*
Global All_SumDev (10000)	*Sum of squared deviations*

Least squares algorithm (continued)

```
'****************************************************************************
   Find Minimum sum of squared deviations between the observed travel times and
                  the predicted travel times for each road trip.
'****************************************************************************
 Sub Least_Squares_Algo()

Dim SumDev(100)          Squared deviation between predicted and observed time
Dim TimeT(100)           Time taken on each road trip
Dim Time_Road(100)       Store value for time taken on road trip

'Name columns in excel sheet where results will be exported.

     Range("AA" & (1)).Value = "Predicted Time"

     Range ("AB" & (1)).Value = "Time Deviation"

     Range ("AC" & (1)).Value = "Minimum sum of Deviations"

     Range ("AD" & (1)).Value = "Acceleration Rate"

     Range ("AE" & (1)).Value = "Deceleration Rates"

 Minimum_SumDev = 10 ^ 10          'Large initial minimum sum of Deviations

For Z  =  2  To 100
   For a1 = 1 To 5 Step 0.5                ' Acceleration Rates
     For a2 = 1 To 10 Step 0.5                  ' Deceleration Rates

 'Calculate Squared Deviations for Each Road Trip

'*********************** Road One ****************************************

     Extent = Range("A" & (2)).Value            ' get number of curves on road

  ' Get  all the velocity and distance values for  the current, next and second next curve.

     For i = 2 To Extent

            V1(i) = (Range("C" & (i)).Value)
             V2(i) = (Range("C" & (i + 1)).Value)
             V3(i) = (Range("C" & (i + 2)).Value)
             Dist1(i) = Range("D" & (i)).Value
             Dist2(i) = Range("D" & (i + 1)).Value
             Dist3(i) = Range("D" & (i + 2)).Value
     Next i
```

Least squares algorithm (continued)

```
    Call subcalc(TimeT)                    ' Go to subroutine(subcalc), calculate
                                             total time  (TimeT)  and call it into the
                                             main algorithm.
       TimeT(1) = TimeT                     'Total time (TimeT(1))
       ActualT1 = Range("B" & (2)).Value     ' Get the observed travel time
       SumDev(1) = (ActualT1 - TimeT(1)) ^ 2    'squared deviation on road trip

'*********************** Road Two *************************************
Extent = Range("A" & (3)).Value            ' get number of curves on road

' Get  all the velocity and distance values for  the current, next and second next curve

   For i = 2 To Extent
         V1(i) = (Range("C" & (i)).Value)
         V2(i) = (Range("C" & (i + 1)).Value)
         V3(i) = (Range("C" & (i + 2)).Value)
         Dist1(i) = Range("D" & (i)).Value
         Dist2(i) = Range("D" & (i + 1)).Value
         Dist3(i) = Range("D" & (i + 2)).Value
    Next I
   Call subcalc(TimeT)                      ' Go to subroutine(subcalc), calculate
                                             total time  (TimeT)  and call it into the
                                             main algorithm.
       TimeT(2) = TimeT                     'Total time (TimeT(2))
       ActualT2 = Range("B" & (3)).Value     ' Get the observed travel time
       SumDev(2) = (ActualT2 - TimeT(2)) ^ 2    'squared deviation on road trip

'********************Road Three ***********************************
Extent = Range("A" & (4)).Value            ' get number of curves on road
' Get  all the velocity and distance values for  the current, next and second next curve
    For i = 2 To Extent

         V1(i) = (Range("C" & (i)).Value)
         V2(i) = (Range("C" & (i + 1)).Value)
```

Least squares algorithm (continued)

```
        V3(i) = (Range("C" & (i + 2)).Value)
        Dist1(i) = Range("D" & (i)).Value
        Dist2(i) = Range("D" & (i + 1)).Value
        Dist3(i) = Range("D" & (i + 2)).Value
  Next i
  Call subcalc(TimeT)                   ' Go to subroutine(subcalc), calculate
                                          total time  (TimeT)  and call it into the
                                          main algorithm.
    TimeT(3) = TimeT                    'Total time (TimeT(3))
    ActualT3 = Range("B" & (4)).Value   ' Get the observed travel time
    SumDev(3) = (ActualT3 - TimeT(3)) ^ 2   'squared deviation on road trip

'************************* Road Four ***********************************
Extent = Range("A" & (5)).Value         ' get number of curves on road
 ' Get  all the velocity and distance values for  the current, next and second next curve

  For i = 2 To Extent
       V1(i) = (Range("C" & (i)).Value)
        V2(i) = (Range("C" & (i + 1)).Value)
        V3(i) = (Range("C" & (i + 2)).Value)
        Dist1(i) = Range("D" & (i)).Value
        Dist2(i) = Range("D" & (i + 1)).Value
        Dist3(i) = Range("D" & (i + 2)).Value
  Next i
 Call subcalc(TimeT)                    ' Go to subroutine(subcalc), calculate total
                                          time  (TimeT)  and call it into the main
                                          algorithm.
    TimeT(4) = TimeT              'Total time for road trip on road (TimeT(4))
    ActualT4 = Range("B" & (5)).Value   ' Get the observed travel time
    SumDev(4) = (ActualT4 - TimeT(4)) ^ 2   'squared deviation on road trip
```

Least squares algorithm (continued)

```
'************************ Road Five ***********************************

Extent = Range("A" & (6)).Value              ' get number of curves on road
  'Get  all the velocity and distance values for  the current, next and second next curve

      For i = 2 To Extent
              V1(i) = (Range("C" & (i)).Value)
              V2(i) = (Range("C" & (i + 1)).Value)
              V3(i) = (Range("C" & (i + 2)).Value)
              Dist1(i) = Range("D" & (i)).Value
              Dist2(i) = Range("D" & (i + 1)).Value
              Dist3(i) = Range("D" & (i + 2)).Value
      Next i
      Call subcalc(TimeT)                      ' Go to subroutine(subcalc), calculate
                                                 total time  (TimeT)  and call it into the
                                                 main algorithm.
         TimeT(5) = TimeT                      'Total time for road trip on road (TimeT(5))
         ActualT5 = Range("B" & (6)).Value     ' Get the observed travel time
         SumDev(5) = (ActualT5 - TimeT(5)) ^ 2    'squared deviation on road trip


'************************ Road Six ************************************

Extent = Range("A" & (7)).Value              ' get number of curves on road
' Get  all the velocity and distance values for  the current, next and second next curve

      For i = 2 To Extent
              V1(i) = (Range("C" & (i)).Value)
              V2(i) = (Range("C" & (i + 1)).Value)
              V3(i) = (Range("C" & (i + 2)).Value)
              Dist1(i) = Range("D" & (i)).Value
              Dist2(i) = Range("D" & (i + 1)).Value
              Dist3(i) = Range("D" & (i + 2)).Value
      Next i
```

Least squares algorithm (continued)

```
Call subcalc(TimeT)                         ' Go to subroutine(subcalc), calculate
                                              total time  (TimeT)  and call it into the
                                              main algorithm.
    TimeT(6) = TimeT                        'Total time (TimeT(6))
    ActualT6 = Range("B" & (7)).Value       ' Get the observed travel time
    SumDev(6) = (ActualT6 - TimeT(6)) ^ 2   'squared deviation on road trip

''*************************Road Seven********************************

Extent = Range("A" & (8)).Value             ' get number of curves on road

' Get  all the velocity and distance values for  the current, next and second next curve

    For i = 2 To Extent
        V1(i) = (Range("C" & (i)).Value)
        V2(i) = (Range("C" & (i + 1)).Value)
        V3(i) = (Range("C" & (i + 2)).Value)
        Dist1(i) = Range("D" & (i)).Value
        Dist2(i) = Range("D" & (i + 1)).Value
        Dist3(i) = Range("D" & (i + 2)).Value
    Next i
    Call subcalc(TimeT)                     ' Go to subroutine(subcalc), calculate
                                              total time  (TimeT)  and call it into the
                                              main algorithm.
    TimeT(7) = TimeT                        'Total time (TimeT(7))
    ActualT7 = Range("B" & (8)).Value       ' Get the observed travel time
    SumDev(7) = (ActualT7 - TimeT(7)) ^ 2   'squared deviation on road trip

''************************* Road Eight *****************************

Extent = Range("A" & (9)).Value             ' get number of curves on road

'Get  all the velocity and distance values for  the current, next and second next curve

    For i = 2 To Extent
        V1(i) = (Range("C" & (i)).Value)
        V2(i) = (Range("C" & (i + 1)).Value)
```

Least squares algorithm (continued)

```
            V3(i) = (Range("C" & (i + 2)).Value)
            Dist1(i) = Range("D" & (i)).Value
            Dist2(i) = Range("D" & (i + 1)).Value
            Dist3(i) = Range("D" & (i + 2)).Value
    Next i
   Call subcalc(TimeT)                    ‘ Go to subroutine(subcalc), calculate
                                            total time  (TimeT)  and call it into the
                                            main algorithm.
       TimeT(8) = TimeT                    ‘Total time (TimeT(8))
       ActualT8 = Range("B" & (9)).Value    ‘ Get the observed travel time
       SumDev(8) = (ActualT8 - TimeT(8)) ^ 2      ‘squared deviation on road trip


''************************** Road Nine ********************************
Extent = Range("A" & (10)).Value              ‘ get number of curves on road
‘ Get  all the velocity and distance values for  the current, next and second next curve

    For i = 2 To Extent
           V1(i) = (Range("C" & (i)).Value)
            V2(i) = (Range("C" & (i + 1)).Value)
            V3(i) = (Range("C" & (i + 2)).Value)
            Dist1(i) = Range("D" & (i)).Value
            Dist2(i) = Range("D" & (i + 1)).Value
            Dist3(i) = Range("D" & (i + 2)).Value
    Next i
   Call subcalc(TimeT)                    ‘ Go to subroutine(subcalc), calculate
                                            total time  (TimeT)  and call it into the
                                            main algorithm.
       TimeT(9) = TimeT                    ‘Total time (TimeT(9))
       ActualT9 = Range("B" & (10)).Value    ‘ Get the observed travel time
       SumDev(9) = (ActualT9 - TimeT(9)) ^ 2      ‘squared deviation on road trip
```

Least squares algorithm (continued)

```
''************************Road Ten********************************

Extent = Range("A" & (11)).Value            ' get number of curves on road

' Get  all the velocity and distance values for  the current, next and second next curve

    For i = 2 To Extent
            V1(i) = (Range("C" & (i)).Value)
             V2(i) = (Range("C" & (i + 1)).Value)
             V3(i) = (Range("C" & (i + 2)).Value)
             Dist1(i) = Range("D" & (i)).Value
             Dist2(i) = Range("D" & (i + 1)).Value
             Dist3(i) = Range("D" & (i + 2)).Value
    Next i
   Call subcalc(TimeT)                        ' Go to subroutine(subcalc), calculate
                                                 total time  (TimeT)  and call it into the
                                                 main algorithm.
      TimeT(10) = TimeT                       'Total time (TimeT(10))
      ActualT10 = Range("B" & (11)).Value  ' Get the observed travel time
      SumDev(10) = (ActualT10 - TimeT(10)) ^ 2     'squared deviation on road trip


''************************Road Eleven*****************************

Extent = Range("A" & (12)).Value            ' get number of curves on road

  ' Get  all the velocity and distance values for  the current, next and second next curve.

    For i = 2 To Extent
            V1(i) = (Range("C" & (i)).Value)
             V2(i) = (Range("C" & (i + 1)).Value)
             V3(i) = (Range("C" & (i + 2)).Value)
             Dist1(i) = Range("D" & (i)).Value
             Dist2(i) = Range("D" & (i + 1)).Value
             Dist3(i) = Range("D" & (i + 2)).Value
    Next i
```

Least squares algorithm (continued)

```
    Call subcalc(TimeT)                         ' Go to subroutine(subcalc),
                                                calculate total time  (TimeT)  and call it
                                                into the main algorithm.
      TimeT(11) = TimeT                         'Total time (TimeT(11))
      ActualT11 = Range("B" & (12)).Value          ' Get the observed travel time
      SumDev(11) = (ActualT11 - TimeT(11)) ^ 2      'Squared deviation on road trip
''************************** Road Twelve *****************************
Extent = Range("A" & (13)).Value              ' get number of curves on road
 ' Get  all the velocity and distance values for  the current, next and second next curve.
    For i = 2 To Extent
        V1(i) = (Range("C" & (i)).Value)
         V2(i) = (Range("C" & (i + 1)).Value)
         V3(i) = (Range("C" & (i + 2)).Value)
         Dist1(i) = Range("D" & (i)).Value
         Dist2(i) = Range("D" & (i + 1)).Value
         Dist3(i) = Range("D" & (i + 2)).Value
    Next i
   Call subcalc(TimeT)                          ' Go to subroutine(subcalc), calculate
                                                total time  (TimeT)  and call it into the
                                                main algorithm.
      TimeT(12) = TimeT                         'Total time (TimeT(12))
      ActualT12 = Range("B" & (13)).Value        ' Get the observed travel time
      SumDev12 = (ActualT12 - TimeT(12)) ^ 2      'squared deviation on road trip
'*********************************************************************
                    Find Minimum Squared Deviations
'*********************************************************************
''Sum up all deviations
All_SumDev(Z) = SumDev(1) + SumDev(2) + SumDev(3) + SumDev(4) + SumDev(5)
                + SumDev(6) + SumDev(7) + SumDev(8) + SumDev(9) +
                SumDev(10) + SumDev(11) + SumDev(12)

'''Now!  If current sum of squared deviations is less than the previous ones, set the new
minimum sum of squared deviations to the current one

If All_SumDev(Z) < Minimum_SumDev Then
        Minimum_SumDev = All_SumDev(Z)
```

Least squares algorithm (continued)

```
        ''' Store all values
           Acceleration = Acc(Z)
           Deceleration = Dec(Z)
           For i = 1 To 12
              Time_Road(i) = TimeT(i)
          Next i
```

' Else If previous sum of squared deviations is less than the current one, keep the previous sum of squared deviations

```
ElseIf All_SumDev(Z) > Minimum_SumDev Then
          Minimum_SumDev = Minimum_SumDev
       ''' Store all values
          Acceleration = Acceleration

          Deceleration = Deceleration

           For i = 1 To 12
             Time_Road(i) = Time_Road(i)
          Next i
        End If
```

'' Reset all values to zero to avoid double counting

```
           Erase All_SumDev   SumDev1 = 0

           Erase SumDev

           Erase TimeT

           TimeTT = 0

     Next a2
   Next a1
 Next Z
```

Least squares algorithm (continued)

```
''************************** Print Results ******************************
    ''Export results to excel sheet
    Range("AF" & (2)).Value = Minimum_SumDev
    Range("AG" & (2)).Value = Acceleration
    Range("AH" & (2)).Value = Deceleration
    Range("AG" & (4)).Value = Time_Road(1)
    Range("AG" & (5)).Value = Time_Road(2)
    Range("AG" & (6)).Value = Time_Road(3)
    Range("AG" & (7)).Value = Time_Road(4)
    Range("AG" & (8)).Value = Time_Road(5)
    Range("AG" & (9)).Value = Time_Road(6)
    Range("AG" & (10)).Value = Time_Road(7)
    Range("AG" & (11)).Value = Time_Road(8)
    Range("AG" & (12)).Value = Time_Road(9)
    Range("AG" & (13)).Value = Time_Road(10)
    Range("AG" & (14)).Value = Time_Road(11)
    Range("AG" & (15)).Value = Time_Road(12)
End Sub
'***********************************************************************
          SUB ROUTINE CALCULATING PREDICTED TRAVEL TIME
'***********************************************************************

'The predicted travel time calculated by this subroutine is called into the main algorithm
to find squared deviation from the observed travel time

Sub subcalc (TimeT)
   'Extent = Range("b" & (8)).Value           '' Get the number of curves
   Spd(1) = 0                                     '' Set initial Speed to zero
   V0(2) = Spd(1)
```

Least squares algorithm (continued)

```
' Apply the four cases modeling the driver's Behavior to calculate predicted travel times

'****************************** Case I ******************************
 (a) Vmax  is greater than Vin and Vfn. with adjustment for Case II ahead

 If  V1(i) > V0(i) And V1(i) > V2(i) And V2(i) > V3(i) Then

      '' look ahead on the next two curves

   Dclrtn_Dist(i) = (V3(i) ^ 2 - V2(i) ^ 2) / (2 * a2)     '' Calculate deceleration distance

   If  Dclrtn_Dist(i) > Dist2(i) Then           '' if deceleration distance > curve distance

   V2(i) = Sqr((V3(i) ^ 2 - (2 * a2 * Dist2(i))))     '' Calculate initial next curve velocity

 End If

 '' Check if maximum speed on curve was reached
        S1(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)              '''Acceleration distance

        S2(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)              '''Deceleration distance

        S(i) = S1(i) + S2(i)                                    '''Total Distance

 '' compare Acceleration and Deceleration distances with curve distance to check if
maxamum speed was reached.

       If  S(i) > Dist1(i) Then  '' if yes

                '' calculate velocity

          Spd(i) = Sqr((((2 * Dist1(i) * a1 * a2) + (a2 * V0(i) ^ 2) - (a1 * V2(i) ^ 2)) _
          / (a2 - a1)))

         T1(i) = (Spd(i) - V0(i)) / a1          '''Acceleration Time

         T2(i) = (V2(i) - Spd(i)) / a2          '''Deceleration Time

         TT(i) = (T1(i) + T2(i)) / 60           '' Total Time on curve in minutes

         V0(i + 1) = V2(i)               '' Set final velocity as initial velocity for next curve
```

Least squares algorithm (continued)

```
ElseIf S(i) < Dist1(i) Then   '' if not

    Spd(i) = V1(i)

    T1(i) = (Spd(i) - V0(i)) / a1            '''Acceleration Time

    T2(i) = (V2(i) - Spd(i)) / a2            '''Deceleration Time

    T3(i) = (Dist1(i) - S(i)) / Spd(i)       '' Time at maximum velocity

    TT(i) = (T1(i) + T2(i) + T3(i)) / 60     '' Total Time on curve in minutes

    V0(i + 1) = V2(i)                '' Set final velocity as initial velocity for next curve

End If
```

***************************** ***Case I*** *****************************

(b)Vmax is greater than Vin and Vfn.) with no need for adjustments for cases ahead

```
ElseIf V1(i) > V0(i) And V1(i) > V2(i) And V2(i) < V3(i) _

Or V1(i) > V0(i) And V1(i) > V2(i) And V2(i) = V3(i) Then


    '' Check if maximum speed on curve was reached

    S1(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)        '''Acceleration distance

    S2(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)        '''Deceleration distance

    S(i) = S1(i) + S2(i)                              '''Total Distance


'' compare Acceleration and Deceleration distances with curve distance to check if max
   speed was reached.

    If  S(i) > Dist1(i) Then  '' if yes

        '' calculate velocity

        Spd(i) = Sqr(((2 * Dist1(i) * a1 * a2) + (a2 * V0(i) ^ 2) - (a1 * V2(i) ^ 2)) / (a2 -
        a1))

        T1(i) = (Spd(i) - V0(i)) / a1       '''Acceleration Time
```

Least squares algorithm (continued)

```
    T2(i) = (V2(i) - Spd(i)) / a2          '''Deceleration Time
    TT(i) = (T1(i) + T2(i)) / 60           '' Total Time on curve in minutes
    V0(i + 1) = V2(i)                      '' Set final velocity as initial velocity for next curve

ElseIf S(i) &lt; Dist1(i) Then   '' if not
        Spd(i) = V1(i)
        T1(i) = (Spd(i) - V0(i)) / a1              '''Acceleration Time
        T2(i) = (V2(i) - Spd(i)) / a2              '''Deceleration Time
        T3(i) = (Dist1(i) - S(i)) / Spd(i)         '' Time at maximum velocity
        TT(i) = (T1(i) + T2(i) + T3(i)) / 60   '' Total Time on curve in minutes
        V0(i + 1) = V2(i)                  '' Set final velocity as initial velocity for next curve
    End If

 ****************************** Case II ******************************

'' Vin is equal to Vmax but Vmax is greater than Vfn

ElseIf V0(i) > V1(i) And V1(i) > V2(i) Or V0(i) = V1(i) And V1(i) > V2(i) Then
    Dclrtn_Dist(i) = (V2(i) ^ 2 - V1(i) ^ 2) / (2 * a2)    ''deceleration distance
    If Dclrtn_Dist(i) > Dist1(i) Then           '' if deceleration distance > curve distance
      Spd(i) = Sqr((V2(i) ^ 2 - (2 * a2 * Dist1(i))))      '' calculate velocity
      TT(i) = (V2(i) - Spd(i)) / a2                      '' Total Time on curve in minutes
      V0(i + 1) = V2(i)                  '' Set final velocity as initial velocity for next curve
```

Least squares algorithm (continued)

```
ElseIf Dclrtn_Dist(i) < Dist1(i) Then
        Spd(i) = V1(i)
        T1(i) = (Dist1(i) - Dclrtn_Dist(i)) / Spd(i)    ''time at constant Speed
        T2(i) = (V2(i) - Spd(i)) / a2                   ''deceleration time
        TT(i) = (T1(i) + T2(i)) / 60                    '' Total Time on curve in minutes
        V0(i + 1) = V2(i)            '' Set final velocity as initial velocity for next curve
End If
```

*********************************** Case III ***********************************

Vin is less than Vmax but Vmax is less than Vfn

```
 ElseIf V0(i) < V1(i) And V1(i) < V2(i) Or V0(i) < V1(i) And V1(i) = V2(i) Then
     Aclrtn_Dist(i) = (V1(i) ^ 2 - V0(i) ^ 2) / (2 * a1)     '''Acceleration distance
     If Aclrtn_Dist(i) < Dist1(i) Then          '' if deceleration distance < curve distance
        Spd(i) = V1(i)
        T1(i) = (V1(i) - V0(i)) / a1                     ''time at constant Speed
        T2(i) = (Dist1(i) - Aclrtn_Dist(i)) / Spd(i)     ''deceleration time
        TT(i) = (T1(i) + T2(i)) / 60                   '' Total Time on curve in minutes
        V0(i + 1) = Spd(i)           '' Set final velocity as initial velocity for next curve
    ElseIf Aclrtn_Dist(i) > Dist1(i) Then      '' if deceleration distance < curve distance
         Spd(i) = Sqr((V0(i) ^ 2 + (2 * a1 * Dist1(i))))    '' Actual speed on curve
         TT(i) = ((Spd(i) - V0(i)) / a1) / 60     '' Total Time on Curve = distance / speed
         V0(i + 1) = Spd(i)         '' Set final velocity as initial velocity for next curve
    End If
```

Least squares algorithm (continued)

*********************************** Case IV ***********************************

Vin is equal to Vmax and Vmax is equal Vfn or Vfn is greater than Vmax

```
 ElseIf V0(i) = V1(i) And V1(i) < V2(i) Or V0(i) = V1(i) And V1(i) = V2(i) Then
        Spd(i) = V1(i)
        TT(i) = (Dist1(i) / V1(i)) / 60         " Total Time on Curve in minutes
        V0(i + 1) = V1(i)              " Set final velocity as initial velocity for next curve
End If

     Range("N" & (i)).Value = TT(i)       " export total time on each curve to excel
     TimeT = TimeT + TT(i)      " Calculate total time on entire road section cumulatively
Next i

"  *********************Apply all cases to the last curve *********************

If V0(Extent) < V1(Extent) And V1(Extent) > V2(Extent) Then
        Spd(Extent) = Sqr((((2 * Dist1(Extent) * a1 * a2) + (a2 * V0(Extent) ^ 2) - (a1 *
        V2(Extent) ^  2)) / (a2 - a1)))
        TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60
ElseIf V0(Extent) > V1(Extent) And V1(Extent) < V2(Extent) Then
        Spd(Extent) = Sqr((((2 * Dist1(Extent) * a1 * a2) + (a2 * V0(Extent) ^ 2) - (a1 *
        V2(Extent) ^  2)) / (a2 - a1)))
        TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60
ElseIf V0(Extent) > V1(Extent) And V1(Extent) > V2(Extent) Then
        Spd(Extent) = Sqr((V2(Extent) ^ 2 - (2 * a2 * Dist1(Extent))))
        TT(Extent) = (V2(Extent) - Spd(Extent)) / a2
```

Least squares algorithm (continued)

```
ElseIf  V0(Extent) < V1(Extent) And V1(Extent) < V2(Extent) Or V0(Extent) <
V1(Extent) And      V1(Extent) = V2(Extent) Then
        Spd(Extent) = V1(Extent)
        TT(Extent) = (Dist1(Extent) / Spd(Extent)) / 60
End If

      TimeT = TimeT + TT(Extent)        '' Calculate total time on entire road section
                                           cumulatively
       TimeT = TimeT + No_of_Stops        '' Add empty chip van delay time on turnouts
```

‘TimeT is the total predicted travel time and it is imported by the main algorithm to calculated the squared deviations from the observed travel time

```
End Sub

'****************************** END *****************************
```