Improving Off-Road Vehicle Powertrain Modeling and Simulation Through the Use of a Geographic Information System

Simon Ouellette

A thesis submitted to the Faculty of Graduate and Postdoctoral Studies

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Mechanical Engineering

McGill University

Montreal, Quebec, Canada

Aug 15, 2014

ACKNOWLEDGMENTS

I would like to thank Prof. Peter Radziszewski, who, with his limitless ability at starting new projects, got me to complete this thesis by constantly being able to propose new challenges which led me down this path.

I also must acknowledge all the sources of scholarship funding and project funding which have made this thesis possible:

- NSERC PGS D
- Hydro-Quebec Doctoral Award
- GE Green Sustainability Fund Doctoral Award
- McGill Engineering Doctoral Award
- McGill Provost Doctoral Scholarship
- Canadian Snowmobile Adventures
- Transport Canada
- Defence R&D Canada
- CrossChasm Technologies

Lastly it is important to acknowledge the role of some fellow students / teammates / friends who have made the results of this thesis possible through their work and insight over the years: Olivier Proulx, Jeff Turner, Albert Mathews, Francis De Broux and Suda Martins.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ANL PSAT: Argonne National Lab's Powertrain Systems Analysis Toolkit

Baseline Gen2 PM&S: Second generation powertrain modeling and simulation software without a geographical information system application add-on

CFL: Curve Fit Losses

CWA: Canadian Wilderness Adventures

DEM: Digital Elevation Model

DVL: Dynamometer Vehicle Losses

DOE: U.S. Department of Energy

EPA: U.S. Environmental Protection agency

FTP: Federal Test Procedure

Gen1: First Generation

Gen2: Second Generation

Gen2 PM&S + GIS : Second generation powertrain modeling and simulation software with a geographical information system application add-on

Gen3: Third Generation

GIS: Geographic Information System

HEV: Hybrid Electric Vehicle

HIL: Hardware-in-the-loop

Lat-Long: Latitude-Longitude

LRV: Lunar Rover Vehicle

MAE: Mean Absolute Error

MAPE: Mean Absolute Percent Error

MBD: Model Based Design

OEM: Original Equipment Manufacturer

PM&S: Powertrain Modeling and Simulation

PSAT: Powertrain Systems Analysis Toolkit

TIN: Triangulated Irregular Network

UDDS: Urban Dynamometer Drive Schedule

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The tools available to the off-road vehicle industry for powertrain modeling and simulation (PM&S) are limited compared to those available to the automotive industry. This work looks at means of modifying automotive PM&S software tools to suit the needs of the off-road vehicle industry.

This project defines, tests and validates at full scale, an improved modeling and simulation methodology to accurately predict the power flow between components in an off-road vehicle driven in a complex real life environment.

The approach used is to combine automotive PM&S with a geographic information system (GIS) application to enable variation of parameters defining the vehicle, its environment and their interactions, throughout the simulation.

The results obtained yield significantly more accurate simulations results than simply applying baseline automotive PM&S tools to an off-road vehicle test case using a snowmobile. Improvements show a ~75% reduction error in vehicle speed prediction with a ~90% reduction in standard deviation.

ABRÉGÉ

Les outils disponibles pour modéliser et simuler avec précision des systèmes de traction complexes pour véhicules hors route sont limités. En comparaison, l'industrie automobile peut compter sur une vaste gamme d'outils en ce genre. Le travail présenté dans ce document vise à offrir au domaine des véhicules hors route de meilleurs outils de modélisation et simulation des systèmes de traction en adaptant certains outils du domaine automobile.

Ce projet défini, teste et valide à pleine échelle, une nouvelle approche combinant un système d'information géographique (SIG) avec un outil de simulation automobile traditionnel afin de prédire de façon précise le comportement des différents composants de puissance dans un véhicule hors route.

L'utilisation d'un SIG permet de faire varier différents aspect du véhicule, de son environnement et de la relation entre les deux, tout au long de la simulation.

La fidélité des simulations obtenues avec cette approche s'avère de loin supérieure aux résultats obtenus sans l'utilisation d'un SIG lors des essais hors routes effectués avec une motoneige. Lors des tests effectués, les résultats obtenus avec l'approche SIG ont permis de diminuer la marge d'erreur des prédictions de vitesse du véhicule d'environ 75% et ce avec un écart-type 90% moins élevé qu'avec l'approche utilisant seulement un outil de simulation automobile traditionnel.

CONTRIBUTIONS

The key contribution from this work is the definition and validation of a novel modeling and simulation methodology to accurately predict the power flow between components in an off-road vehicle, driven in a complex real life environment.

The novel methodology combines proven automotive powertrain modeling and simulation tools with the intrinsic capability of GIS applications at relating unrelated information by using location as the key index variable.

This approach required the modification of the baseline vehicle model's chassis component in order to query the geo-referenced information at each simulation time step.

In this project, two unrelated variables (terrain topology and vehicle turning radius) were related via GIS and this information was used to adjust the vehicle model's chassis component at each simulation time step.

The approach and the tools used are generic and hence can be applied to different types of vehicles. It is expected that off-road vehicles would in general benefit the most from this approach of varying the vehicle model at each time step based on information contained in a GIS. Any off-road vehicle that sees its chassis loads vary significantly as a factor of location during normal use can benefit from this approach. However, on-road vehicles could also benefit from the approach, albeit to a lesser scale given that factors affecting their chassis model tend to be more homogeneous. Examples of on-road applications could be a bus with a passenger mass that varies greatly throughout its drive cycle based on the location of the bus stops or a courier truck with a variable load as a function of location.

The validation of this approach was done using a snowmobile as the off-road test vehicle.

In the validation process of this novel approach, other contributions are made with regards to the quantification of the impact of different factors on the force requirement to propel a snowmobile at different speeds.

More specifically, the results obtained confirmed that performing coast down testing while turning yielded sufficiently accurate estimates of the snowmobile chassis's longitudinal power vs speed dissipation to significantly improve simulation results.

It is also demonstrated that the snowmobile's propelling track temperature should be accounted for both in testing and simulation in order to obtain high quality results.

1. Introduction

In the automotive field, powertrain design and control relies more and more on powertrain modeling and simulation (PM&S). This trend should be seen as no surprise since a recent study has shown that a model based design (MBD) approach provides a 39% total cost of design advantage over a non-MBD approach in this field [1].

One MBD approach used in the automotive industry for powertrain design and control is illustrated in its simplest form in Figure 1. This MBD approach is a multi-level iterative approach where PM&S is the common denominator for each design iteration loop.

Figure 1 demonstrates the importance of PM&S in the automotive field by visually showing its location at the root of each step of the MBD approach.

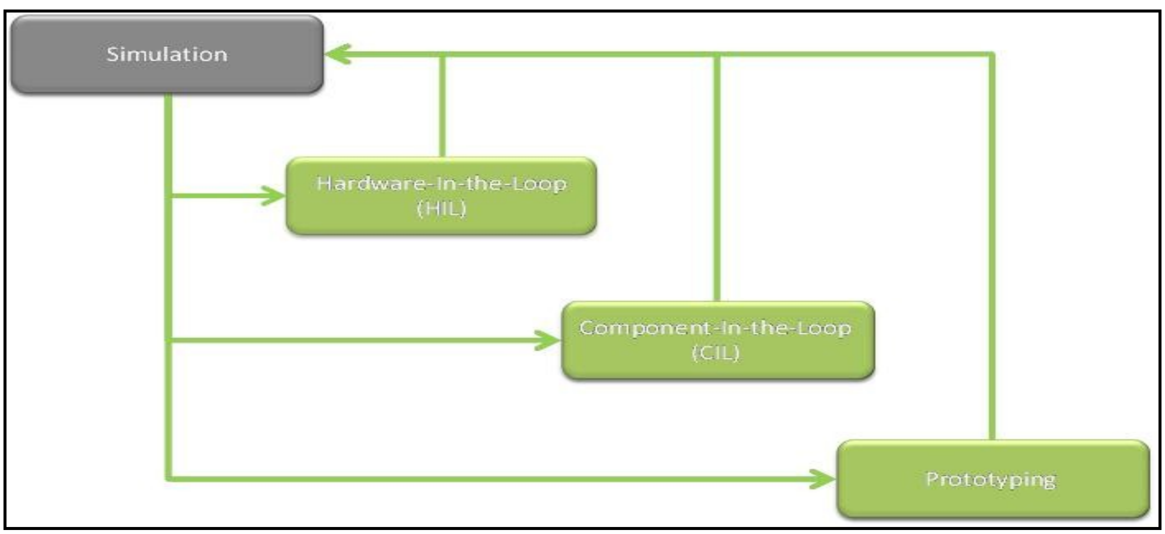

Figure 1: MBD Approach Example Overview

As the Canadian Space Agency spends millions of dollars to turn Canada’s aerospace industry’s main focus toward extraterrestrial rover vehicle design, one can hardly ignore the potential role PM&S might play in this endeavour and in other current and future off-road vehicle designs.

Interestingly, PM&S finds its origin in the quest for the moon. The first documented approach found to have resemblance to today’s PM&S can be traced back to the powertrain design of the Apollo Lunar Rover Vehicle (LRV) [2].

The field of PM&S has undergone tremendous expansion in recent years. Interestingly, while its origin started with an off-road vehicle as the primary case study, the vast majority of the field’s expansion can be attributed to road vehicles. Today a number of simulation platforms exist for PM&S of road vehicles. Many of these platforms have evolved from the automotive sector’s need for simulating standard tests cycles performed in controlled environments.

As the off-road vehicle industry starts to look at new advanced complex powertrains it is expected that it will face powertrain topology/component/system/control design, testing and optimization problems similar to those faced by the automotive industry ever since it started to seriously invest time and resources in advanced complex powertrain topologies.

Given this, one may ask: Should the off-road vehicle industry invest in building new software tools dedicated to its advanced complex powertrain needs or can it leverage existing software developed for the needs of the automotive sector and adapt them to the needs of the off-road vehicle industry?

It is the author's belief that there is merit in modifying well documented and proven automotive PM&S software tools to suit the needs of the off-road vehicle industry when possible. Past work on snowmobiles has shown promising early results down this path. [3,4]

1.1 Goal

The ultimate goal of this project is to define, test and validate at full scale, an improved modeling and simulation methodology to accurately predict the power flow between components in an off-road vehicle driven in a complex real life environment in situations where the vehicle's future speed is not accurately known prior to the simulation (ex: the driver will be requesting maximum "accelerator" input).

1.2 Proposed Approach

The proposed approach to achieve this goal is to improve on the second generation powertrain modeling and simulation (Gen2 PM&S) approach currently used in the automotive sector by using a geographic information system (GIS) to enable variability of parameters defining the vehicle, its environment and their interactions throughout the simulation.

1.2.1 Hypotheses

In order to attain the stated goal using the proposed approach, the following hypotheses must be tested and validated:

1- A significant number of aspects negatively impacting off-road vehicle PM&S result fidelity which are not covered in sufficient detail by Gen2 PM&S software are related to the chassis model, its environment, and the interaction between the two.

2- The different aspects that affect off-road vehicle PM&S result fidelity in Gen2 PM&S software can for the most part be:

   i. catalogued in a GIS application

   ii. synchronized with one another

   iii. and eventually output as lookup tables

3- Gen2 PM&S software can be modified in such a way that it can accept and integrate, in the model and the simulation, spatio-temporally referenced information from a GIS application.

4- Provided hypotheses 1, 2 and 3 are validated, results from a Gen2 PM&S software with GIS add-on (Gen2 PM&S + GIS) should be significantly closer to data obtained in full scale real life trials than simulation results from the same Gen2 PM&S software without GIS add-on (baseline Gen2 PM&S).

1.2.2 Step-by-step approach

Due to the complexity associated with full scale validation of this approach, the route taken to test and validate it was broken up in smaller legs. Each leg attempted to test and validate a portion of the overall approach thus reducing the risks and unknowns prior to devising and implementing tests equipment and experiments to provide full scale validation.

The steps taken are as follows:

1- A literature review is performed (Section 2)

2- The role of the chassis model, its environment and their interactions in PSAT are analyzed (Section 3.1)

3- The effect of grade, environmental conditions, and sinuosity of path on vehicle power usage are analyzed individually. (Sections 3.2, 3.3 and 3.4)

4- A representative real life test scenario is devised and integrated into a GIS application while PSAT, the selected Gen2 PM&S software, is modified to interact with the GIS application's output. (Section 4.1)

5- A vehicle model is created and initialized in both the baseline Gen2 PM&S software and the new Gen2 PM&S + GIS software combination. (Section 4.2)

6- The initial simulation results obtained for the baseline Gen2 PM&S case and the Gen2 PM&S + GIS case are compared to data gathered during real life testing. (Section 5.1)

7- Based on the initial results obtained, attempts are made to further improve the Gen2 PM&S + GIS approach (Section 5.2)

1.3 Measure of success

Success of the proposed methodology is measured by its ability to predict vehicle speed and controller power input as a function of vehicle location along a known path. This is done for a test drive during which a driver mounts on a series hybrid snowmobile prototype[1] at rest and then, promptly, fully engages the accelerator thumb lever of the vehicle. The driver keeps the accelerator thumb lever of the vehicle fully

[1] A series hybrid vehicle uses exclusively an electric motor to propel itself. The electricity used by the motor can come from multiple sources. In this case, the snowmobile prototype used for validation purposes has a battery pack and a generator which uses a spark ignition gasoline burning engine.

engaged throughout the test drive while using the vehicle's steering and his body positioning to keep the snowmobile on a pre-defined course.

2. Background

It has been demonstrated that advanced automotive PM&S software can be used to model and simulate a snowmobile's powertrain behavior for simple test cases by using an empirical methodology to define the vehicle's dissipative loads as a function of speed. [3]

This project builds on this result and looks at extending the use of automotive PM&S software to complex off-road vehicle driving situations and more specifically to the case of a hybrid electric snowmobile driving on a real course on a trail in an open field.

Prior to diving into the core of the subject, an extensive background section is presented since most readers may not be familiar with one or many of the aspects of this multi-disciplinary subject and the various tools which will be used in this project.

The background section provides an introduction and insight on the following aspects:

- PM&S software platforms and justification for the type of platform selected
- Drive cycles and how their use in mandated governmental testing has influenced the Gen2 PM&S tools currently available
- Key differences in backward vs. forward-facing PM&S
- Limitations of baseline Gen2 PM&S
- GIS

2.1 PM&S Software Platforms

Past work done by the author and other group members at McGill on off-road vehicle PM&S used the Argonne National Lab's Powertrain Systems Analysis Toolkit (ANL PSAT) built on the Matlab software platform. Prior to either continuing the work using this platform or investing in a new platform, a general review of the subject was conducted to determine if there was enough value to justify the time and cost investment required to move to a new automotive PM&S platform.

2.1.1 Introduction to PM&S Software Platform Types

In general PM&S software can be divided into three general categories/generations.

1. The first generation (Gen1) of commercially available PM&S software were backward-facing simulation platforms (ex: NREL Advanced Vehicle Simulator – ADVISOR) which met the need of users looking to evaluate, high level design control logic and energy management strategies through an iterative process. In a backward-facing simulation[2], the vehicle drive schedule is equal to the simulated vehicle's speed. Hence the limitations of this approach.

2. The second generation (Gen2) of PM&S software were forward-facing[2] simulation platforms (ex: ANL PSAT, and early versions of AVL's CRUISE

[2] More information on backward vs. forward-facing simulation available in section 2.2

software). These software were developed out of a need for better tools to model vehicle, systems and component behavior in a way that mimics real life flow of information, signals and effort/flow through the system in order to help implement control logic through a model based design approach that can include hardware-in-the-loop (HIL). In a forward-facing simulation, the input drive schedule is the desired simulated vehicle speed, but this speed vs. time trace will not necessarily be achieved by the vehicle. This difference with backward-facing simulation is what makes this approach capable of truly mimicking reality, and hence, usable in HIL tests.

3. The third and latest generation (Gen3) of PM&S software (ex: ANL Autonomie and later versions of AVL Cruise) have kept most of the forward-facing lookup table based simulation approach of the second generation, but now offer more capabilities in terms of replacing the model of different vehicle components by a dynamic simulation more often than not running on an external add-on software.

For example, for an internal combustion engine car simulated using Gen1 PM&S, the software would be able to output various single point information data for different drive cycles.

The same vehicle simulated using Gen 2 PM&S software, would be able to output the real behavior of the vehicle and its components throughout the drive cycle when a driver attempts to follow a certain drive schedule. The components in the Gen2 model such as its engine would be modeled by a set of static look-up tables.

The same vehicle simulated in a Gen3 PM&S software would output the same type of information at the global vehicle level as the Gen2 PM&S; however, it could also provide much more detailed information on the individual component behavior during the test. In the case of the vehicle's engine component model, this would be done by having it modeled and simulated in parallel to the PM&S software in a simulation program dedicated to dynamic engine simulation and capable of mimicking the engine's thermodynamic / mechanical / acoustical / electrical behavior at simulation speeds much higher than those required by the PM&S software (ex: GT-Power, AVL Boost, AVL Cruise M).

.

2.1.2 Selection of PM&S Software Platform Type

The interest in this project is not in having a more in depth analysis of the dynamic behavior of some of the components of hybrid off-road vehicles. The interest of this project is in having a PM&S environment capable of helping designers implement vehicle control algorithms and not just evaluate them. Based on the above a Gen2 or a Gen3 PM&S platform could meet the needs of this project. However, since cost generally goes up significantly as one goes from an early generation PM&S solution to a more recent one, and the added performance aspect of the Gen3 PM&S is not required for this work, it was decided that the platform of choice would be a Gen2 PM&S platform.

2.1.3 Introduction to Gen2 PM&S Platforms and Gen2 PM&S Platform Selection

The following sections provides a more in depth introduction to Gen2 PM&S platforms, and a comparison between PM&S simulation environments potentially suitable for this project.

2.1.3.1 Gen 2 PM&S Platform Selection

A study of twenty-three PM&S software platforms by RICARDO for the International Council on Clean Transportation concluded that the top two platforms in terms of model complexity, capability and accuracy were 3DS Dymola and ANL PSAT. Both of these were also the top two on the overall scale. In close third and fourth position on the overall scale were AMESim and AVL Cruise. One of the report’s main conclusions was that there was only 7% difference in the overall weighted ratings of the “top 6” rated tools [5].

Overall, with ANL PSAT readily available and familiar to the author, a change in PM&S platform was deemed extremely unlikely to have a strong enough positive impact on the project to warrant the time, resources and risk associated with it. Thus it was decided that the development would be concentrated around the ANL PSAT work environment.

According to ANL, PSAT has become widely accepted by industry and has been licensed to more than 130 companies, universities, and research laboratories worldwide. As one of the major tools of the U.S. Department of Energy (DOE), it has been used for numerous studies to assist the DOE in identifying future research directions regarding plug-in hybrid electric vehicles (HEVs) as well as Plug-in HEVs. [6]

2.1.3.2 Gen2 PM&S Common Usages

With the automotive sector being a dominant user of the various PM&S platforms, it is no surprise that these software have an extensive number of common functionalities and features designed to cater to the needs of the vast majority of the users in the automotive sector. One of these common aspects is the capacity of the software to simulate powertrain behaviour as the vehicle is driven through a standard automotive drive schedule test.

One example of such a drive schedule is the U.S. Environmental Protection Agency (EPA) Urban Dynamometer Drive Schedule (UDDS). This test specifies a target speed trace over time that a vehicle must follow and during which standardized information such as fuel consumption is gathered.

Figure 2 illustrates the U.S. EPA UDDS drive schedule [7]. The U.S. EPA UDDS test, as most standard automotive tests, is defined by a desired vehicle speed vs. time schedule.

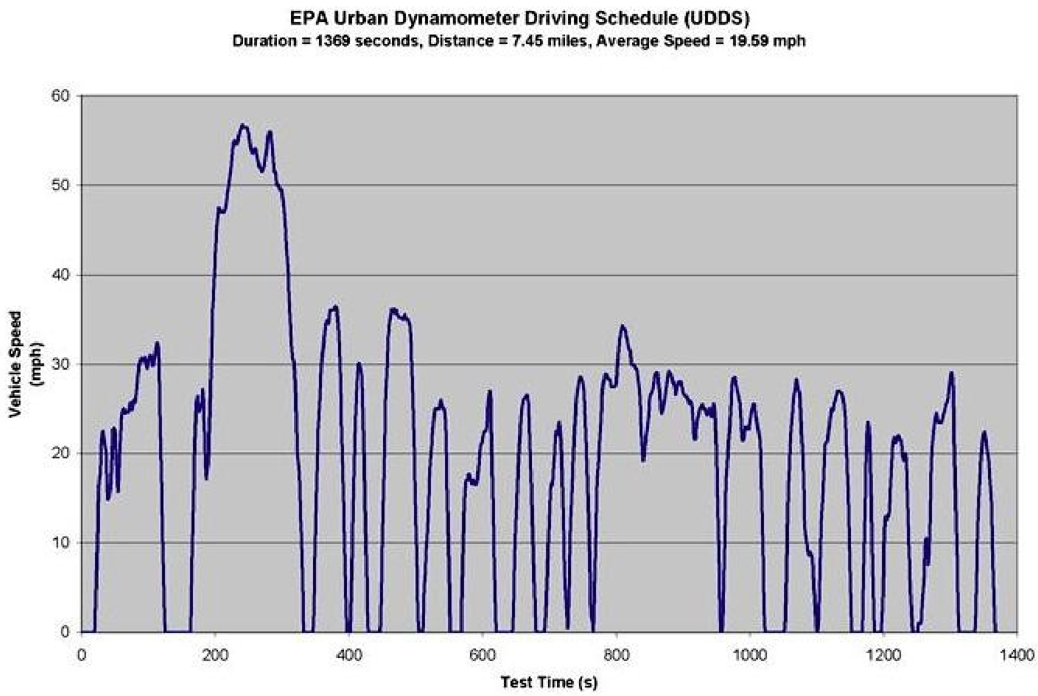

Figure 2: U.S. EPA UDDS Speed vs. Time Trace

Gen2 PM&S is a standard in the automotive world due to its vehicle modeling and simulating capabilities. In Gen2Pm&S, systems and component behavior can mimic real life flow of information, signals and effort/flow through the system for mandated drive cycle tests defined by speed vs. time drive schedules.

Since drive cycles are central to the role of Gen2 PM&S, they will be explored in the case of both the automotive and the off-road industry in the sub-sections below.

2.1.3.2.1 Drive Cycles in the Automotive Industry

The automotive industry is unique in the vehicle world by the amount of standard tests defined by vehicle speed vs. time drive schedules. This characteristic is believed to be due to the large number of stakeholders (governments, OEM, suppliers, researchers, users, etc) in this industry which can benefit from different relevant common bases on which to compare results.

There are factors other than the vehicle's speed which can affect a vehicle's power and energy requirements. However, since almost all cars evolve on similar ground and navigate using a common approach (4 wheel platform with the front 2 wheels doing the steering), speed vs. time remains a common dominant factor of a car's power and energy requirements in general.

The approach of defining drive cycles via a speed vs. time schedule was already in place over 50 years ago and continues to be relevant today. An example of this is, the EPA city fuel economy estimates based on the Federal Test Procedure (FTP), which was designed to measure a vehicle's tailpipe emissions under urban driving conditions. The driving cycle used for the FTP is called the LA – 4. It was developed in the mid-1960's to represent home-to-work commuting in Los Angeles. [8]

The goal of this section is not to dissect automotive drive cycles in details, but simply to illustrate their role in the state of automotive PM&S today.

More information on the different drive cycles in use, ranging from a practical overview to an in depth analysis, can be found from these resources:

- Chapter 9 from :

  Liu, W.; INTRODUCTION TO HYBRID VEHICLE SYSTEM MODELING AND CONTROL, © John Wiley & Sons Inc, 2013, ISBN: 9781118308400

- The brochure titled "WORLDWIDE EMISSIONS STANDARDS PASSENGER CARS & LIGHT DUTY TRUCKS" published by Delphi available via the following link: https://delphi.com/pdf/emissions/Delphi-Passenger-Car-Light-Duty-Truck-Emissions-Brochure-2012-2013.pdf

- AUTOMOTIVE TEST DRIVE CYCLES FOR EMISSION MEASUREMENT AND REAL-WORLD EMISSION LEVELS-A REVIEW, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering July 1, 2002 216: 555-564

- Section "Final Rule for New Test Methods and Label Design for Fuel Economy Window Stickers" from the EPA's Fuel Economy and Environment Labels Regulation web page accessible via the following link: http://www.epa.gov/otaq/carlabel/regulations

The results of automotive drive cycle based test procedures are often a single global value for a given item of interest (ex: average fuel consumption per distance or emissions produced). However, over time, given that cars were measured using a vehicle drive schedule approach by governing authorities, the entire automotive industry has evolved in a direction where the use of speed vs. time drive cycle based testing (virtual and real) has become a common practice. With this approach, the vehicle as a whole is being used as the common baseline for comparison.

Therefore, when the automotive industry started to look at new advanced complex powertrain technologies, the software tools developed for this field were able to build on this common standards based approach of testing using speed vs. time drive schedule and make it possible to perform comparisons and optimization at the vehicle level.

Even though there are multiple factors affecting a passenger car's power flow, speed remains the biggest factor in normal every day driving. Therefore, Gen2 PM&S are extensively optimized around this aspect. The fact that norms and regulations are primarily focused on this aspect also probably plays a large role in this.

For example, the U.S. EPA acknowledges that there are many factors other than speed that affect a vehicle's energy consumption and emissions and it is implementing different means to try and account for them in its tests. However, these new tests remain speed vs. time based and only look at adding the effect of some cold temperature operation and auxiliary load usage. [8]

Other effects such as roadway roughness, road grade (hills), wind, tire pressure, heavier loads, hills, snow/ice, effects of ethanol in gasoline, larger vehicle loads (e.g., trailers, cargo, multiple passengers), and more are believed to account, on average, for ~9 to 13% difference in fuel economy. Hence, the EPA initially proposed to lump their impact all in a single 11% reduction factor applied to the final test results. [8]

In the end the EPA decided to use a 9.5% reduction factor.

Given this, it makes sense that software tools for the automotive sector continue to primarily grow from the need of this industry to test on common and simple, speed vs. time drive schedules with some functionality to take into account temperature effects and auxiliary loads.

2.1.3.2.2 Drive Cycles in the Off-Road Industry

The off-road industry is much more segmented than the automotive industry and it is composed of a plethora of different vehicle types that vary widely in size, shape, technology, power and form. Each off-road vehicle niche tends to be designed to accomplish one or a set of specific tasks, and vehicles in each niche will likely evolve in very different environments. Furthermore, vehicles in a single specific niche are in many cases required to evolve in a constantly changing environment. An extreme case of this would be an amphibious tour vehicle driving on a road at one instant, and them, propelling itself on a river the next instant.

It is believed that the segmentation of the off-road vehicle industry has been one of the barriers to the development of PM&S software tools targeted at the specific needs of this industry.

With industry segmentation comes widely varying regulations for different segments. Since the vehicles themselves vary so much in their real life drive cycles, most of the regulations for off-road vehicles focus on engine specific testing. In most off-road vehicle sectors, the core of the design/modeling/simulation/optimization/testing effort of each sector is centered on engine modal testing cycles.

In the off-road world, there isn't an extremely large number of very similar vehicles to test and compare and regulations are almost exclusively focused on measuring engine emissions in bench testing setups. Therefore, it should be no surprise that advanced PM&S software tools that have been designed to look at the entire vehicle's power flow haven't extensively penetrated this industry.

This industry would benefit from highly specific design software tools. However, it is currently not compelling from a cost perspective for a software company to develop highly specific software tools for each niche. As a result of this, modeling and simulation software tools used in the off road industry therefore tend to be very generic and basic. Such tools require an extensive amount of custom programming “in-house” in order to be able to provide high quality PM&S results. Users must often completely rebuild a vehicle model from scratch every time a vehicle variant must be simulated.

Since this work is using a hybrid snowmobile as its test case, the following sub-section provides a quick overview of North American regulatory testing for this type of vehicle.

2.1.3.2.3 Snowmobile Engine Modal Testing

Snowmobile engine modal testing, like most other off-road vehicle testing, is performed by measuring emissions produced by the vehicle’s engine at different operating points. Different types of off-road vehicles have different operating points they are required to operate at during these types of tests. Some of these tests require steady-state measurement points only. Other tests include a form of ramp up between points. Also some newer tests required for some categories of engines use transient testing defined by a specific engine speed and load profile vs. time.

Snowmobile engine testing steady-state and ramp up test values are shown in Tables 1 and 2 below [9].

Table 1: EPA Modal Testing Duty Cycle for Snowmobiles

TABLE 1 OF § 1051.505—5-MODE DUTY CYCLE FOR SNOWMOBILES

Mode No.	Speed(percent) [1]	Torque(percent) [2]	Minimum time in mode(minutes)	Weighting factors
1	100	100	3.0	0.12
2	85	51	3.0	0.27
3	75	33	3.0	0.25
4	65	19	3.0	0.31
5	Idle	0	3.0	0.05

[1] Percent speed is percent of maximum test speed.

[2] Percent torque is percent of maximum torque at maximum test speed.

Table 2: EPA Ramped-Modal Testing Duty Cycle for Snowmobiles

TABLE 2 OF § 1051.505 —RAMPED-MODAL CYCLE FOR TESTING SNOWMOBILES

RMC mode	Time in mode	Speed (percent) [1]	Torque (percent) [2, 3]
1a Steady-state	27	Warm Idle	0
1b Transition	20	Linear Transition	Linear Transition
2a Steady-state	121	100	100
2b Transition	20	Linear Transition	Linear Transition
3a Steady-state	347	65	19
3b Transition	20	Linear Transition	Linear Transition
4a Steady-state	305	85	51
4b Transition	20	Linear Transition	Linear Transition
5a Steady-state	272	75	33
5b Transition	20	Linear Transition	Linear Transition
6 Steady-state	28	Warm Idle	0

[1] Percent speed is percent of maximum test speed.

[2] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the torque setting of the current mode to the torque setting of the next mode.

[3] Percent torque is percent of maximum torque at maximum test speed.

2.1.3.2.4 Vehicle Drive Cycles and Fuel Consumption

One key driver behind the use of vehicle drive cycle based testing in the automotive sector is the implementation of energy efficiency standards and regulations. Much of the intent behind the automotive standards and regulations referencing drive cycles is to:

- Have them be representative of some form of an average of a given set of vehicles.
- Have original equipment manufacturers (OEMs) incentivized (or required) to improve the energy efficiency of their vehicles, based on these drive cycles.
- Provide a baseline for the consumer to take into account fuel consumption at the time of purchase based on a standard relevant test protocol.

The automotive sector's full vehicle drive cycle based approach has demonstrated in recent years that consumer satisfaction is increased by reducing the discrepancy between customer expectation and the vehicle's actual performance. This was achieved by continuously improving the relevance of the drive cycles used for vehicle testing in order to make them fit the real-world usage of the tested vehicles. [10]

The North American off-road vehicle industry is generally not subject to fuel consumption regulation and/or incentives. The main incentive for this is a sales argument, but with the lack of a common measuring stick for the buyer to compare different vehicles with the incentive loses some of its appeal.

Therefore, the off-road vehicle industry hasn't had as strong of a need for vehicle level PM&S software tools to help them save time and money in the design and testing of their vehicles powertrain and its control algorithm.

Now, as new technologies open up new possibilities in terms of drive train topologies, the off-road vehicles industry lacks the well established software tools and approach the automotive industry can count on to model and simulate an entire vehicle's drive and control systems in an environment representative of what the vehicle is expected to evolve in on a regular basis. There may be some platforms which are tailored to very specific needs for very specific off-road vehicles, but there are no known PM&S turnkey solutions and approaches which can perform on par with the automotive Gen2 PM&S turnkey solutions while suiting a majority of off-road vehicle types.

The goal of this work is to provide the off-road vehicle industry a PM&S turnkey solution and methodology that performs similarly to the proven automotive PM&S turnkey solutions.

The next items to explore are the approaches at the core of automotive PM&S solutions.

2.2 PM&S: Forward-Facing vs. Backward-Facing Simulation

There are two common approaches to simulating a vehicle's powertrain on the standard U.S. EPA UDDS speed vs. time test: backward-facing and forward-facing.

2.2.1 Backward-Facing

Vehicle simulators using a backward-facing approach answer the question "Assuming the vehicle met the required trace, how must each component perform?" [11]. The assumption that the vehicle met the required speed trace greatly reduces the computational weight of this approach. Unfortunately, it also reduces this approach's capability of integrating all the elements required for true vehicle design optimization. These traits make this approach suitable for early design orientation of simple, single energy source, vehicles. However, detailed vehicle powertrain design, control and optimization requires a more complex simulation approach.

2.2.2 Forward-Facing

Forward-facing vehicle simulation includes a driver model which considers both the required speed and the present vehicle speed to develop appropriate throttle and brake commands [11]. This approach has a much larger computational cost. However, it permits detailed simulation including vehicle system controls, dynamic component and system models, and driver behaviour.

To perform a forward-facing vehicle powertrain simulation, three distinct entities are used:

1. A desired/target speed vs. time drive schedule (ex: U.S. EPA UDDS portrayed in Figure 2)
2. A driver. Often a PI controller is used [11].
3. A vehicle model. Composed of individual component models and a vehicle powertrain strategy controller.

Figure 3 shows a simple block diagram representation of the various individual vehicle component models that need to be populated in ANL PSAT for a fuel cell series hybrid vehicle with wheel motors.

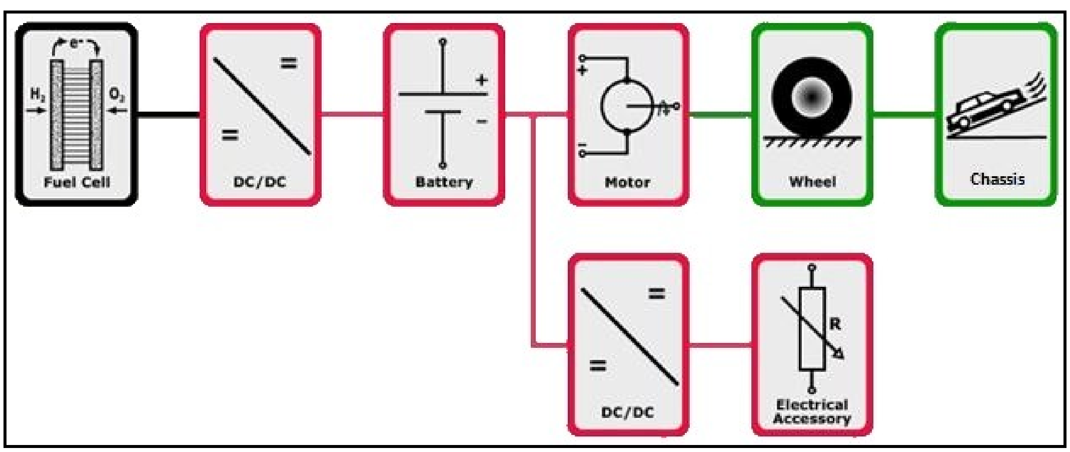

Figure 3: PSAT Block Diagram of Fuel Cell Hybrid with Wheel Motors

The three aforementioned distinct entities interact in the following manner for standard forward-facing automotive powertrain simulation:

1- First the driver receives the required speed information for the next time step.

2- Next the driver receives the vehicle's current speed information.

3- Lastly, based on the information gained in steps 1 and 2, the driver sends the appropriate accelerator or brake command to the vehicle to try to match the speed trace.

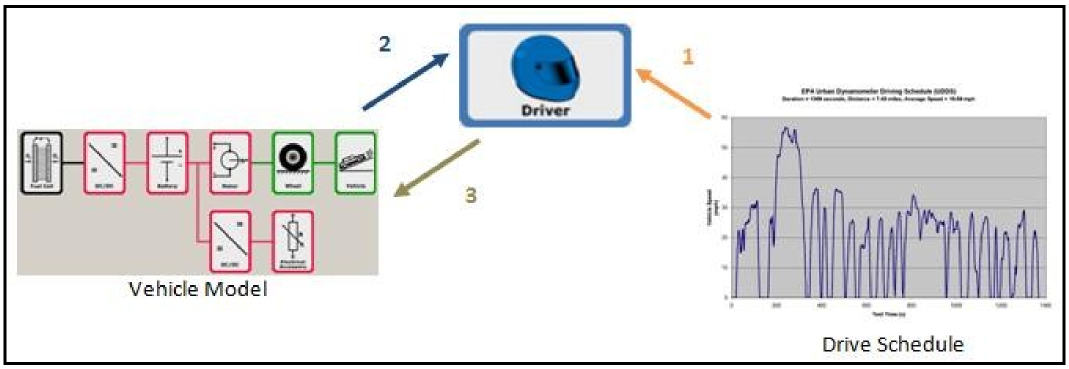

Figure 4: Step by step interaction between input/driver/vehicle in Gen2 PM&S (vehicle model and driver graphics taken from PSAT)

2.3 Successes and Limitations of Unmodified Gen2 PM&S Software

Forward-facing PM&S has demonstrated that it can accurately simulate and predict vehicle performance for complex vehicle powertrain architectures driven on standard drive cycles [12]. However, when this approach was used to simulate and predict off-road vehicle performance, some limitations were found [3]. Some of the results indicated that the assumption of static vehicle and environmental parameters used in

Gen2 PM&S might be the source of discrepancy between the simulation results and the data gathered from the vehicle in real life.

Given the above, it was theorized that, for different vehicles and applications, different sets of input variables into the simulation would likely yield optimal results. Based on this theory, in the case of passenger road vehicles, it intuitively seems that for many applications, making speed the only variable into the simulation can likely yield satisfactory simulated vehicle power demand when compared to the real power demand. Various examples in the literature appear to confirm this [12-14]. However, based on this theory, it also appeared that for many off-road vehicles, using speed as the only variable input into the simulation would likely not yield satisfactory results. The example in Figure 5 illustrates this.

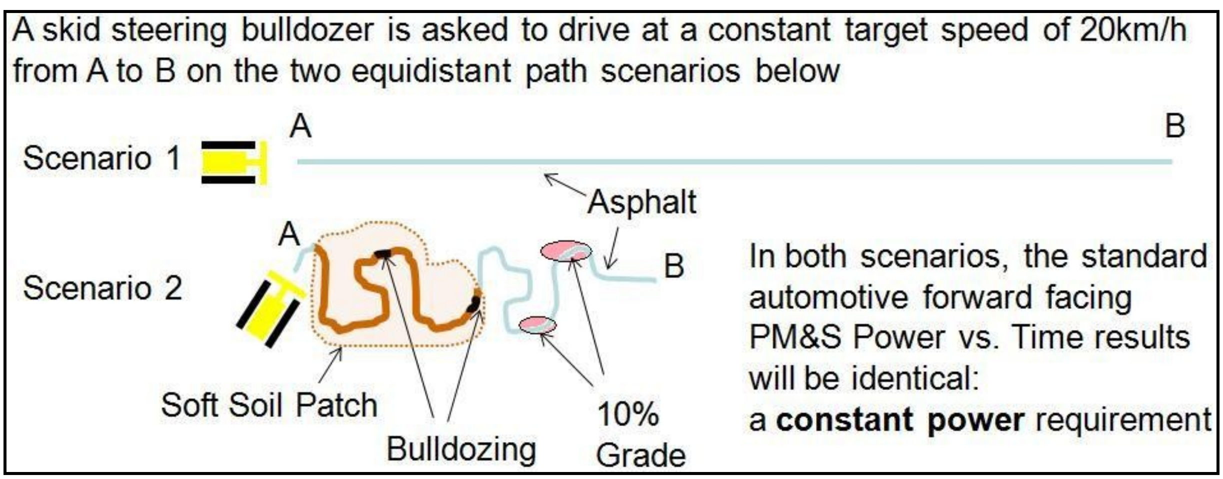

Figure 5: Bulldozer Example - Illustrating Some Limitations of Gen2 PM&S

A unmodified Gen2 PM&S and more specifically PSAT yields identical power requirement traces for both scenarios in Figure 5. However, it is obvious to any technically trained person that it is extremely unlikely that both scenarios would yield the same power trace if performed and monitored in real life.

If the fidelity of Gen2 PM&S varies based on the vehicle and the application, one can rightfully look for means of improving the fidelity of Gen2 PM&S for cases where it performs below the current automotive standard.

Looking at the example in Figure 5 and analyzing the difference between the two scenarios, one can express the main difference between Scenario 1 and 2 as the variability of the chassis component of the model, the variability of its environment, and the variability of interaction between the two. Thus, one of the limitations of unmodified Gen2 PM&S software in general and PSAT in particular can be seen as the assumption that the parameters defining a vehicle and its environment are constant throughout a drive cycle.

Since Gen2 PM&S uses primarily lookup tables, the selected approach to try and improve Gen2 PM&S simulation fidelity focused on means of efficiently supplying PSAT with lookup tables capable to describing the essential variables representing a complex real-life driving environment.

The search for such a solution zeroed in on Geographic Information System (GIS) applications as prime candidates for being able to efficiently synthesize complex environmental information into multiple lookup tables.

2.4 Geographic Information System (GIS)

GIS tools are used in a plethora of domains as varied as epidemiology, urban planning, hydrology, forestry and site surveying. GIS applications are tools that excel at interactive queries and the analysis and editing of spatially referenced information [15, 16]. These key qualities of a GIS application are of particular interest to this project.

Looking back to the example of the bulldozer in Figure 5, a first hypothesis was formulated stating that the aspects that primarily affect off-road vehicle simulation fidelity in Gen2 PM&S software can for the most part be catalogued in a GIS application, synchronized with one another, and eventually output as lookup tables.

This hypothesis was formed based on a GIS's approach for dealing with information from different sources.

Wikipedia provides this very relevant and succinct explanation of how GIS does this:

GIS uses spatio-temporal location as the key index variable for all other information. Just as a relational database containing text or numbers can relate many different tables using common key index variables, GIS can relate unrelated information by using location as the key index variable. The key is the location and/or extent in space-time. Any variable that can be located spatially, and increasingly also temporally, can be referenced using a GIS.

Related by accurate spatial information, an incredible variety of real-world and projected past or future data can be analyzed, interpreted and represented to facilitate education and decision making.[17] This key characteristic of GIS has begun to open new avenues of scientific inquiry into behaviors and patterns of previously considered unrelated real-world information.

The idea in this case is not to use GIS as a direct decision making tool, but rather to use its capability of storing, referencing and operating between datasets to enhance the capabilities of Gen2 PM&S software.

In order to tap into this capability of GIS applications, information which may have relevant impact on the vehicle, its environment, and the interactions between both, needs to be identified, gathered and spatio-temporally referenced.

Another hypothesis was formulated stating that once relevant information has been collected and referenced in a GIS, operations can be performed in the GIS and the result of these operations can be imported into a modified version of a Gen2 PM&S software.

A third hypothesis related to GIS was also formulated with regards to the nature of the information. The hypothesis is that the spatio-temporally referenced information required to improve off-road Gen2 PM&S results is related to the chassis model, its environment, and the interaction between the two.

Studies focused on modeling air pollution and/or fuel use in vehicles have already successfully used GIS as a means of referencing variability of vehicle/environment/interaction parameters [18, 19, 20].

2.5 GIS Data – Raster vs. Vector

Data can be stored in a GIS using two different approaches for feature referencing and visualization: Vector or Raster. The selection of one approach over another is influenced based on a number of factors. The type of data, the collection method, the end use of the data and the manipulations required to reach this end use heavily impact the choice of GIS format.

- Vector data is stored as points, lines and polygons whose location, length and shape are referenced from a known datum.
- Raster data is stored as a set of unique values assigned to each cell in a grid overlaid on a geographic location.

The example in Figure 6 illustrates GIS data representation examples of the same area using both the raster and the vector approach. Each type of data has unique aspects that may be advantages or disadvantages depending on the required use.

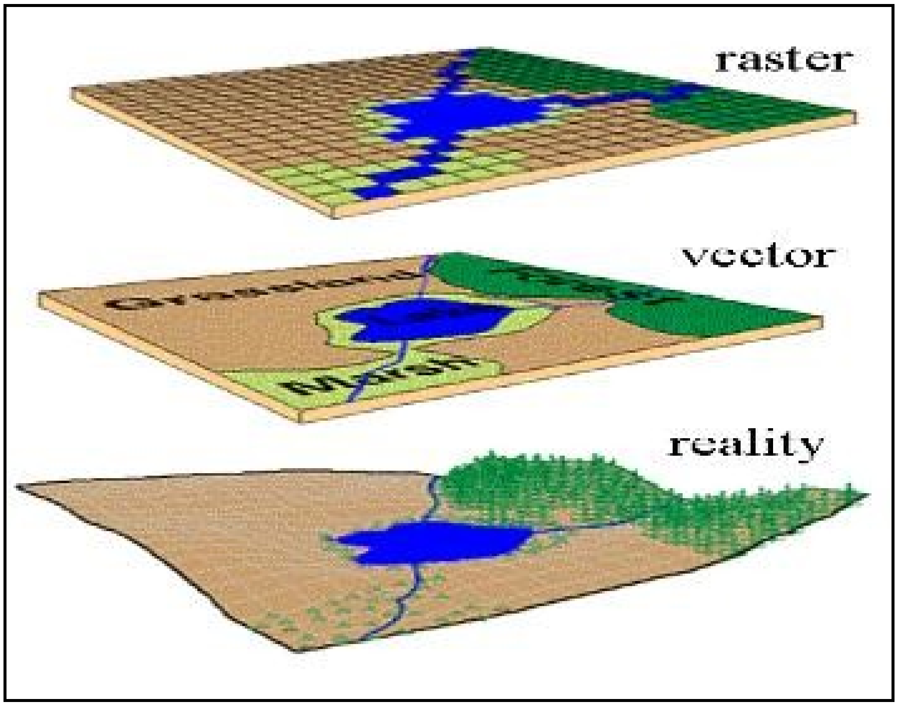

Figure 6: Raster & Vector Representation of Given Area [21]

Regardless of the chosen approach, one key feature of GIS is its ability to superimpose numerous layers of information over a designated area and to perform complex calculations between each of these layers.

3. Understanding the Role of the Chassis Model and the Environment in Gen2 PM&S

Hypothesis #1 presented in section 1.2.1 pertains to aspects negatively impacting off-road vehicle PM&S results because they are not covered in sufficient detail by Gen2 PM&S software.

More specifically, it is believed that the interaction of the chassis component model and its environment is a key limiting factor for simulation result fidelity in the case of off-road vehicles.

In order to validate this hypothesis and then try to improve how the baseline Gen2 PM&S chassis component model interacts with its environment, a solid understanding of how the two currently interact in PSAT is required.

3.1 Understanding the Role of the Chassis Model

This section analyses the PSAT chassis component model block and the equations used in PSAT to simulate the chassis. By the end of this section it should be clear that:

1. Only time based indexed variables can have an impact on the chassis component model in baseline Gen2 PM&S.

2. The only time based indexed variables which can have an impact on the chassis component model in baseline Gen2 PM&S are scheduled speed and grade.

A first step in understanding the role of the chassis model and its environment in Gen2 PM&S is to review the fundamental equations of motions relevant to this subject. The second step is to look at an overview of how these equations are used in ANL PSAT, the chosen Gen2 PM&S platform for this project.

3.1.1 Fundamental Equations of Motion

The elementary equation derived from Newton's second law that describes the longitudinal dynamics of a road vehicle can have the following general form:

$$m\frac{dV_{(t)}}{dt} = Ftrac_{(t)} - \left(Faero_{(t)} + Froll_{(t)} + Fgrade_{(t)} + Fdist_{(t)}\right) \quad \text{(eq. 1)}$$

where $Faero_{(t)}$ is the aerodynamic friction, $Froll_{(t)}$ the rolling friction, $Fgrade_{(t)}$ the force caused by gravity when driving on non-horizontal paths, and $Fdist_{(t)}$ the disturbance force that summarizes all other not yet specified effects. The traction force ($Ftrac_{(t)}$) is the force generated by the prime mover minus the force that is used to accelerate the rotating parts inside the vehicle and minus all friction losses in the powertrain [22].

Since power can be defined as the product of force and velocity, by assuming $Fdist_{(t)}$ = 0 and multiplying both sides of eq. 1 by the speed of the vehicle ($V_{(t)}$), a five term power equation can be obtained.

As seen in eq. 2, by rearranging the terms one can obtain that the total power used by a vehicle at any given time ($Ptrac_{(t)}$) can be seen as being the sum of the power to overcome rolling resistance ($Proll_{(t)}$) and aerodynamic drag ($Pdrag_{(t)}$), to accelerate the vehicle ($Pacc_{(t)}$) and to climb an incline ($Pgrade_{(t)}$).

$$Ptrac_{(t)} = Proll_{(t)} + Pdrag_{(t)} + Pacc_{(t)} + Pgrade_{(t)} \qquad \text{(eq. 2)}$$

In a forward-facing powertrain simulation with a no slip condition, for the case of a wheel motor such as the one presented in Figure 3, $Ptrac_{(t)}$ is equal to driver torque demand ($Tdrive_{(t)}$) times wheel rotational speed ($W_{(t)}$). Given the no slip condition assumption, wheel rotational speed can be equated to vehicle speed ($V_{(t)}$) divided by wheel radius (R)

$$Ptrac_{(t)} = Tdrive_{(t)}\ W_{(t)} = \frac{Tdrive_{(t)}\ V_{(t)}}{R} = Fdrive_{(t)}\ V_{(t)} \qquad \text{(eq. 3)}$$

One measure of fidelity of a powertrain simulation vehicle model is the ability of the simulated vehicle to match the real vehicle's speed trace while using the same amount of power as the real vehicle at any given time. Given this, since the fidelity of a forward-facing powertrain simulation is linked to the force input and the vehicle speed (eq. 3), the following section will briefly explore the interaction between vehicle parameters, environmental parameters, force input and vehicle speed in PSAT's chassis model.

3.1.2 Determining Vehicle Speed in a Forward-Facing Simulation (one time step simplified snapshot overview of ANL PSAT chassis model block)

For a vehicle model with speed $V_{(t)}$ at the end of time step t and a vehicle model desired speed of $D_{(t+1)}$ at time step $t+1$, if $V_{(t)} < D_{(t+1)}$ then an "increase wheel torque" demand will be given by the driver. After passing through the vehicle control system, this "increase wheel torque" is moved forward through the different vehicle component models until it eventually reaches the PSAT chassis model block as a force input $Fin_{(t+1)}$.

This force input affects vehicle model speed at time = $t+1$, $\left(V_{(t+1)}\right)$ in the following way:

$$V_{(t+1)} = V_{(t)} + \int a_{(t+1)}\, dt \qquad \text{(eq. 4)}$$

where $a_{(t+1)}$, the acceleration of the vehicle, is defined as

$$a_{(t+1)} = \frac{F_{(t+1)}}{M} \qquad \text{(eq. 5)}$$

where $F_{(t+1)}$ is the linear motive force defined by eq. 6 and M is the vehicle's effective mass defined by eq.7

$$F_{(t+1)} = Fin_{(t+1)} - Floss_{(t+1)} \quad \text{(eq. 6)} \qquad M = M' + \frac{\sum J}{R^2} \quad \text{(eq. 7)}$$

where M' is the vehicle's static mass and $\frac{\sum J}{R^2}$ is the sum of the vehicle's components rotational inertia divided by the square of the wheel radius and where $Fin_{(t+1)}$ is the force input to the chassis model at time = $t+1$ and $Floss_{(t+1)}$, the force required to counter vehicles losses, can be defined as follows in eq. 8.

$$Floss_{(t+1)} = Faero_{(t+1)} + Froll_{(t+1)} + Fgrade_{(t+1)} = F_2\, V_{(t)}^2 + F_1\, V_{(t)} + F_{0'} + M'\, g \sin\theta_{(t+1)}$$

(eq. 8)

Since

$$Faero_{(t+1)} + Froll_{(t+1)} = F_2\, V_{(t)}^2 + F_1\, V_{(t)} + F_{0'} = F_2\, V_{(t)}^2 + F_1\, V_{(t)} + \min\left(F_0\, , \frac{F_0\, V_{(t)}}{0.05} \right)$$

(eq. 9)

and

$$Fgrade_{(t+1)} = M'\, g \sin\theta_{(t+1)} \qquad \text{(eq. 10)}$$

where $Faero_{(t+1)} + Froll_{(t+1)}$ is defined as a function of the vehicle speed ($V_{(t)}$) and the constant coefficients F_2, F_1, F_0. These coefficients are measured from curve fitting a second order polynomial to measured data gathered from vehicle coast down tests. Meanwhile, $Fgrade_{(t+1)}$ is defined by three constants. The vehicle's static mass (M'), gravity (g) and grade ($\theta_{(t+1)}$).

Therefore, from the chassis model's point of view, the relationship between the force input at a given time step and the resulting vehicle speed can be summarized in eq.11 below.

$$V_{(t+1)} = V_{(t)} + \int_{t}^{t+1} \frac{Fin_{(t+1)} - F_2\, V_{(t)}^2 + F_1\, V_{(t)} + F_{0'} + M'\, g \sin\theta_{(t+1)}}{M' + \dfrac{\sum J}{R^2}} dt \qquad \text{(eq.11)}$$

Most of the individual equations and parameters shown in section 3.1.2 can be seen in the top two levels of PSAT's Matlab chassis model block diagram shown in Figures 7 and 8 below. Figure 7 is the top level block while Figure 8 represents what is found within the Dyno Vehicle Losses block seen in Figure 7.

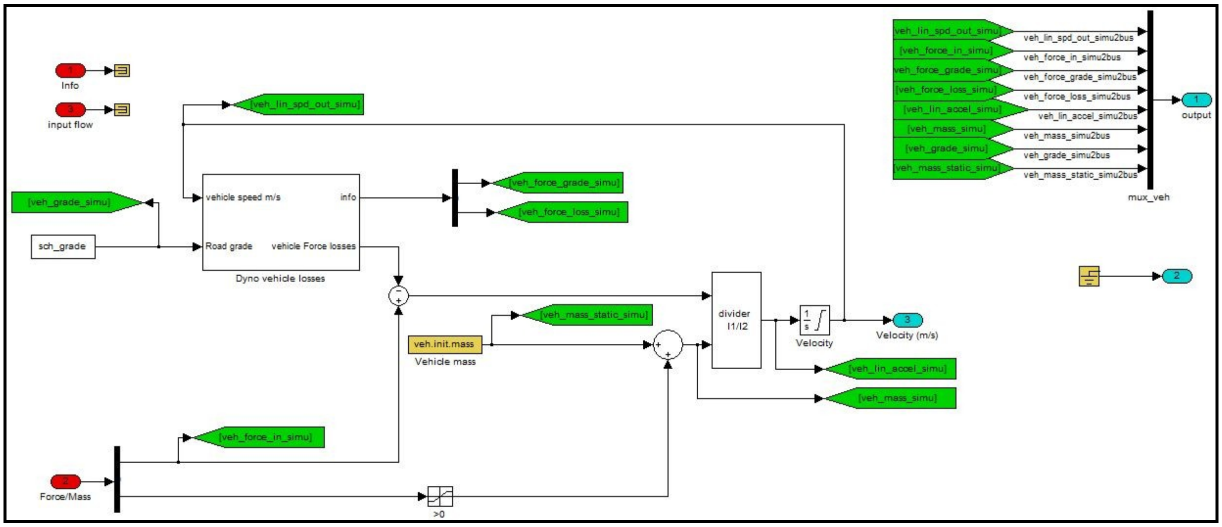

Figure 7: Complete PSAT Chassis Block (Top Level)

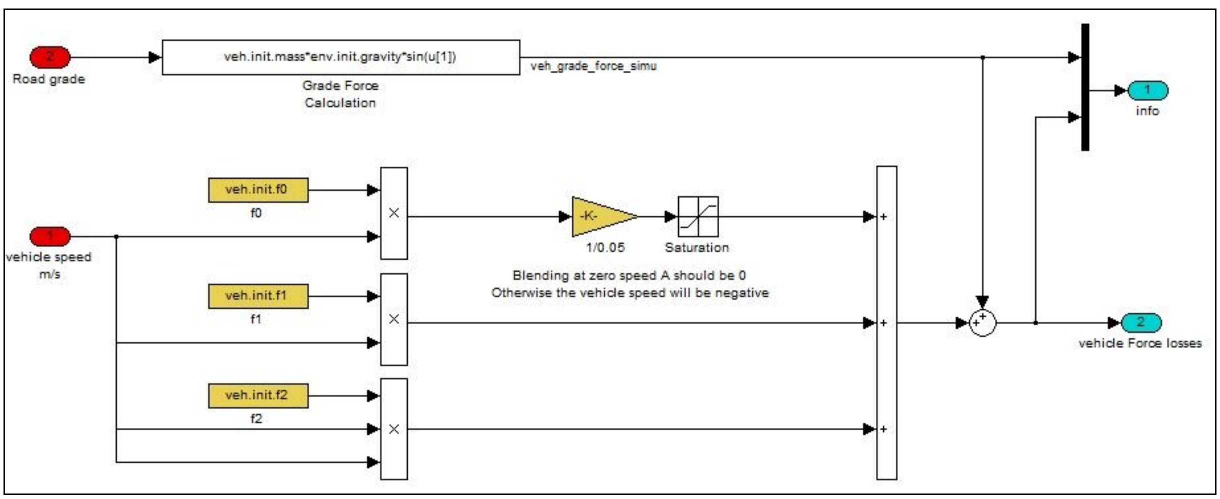

Figure 8: Complete PSAT Dyno Vehicle Losses (in Chassis Block)

To help follow the various inputs, outputs and operations in Figures 7 and 8, a simplified version of each block diagram has been copied below in which each element has been annotated with the corresponding equation number or parameter name as defined in section 3.1.2.

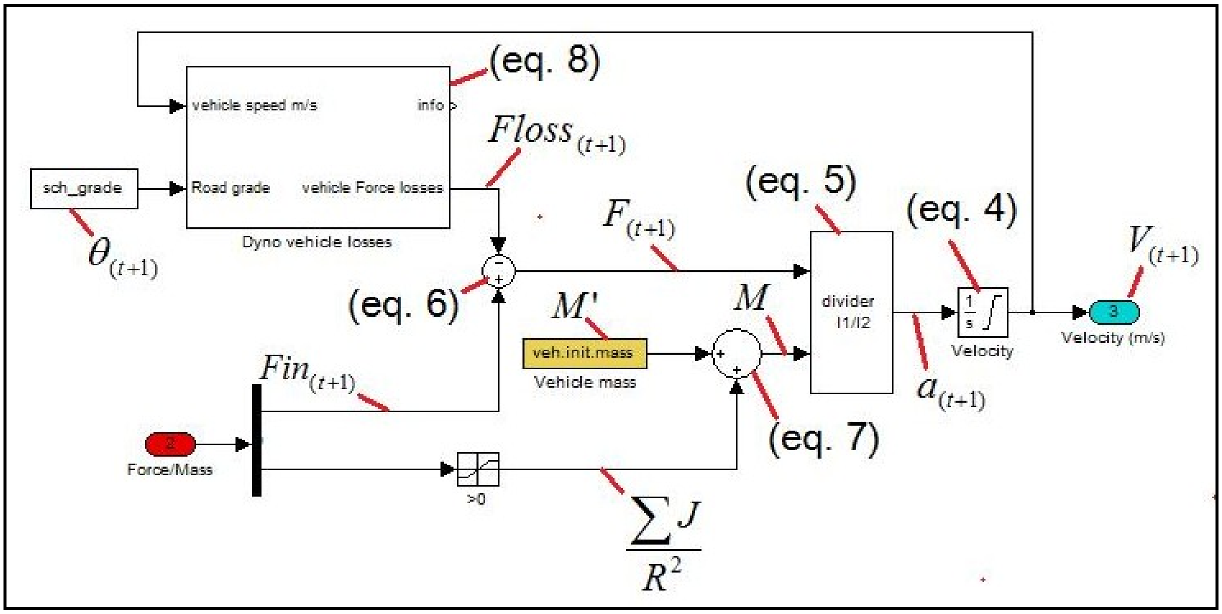

Figure 9: Simplified and Annotated PSAT Chassis Block (Top Level)

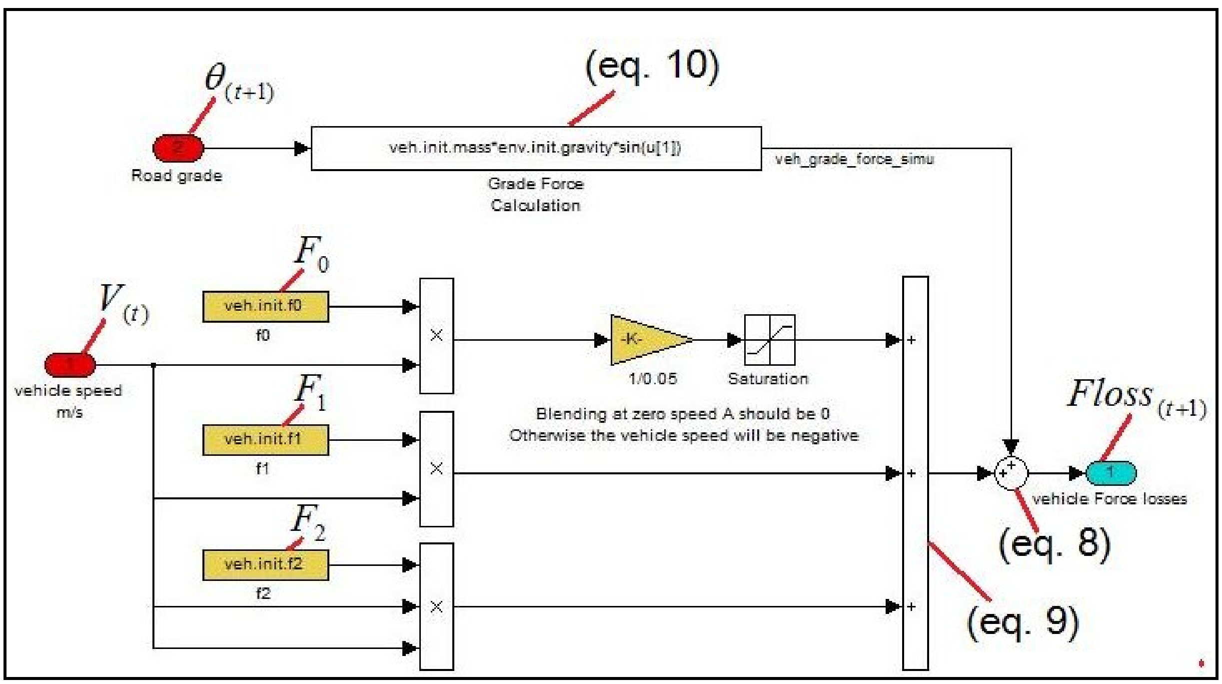

Figure 10: Simplified and Annotated PSAT Dyno Vehicle Losses (in Chassis Block)

3.1.3 Analysis

Eq. 11 obtained in section 3.1.2 describes the elements that are taken into account to determine the vehicle speed at each time step. This equation clearly shows that the only elements having an impact on speed are either constants or time based variables. Therefore, the only items which can make speed vary in a baseline PSAT Gen2 PM&S are time based variables.

Having a closer look at the time based variables present in eq. 11, one can see that there are only two independent time based variables present: force and grade. However, tracing back the source of the force input to the driver, one can see that this force input is the result of the driver's reaction to the difference in actual speed and scheduled speed. Therefore, it can be concluded that for the baseline PSAT Gen2 PM&S the only things that can affect the output of the vehicle model are two time indexed variables: speed and grade.

Therefore, any variation in the environment currently cannot be accounted for. Furthermore, variations in grade can only be accounted for accurately if the simulated vehicle's speed at any given time step is know in advance in order for the grade variations to happen at the right moment in the simulation. In a case such as the one being investigated where there is no target speed schedule the vehicle is expected to follow, but instead, the driver is requesting "maximum accelerator input", there is no way to accurately account for grade given that it can only be input as a function of time.

3.1.4 Conclusion

The objective of this section was to gain a solid understanding of how the baseline Gen2 PM&S chassis component model interacts with its environment.

After deriving the fundamental equations of motion and demonstrating in detail how they are used in the baseline PSAT chassis model, it should be clear that:

1. Only time based indexed variables can cause a change in the baseline PSAT chassis component model’s output during a simulation.
2. The only time based indexed variables which can have an impact on the baseline PSAT chassis component model’s output during a simulation are the time indexed scheduled speed and grade.

The next section provides more information on the effect of grade.

3.2 Understanding the Effect of Grade

Section 3.1 demonstrated that grade is the only environmental input which can readily be made to vary during a baseline PSAT simulation. Unfortunately, the means by which grade can be changed during the simulation, by indexing it as a function of time, causes fidelity issues in a forward-facing environment since the exact vehicle speed cannot be know in advance. Therefore, when trying to use PSAT to simulate a real life drive cycle, it is unlikely that the simulation environment's grade will match the real life environment's grade throughout the cycle since the slightest deviation in simulated vehicle speed with regards to the scheduled speed will cause an offset in grade with regards to reality. This effect is pushed to the extreme in the case of a drive cycle without a target speed trace, where the driver is requesting maximum "accelerator" input and there is no way to know the vehicle's speed ahead of time.

In section 3.2 the effect of grade on instantaneous power requirement will be investigated. First by using a standard automotive drive cycle and second by looking at a real life test performed with a snowmobile.

3.2.1 Why the Effects of Grade Need to Be Taken Into Account in the Simulation

Gen1 and Gen2 PM&S software development has been heavily driven by the need to predict vehicle fuel economy performance in government regulated tests.

These tests are performed on a dynamometer and do not directly incorporate a grade aspect. [8]

As a result, PM&S platforms, while they do have some means to incorporate the effect of grade in a simulation (primarily for gradability testing), are not optimized to take into account this important parameter for real life testing. [8] Nevertheless, in order to achieve high fidelity results, it is important to incorporate the grade effects in the simulation as opposed to try and factor it in after the fact. Section 3.2 explores the current means of dealing with the effect of grade in PM&S through the use of PSAT's built in Prius vehicle model [15].

3.2.1.2 Prius UDDS Baseline – 0% Grade

As a baseline, the PSAT Prius model was tested on the UDDS cycle.

Figure 11 below shows the standard UDDS driving speed schedule as a function of time (i.e. how it is specified in the standard), along with grade and elevation.

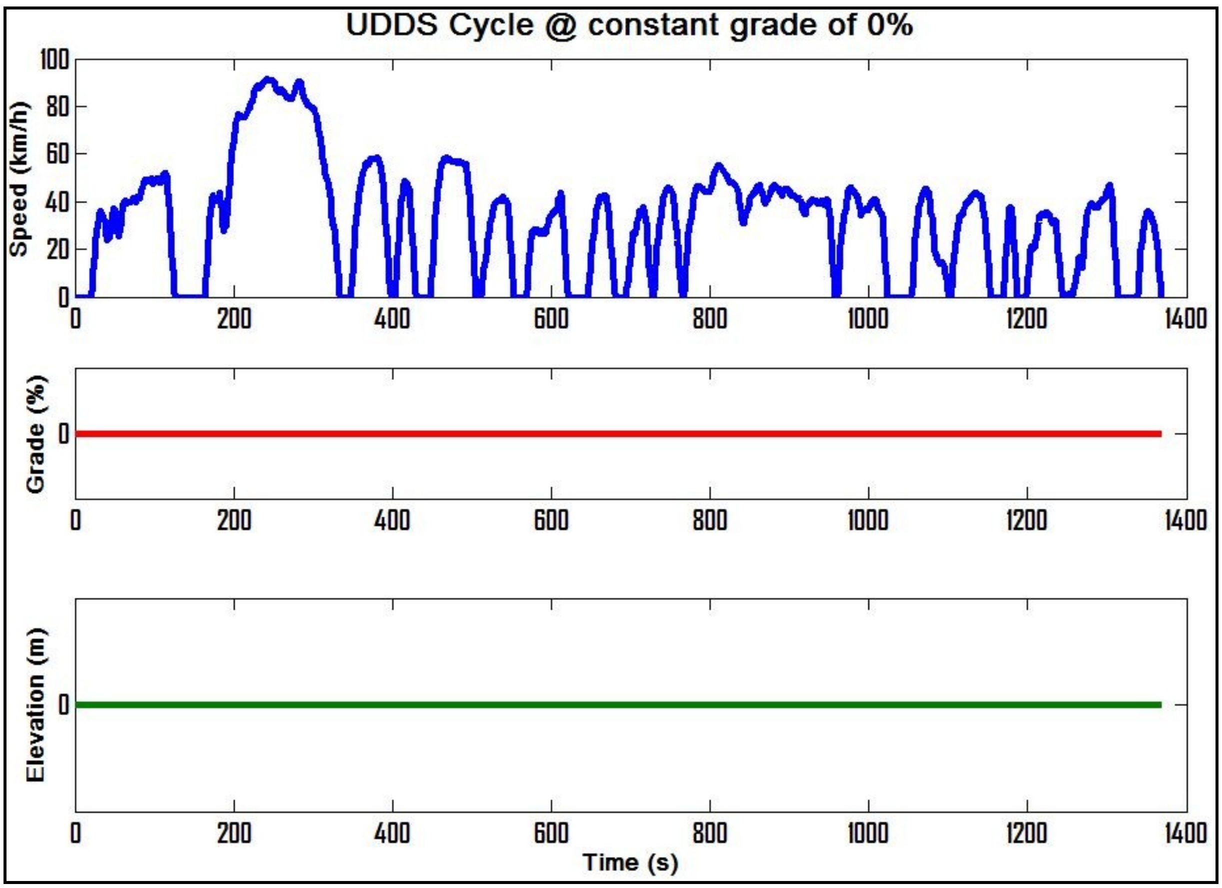

Figure 11: UDDS Cycle Drive Schedule Input

The resulting speed vs. time output of the simulated vehicle is overlaid over the scheduled speed in Figure 12 below.

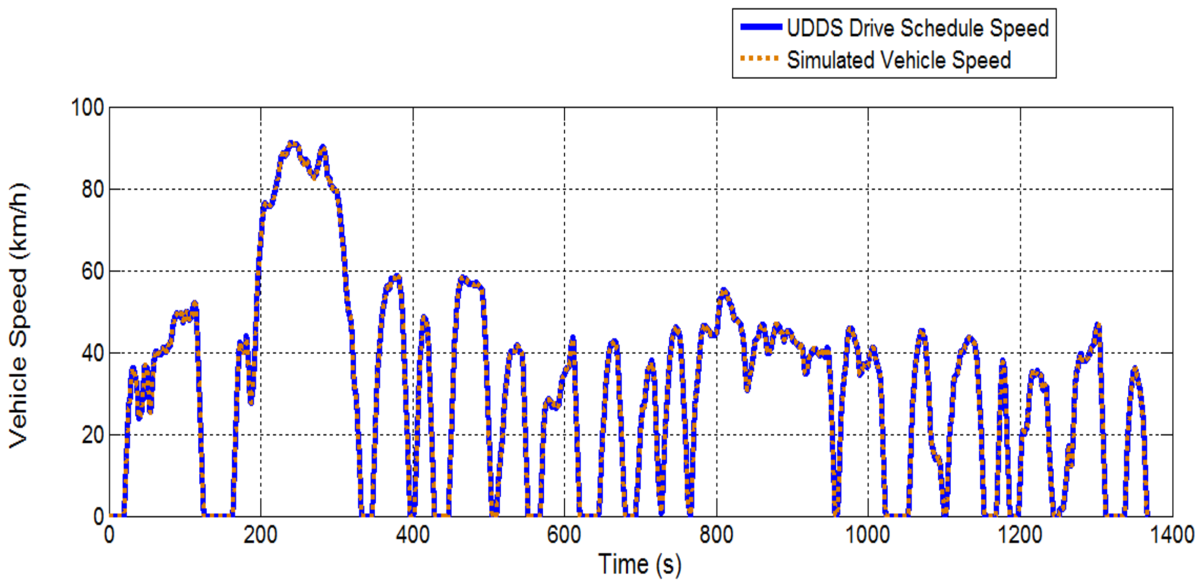

Figure 12: UDDS Prius Speed vs. Time - Simulation Output & Drive Schedule

As a result of running this simulation it can be seen in Figure 12 that the vehicle was able to follow the desired UDDS speed trace accurately throughout the simulation.

The next item to verify is to see if the vehicle matched the speed schedule with a "normal" driver behavior. In other word's did the driver provide relatively smooth torque demand or did it request "full acceleration - full brake - full acceleration - full brake - etc" at a very high frequency to achieve what should normally be a smooth drive cycle? Figure 13 below, which shows the driver torque demand, provides insight into this.

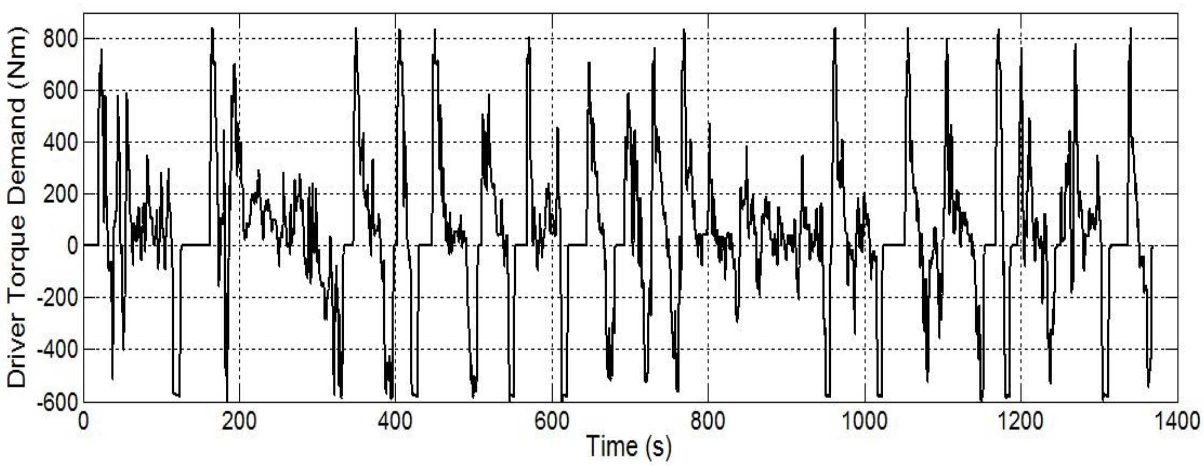

Figure 13: UDDS Prius Driver Torque Demand vs. Time

As seen in Figure 13 the torque demand is relatively smooth and matches the expected vehicle speed behavior for a smooth drive. Knowing that the drive cycle's speed schedule has modest acceleration rates and that there are no environmental changes in the simulation, this smoothness means the results from this simulation can be deemed representative of everyday "normal" driving.

Having validated that the simulation speed and power demand are satisfactory, attention can be directed to the instantaneous power usage and the energy consumption results. Power vs. time is presented in Figure 14 below and total energy consumed vs. time is presented in Figure 15.

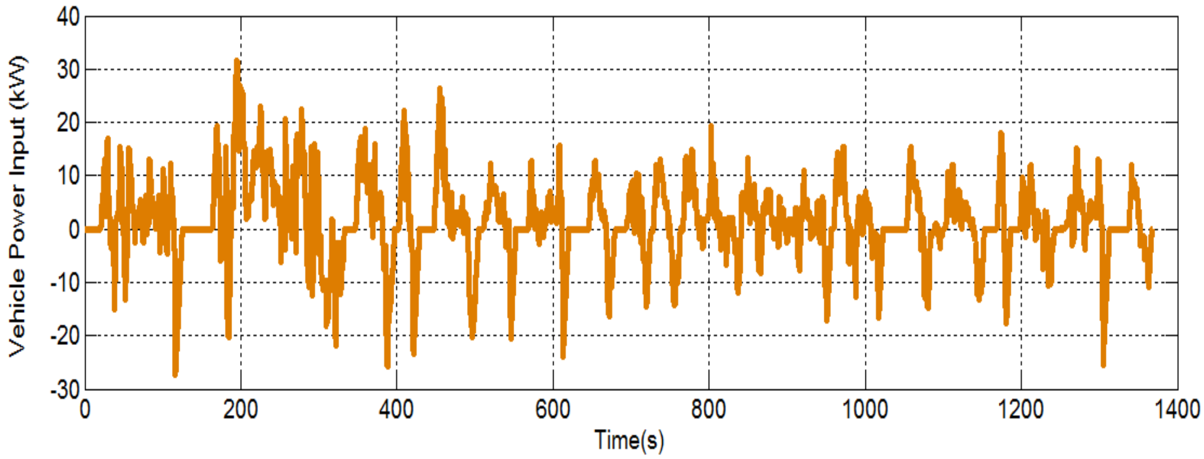

Figure 14: UDDS Prius Power Input vs. Time

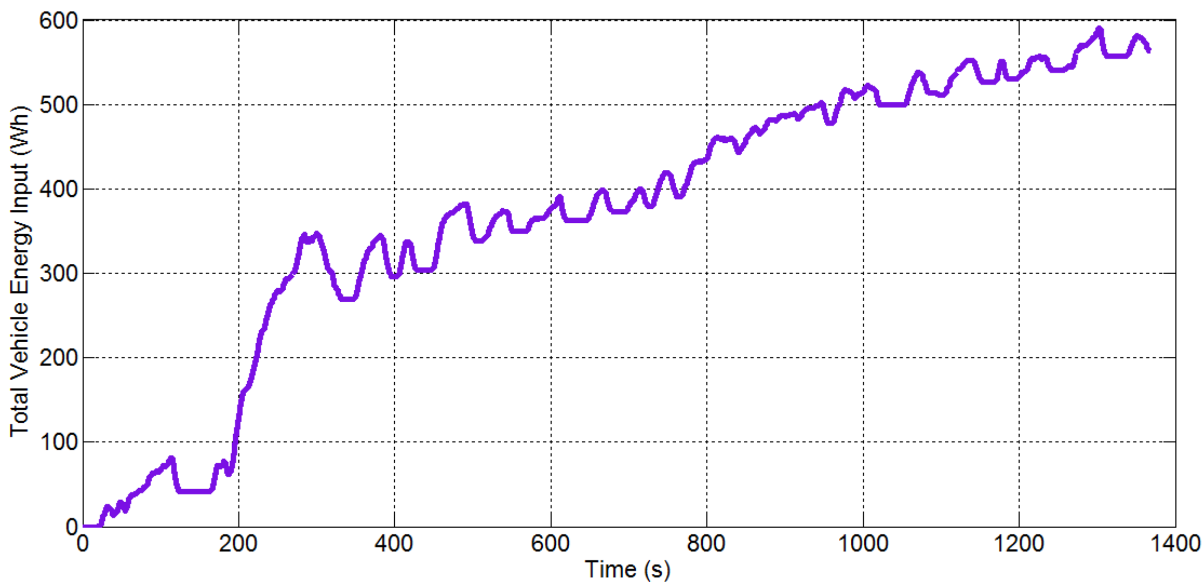

Figure 15: UDDS Prius Total Energy Input vs. Time

3.2.1.2 Prius UDDS @ 1% Constant Grade

This subsection compares two possible approaches to take into account the effect of a steady grade on vehicle PM&S.

1- Factoring in a constant grade using post-simulation calculations

2- Adding a constant grade factor to the simulation

3.2.2.1.1 Factoring in a constant grade using post-simulation calculations

It is possible to calculate the theoretical energy required to elevate the Prius to a certain height in a very straight forward manner. The energy (E) required to elevate a mass (M) by a certain height (H) can be calculated using the formula:

$$E = M\ g\ H \qquad \text{eq. 12}$$

Where g is the gravitational acceleration. By knowing the mass of the Prius, the length of the UDDS drive cycle and the steady grade, it is possible to calculate the theoretical energy required to elevate a Prius over the distance of a UDDS cycle on a steady grade.

In the case of a Prius with a mass of 1449kg, driving the 11,990m long UDDS cycle on a 1% incline, and using 9.81m/s^2 as the gravitational acceleration, the theoretical extra energy due to grade can be calculated to be 473.4 Wh.

In order to factor in the effect of grade after the 0% grade baseline simulation was performed, the theoretical extra energy can be added to the results from the baseline 0% grade simulation energy results.

Table 3 below shows the drive cycle energy results when adding the energy required by the flat ground simulation and the constant grade estimate.

Table 3: UDDS Prius Theoretical Energy @ 1% Grade

0 grade UDDS Energy (Wh)	Extra energy required by 1% incline (Wh)	Total Energy Estimated for 1% grade (Wh)
564	473	1037

Adding these two numbers is simple and straight forward for calculating the drive cycle's total energy. However, extra calculations are required to try and have an estimate of the vehicle's power throughout the drive cycle.

Since energy can be defined as the product of power and time, an average additional power requirement due to grade can be estimated by dividing the total energy calculated in Table 3 by the cycle duration. This result can then be added to the vehicle's second by second power requirement for the entire simulation.

Table 4 below presents the results of this calculation along with the previous results from Table 3.

Table 4: UDDS Prius Theoretical Extra Power Due to 1% Grade

0% grade UDDS Energy (Wh)	Extra energy required by 1% incline (Wh)	Total Energy Estimated for 1% grade (Wh)	Cycle Time (h)	Average Extra Power Due to Grade (W)
564	473	1037	0.38	1245

Unfortunately this approach cannot yield high fidelity results unless the vehicle is going at exactly the same speed throughout the simulation. In reality the vehicle is not using the same amount of extra energy due to grade at each time step. When the vehicle's speed is above the cycle's average speed, this approach underestimates the energy consumed in each time step. The opposite happens when the vehicle's speed is less than the cycle's average speed. A clear manifestation of this issue is that with this approach, a vehicle at rest uses the same amount of energy due to grade at each time step as a vehicle going at full speed.

3.2.2.1.2 Comparing the “After the fact” results to the “Integrated” results

As presented in section 3.1, PSAT has a means of defining grade as a function of time within a simulation. This feature is primarily used for gradability testing; however, it can also accurately predict vehicle behavior for any drive schedule on steady grade.

A simulation was performed in PSAT for a Prius on a UDDS cycle with a 1% grade. Looking at the result graphs for this approach and comparing them with the “After the fact” approach helps visualize the limitations of the latter one.

Figure 16 below shows the power vs. time results for the two approaches and the difference in instantaneous power over time.

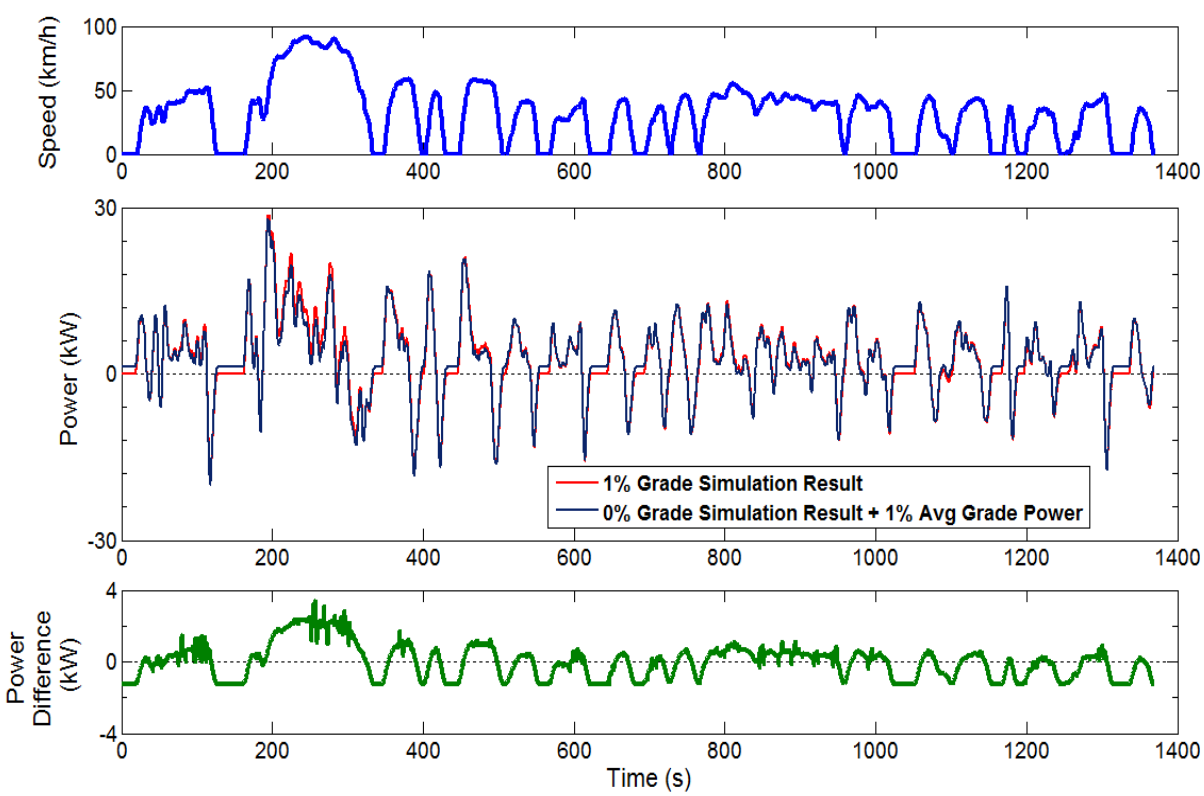

Figure 16: UDDS Prius Power Difference - Adding Grade “After the fact” vs. Integrating Grade to Simulation

Even in a simple case such as adding a small constant grade, the “after the fact” approach cannot yield high fidelity results. Furthermore, the fidelity of this approach is even lower as grade increases and it is not scalable to more complex scenarios such as a round trip with variable grade. In order to cope with such a scenario the “after the fact” approach would have to be divided into multiple segments each with a steady grade. At this point it is essentially equivalent to trying to replicate manually what the simulation can do automatically.

In conclusion, environmental aspects affecting the vehicle’s power requirement such as grade must be incorporated directly into the simulation in order to obtain high fidelity results.

That being said, current Gen2 PM&S software are limited when it comes to adding grade directly in the simulation. Their results can only be accurate if either:

1- The grade is constant throughout the simulation

Or

2- The actual vehicle speed matches the scheduled speed exactly and grade vs. time is pre-calculated ahead of the simulation using the scheduled speed and some information to reference the actual grade present on the vehicle’s path.

Section 3.2.2 below looks at a test performed to quantify the accuracy of case 2 above for an off-road vehicle on a round trip cycle along the Fitzsimmons Creek valley between Whistler and BlackComb mountains in British Columbia.

3.2.2 Preliminary testing of the Integration of Variable Grade in Gen2 PM&S for Off-Road Vehicles

A project was undertaken in collaboration with Canadian Wilderness Adventures (CWA, previously Canadian Snowmobile Adventures) located in Whistler, one of British Columbia's largest snowmobile tour operator. Through this project, the accuracy of Gen2 PM&S was measured as a means of predicting an off-road vehicle's instantaneous power demand throughout a real life drive cycle with variable grade.

This section presents a brief overview of the project and some results. The methodology used and the results obtained in this project laid the ground for the work and methodology presented in future sections.

3.2.2.1 CWA Project

This section presents a brief overview of the CWA project along with a short step by step illustration of the work accomplished as initially presented as a poster presentation at EV 2010 Conference in Vancouver.

3.2.2.1.1 Overview

- Goal: Analyze the possibility of integrating plug-in vehicle technology in the touring snowmobile fleet.
- How ? : Develop a methodology to compare the performance of different off-road vehicle powertrains. Apply this to numerous tour paths and duty cycles with various recharging opportunities to find optimal vehicle/application combination.
- Key challenge: Off-road application
- Proposed approach: Use GIS to gather topographical data from tour paths and enter this information as a grade vs. time schedule in PSAT based on measured vehicle speed from an actual tour. Rely on having the simulated vehicle match the drive schedule speed as closely as possible to obtain good fidelity of results.

3.2.2.1.2 Step-by-Step Illustrated Project Breakdown

The following pages illustrate the steps taken for one vehicle/tour combination on the flattest tour CWA offrers.

First, vehicle component data was gathered and from this data a vehicle model was created.

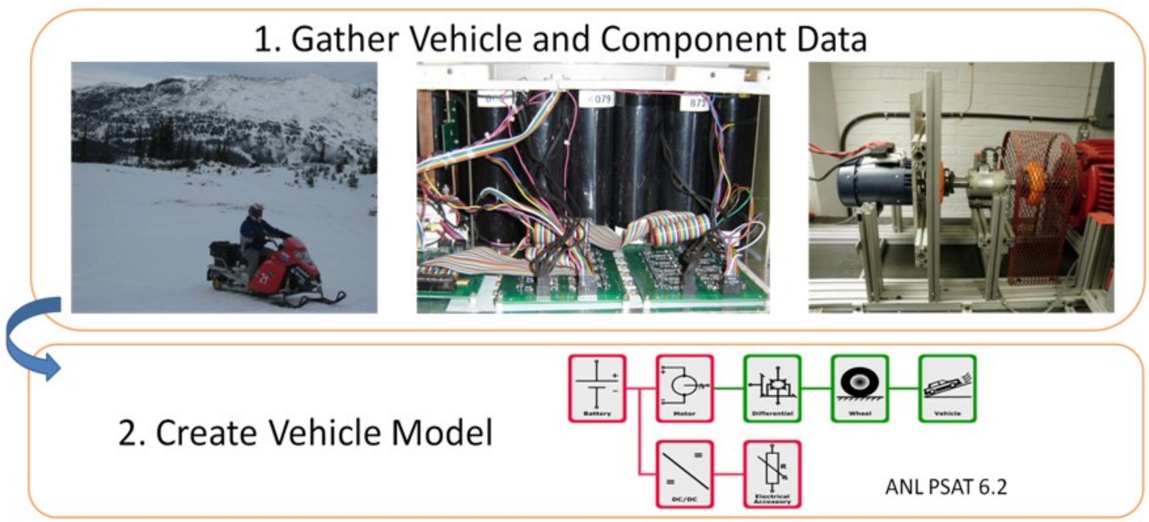

Figure 17: CWA Project – Data Acquisition and Model Creation

Next, through the use of high resolution aerial imagery provided by the Municipality of Whistler the tour path trail was identified and georeferenced manually from the high resolution imagery. Also, based on real life touring vehicle data acquisition, a standard drive cycle for this tour path was created.

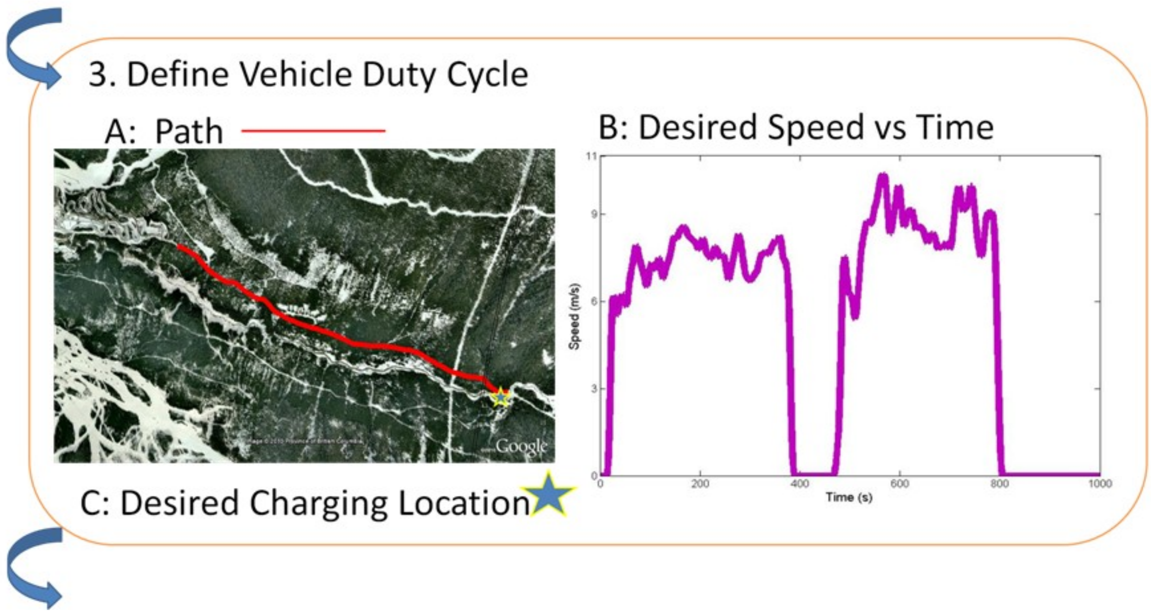

Figure 18: CWA Project – Path Identification and Drive Schedule Creation

By using a georeferenced digital elevation model file provided by the Municipality of Whistler, the profile of the tour path was extracted as a function of location using the GIS application suite ArcGIS from ESRI. From this elevation profile and the drive schedule speed, grade was calculated as a function of time for the recorded drive schedule.

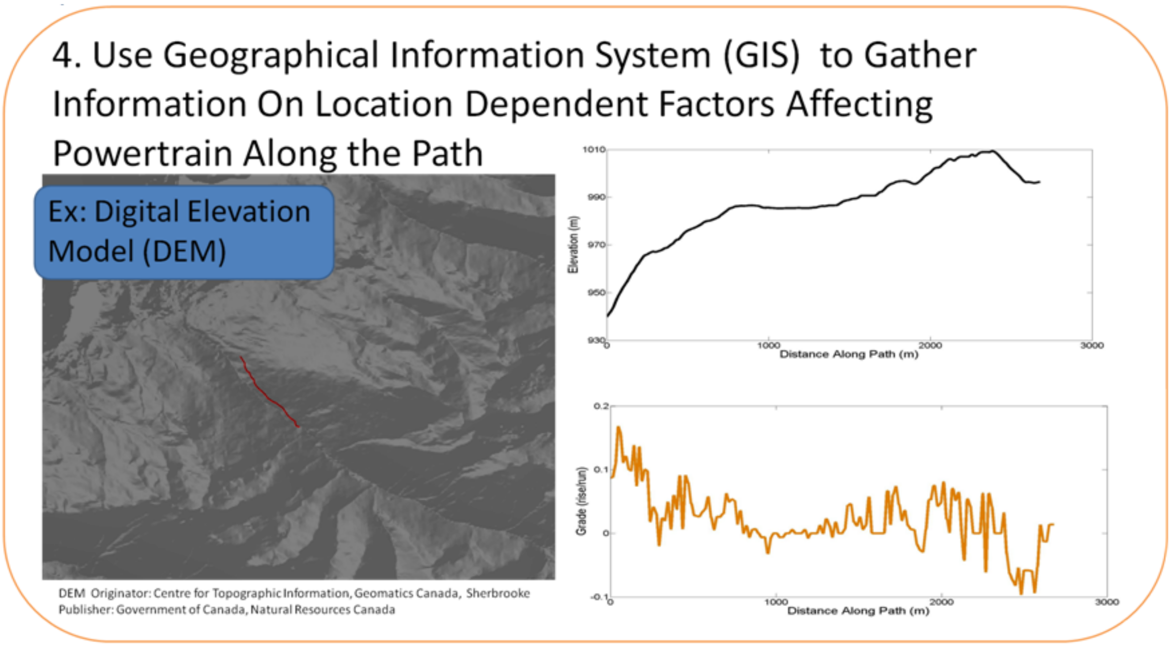

Figure 19: CWA Project – Extraction of Elevation Profile and Grade Schedule Creation

The speed and grade schedules were input into PSAT and simulations were performed for a round trip tour in the valley along Fitzsimmons creek. As a reference, simulations were also performed without accounting for grade. Simulation results are presented in Figure 20 below.

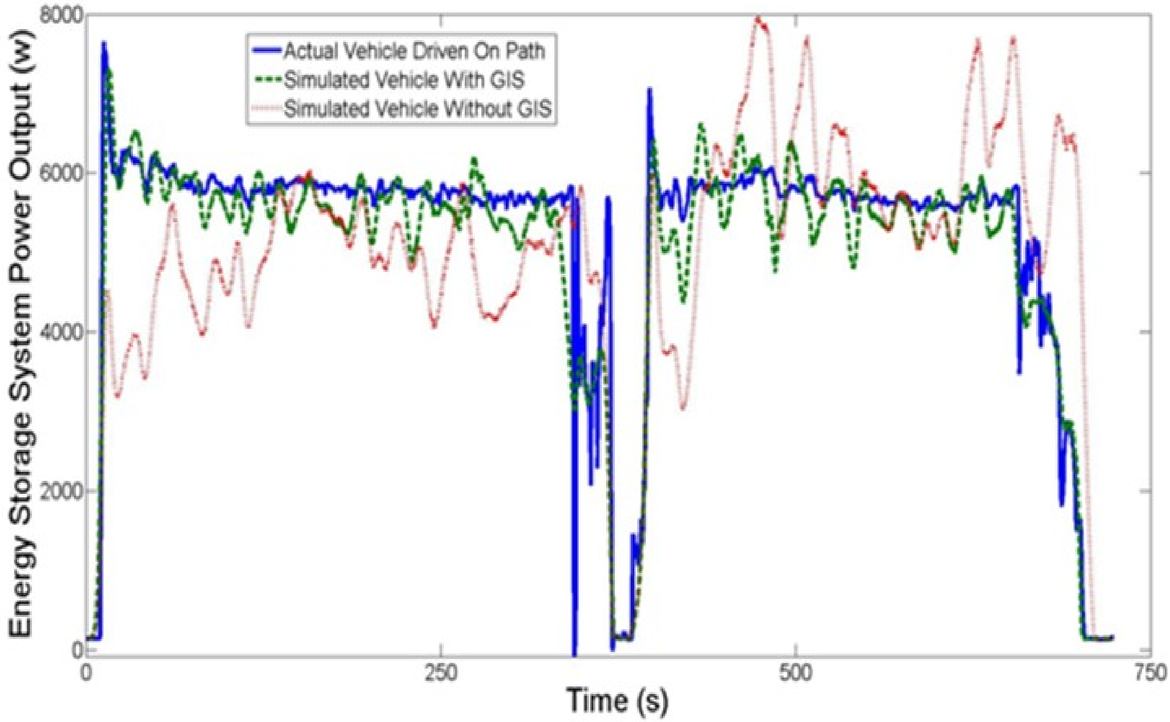

Figure 20: CWA Project – Simulation Results vs. Real Life Data

The results obtained provided an increased level of fidelity when compared to the alternative of not using grade information in the simulations. The approach of using GIS to obtain the grade information was considered an efficient means of doing so.

3.2.2.2 CWA Project Conclusions

The test methodology used for this project yielded promising results in terms of improving Gen2 PM&S fidelity for off-road vehicles for real life drive cycles by using GIS. However, a number of limitations were identified:

- The results seem to show that there were factors other than grade and speed which were having an impact on fidelity.
- Any deviation between drive schedule speed and simulated vehicle speed means that the grade data input into the simulation is wrong.
- The methodology can only yield useful improvement provided the speed at each instant of the simulation is known ahead of time.

3.2.3 Conclusion

Some of the key take away points from this section are:

1- Grade must be integrated in the simulation environment in order to obtain high fidelity results for the instantaneous power requirement of a vehicle in a given drive cycle

2- Baseline Gen2 PM&S can currently accurately integrate grade into simulations provided grade is constant throughout the simulation

3- Baseline Gen2 PM&S can cope with variable grade up to a certain point provided there is as little deviation as possible between the drive schedule speed and the simulated vehicle's speed. The more the grade varies in a simulation, the more likely it will be affected by a deviation in simulation speed vs. schedule speed.

4- Grade can play a significant role in an off-road vehicle simulation even if the path is relatively flat. This result is also reinforced by the data observed in the automotive example where a small 1% grade added to the UDDS drive cycle produced a significant increase in the power requirement.

5- GIS was shown to be a valid means of acquiring path and grade data.

6- Factors other than speed and grade may affect simulation results significantly in off-road vehicles.

In the following sections, other aspects which can have a significant impact on vehicle simulations will be investigated along with a means of ensuring that these aspects as well as grade can be integrated in Gen2 PM&S in a way that doesn't require simulation speed to be known ahead of time.

3.3 Effects of Vehicle-Terrain Interaction

Section 3.2 demonstrated that grade can play a significant role in the instantaneous power consumption of a vehicle and thus it needs to be well accounted for in simulation for accurate results. However, grade is not the only parameter which can vary significantly throughout a simulation.

The vehicle-terrain interaction is believed to be an area which can be of particular interest for off-road vehicles. In section 3.3, the role of vehicle-terrain interaction is investigated. For this, test data on the effect of vehicle-terrain interaction was gathered on three different days during the same week.

The objectives of this exercise are to:

- Determine if varying snow conditions have an impact on the vehicle's force vs. speed requirement
- Quantify this impact if present

3.3.1 Literature Review

A literature review of the effect of road surface type and roughness on light duty and heavy duty road vehicles shows a wide range of results. However, in general, the results almost never demonstrate a variation of more than ~10-12% between different road conditions. [23 - 26]

3.3.2 Effect of Terrain Surface Conditions on Force vs. Speed for Test Vehicle

Understanding and explaining in details the effect of terrain surface condition on a snowmobile's force vs speed requirements is an entire subject of its own at the convergence of vehicle dynamics and complex snow tribology. Little to no work has been published on the detailed linear resistance model of snowmobiles that explains, tests and validates all the variables in action which are specific to a snowmobile and relates them to snow conditions. This project's aim is not to explain detailed snow tribology and its impact on a snowmobile's power consumption. This project only aims to acknowledge that the interaction between the snowmobile and the snow surface is very complex and that it can vary significantly in terms of power requirement from day to day based on environmental conditions. Therefore, instead of modeling each aspect of the snowmobile's interaction with its environment individually, a coast down test approach was used to achieve the desired objective. Using this coast down approach allows one to account for the following aspects in a single all encompassing test:

- Variable plowing resistance of skis, track and carbide runners
- Variable track deformation losses
- Variable lubricated sliding friction of skis on snow, track clips on sliders, carbide runners on snow/ice
- Variable rolling resistance of suspension bogey wheels

In order to test the effect of different terrain surface conditions on the power requirement of the hybrid snowmobile test vehicle using a coast down test campaign inspired by the SAE J1263 standard, one key assumption must be made: a no slip condition must exist between the ground and the snowmobile's propelling track. In order to ensure this condition was valid, the vehicle was equipped with a GPS speed sensor and a drive shaft speed sensor. By comparing the speed output by both sensors, it was possible to ensure that slippage was negligible in the test conditions encountered and that the coast down approach was therefore usable for the intent of this project.

Six coast downs were performed back-to-back (3 in each direction) daily, in the same location, on three different days. The coast downs were performed with identical power limiting settings on the vehicle. Hence, given the effect of conditions encountered, some coast downs span a larger speed range than others.

Figures 21 and 22 below are aerial imagery taken during summer time by DTMI Spatial Inc. of McGill Lods Research center fields with an overlay of one of the coast downs performed in the area used for the straight coast down tests along the main field road. Vehicle speed is mapped in spectral colors with red being the vehicle's top speed during the test and dark blue being a speed of 0m/s.

It should be noted that, although the pictures show a summer time view of the area, the tests were done in winter.

Figure 21: Straight Line Coast Down Test Location within Lods Research Center

Figure 22: Straight Line Coast Down Example – Speed in Spectral Colors

3.3.3 Results

The results obtained for the coast down tests on a straight path on different days are presented in Figures 23, 24 and 25 below. Each figure presents an X-Y scatter cloud of points from the individual test runs as well as an average dotted line of the force vs. speed obtained for each day of testing.

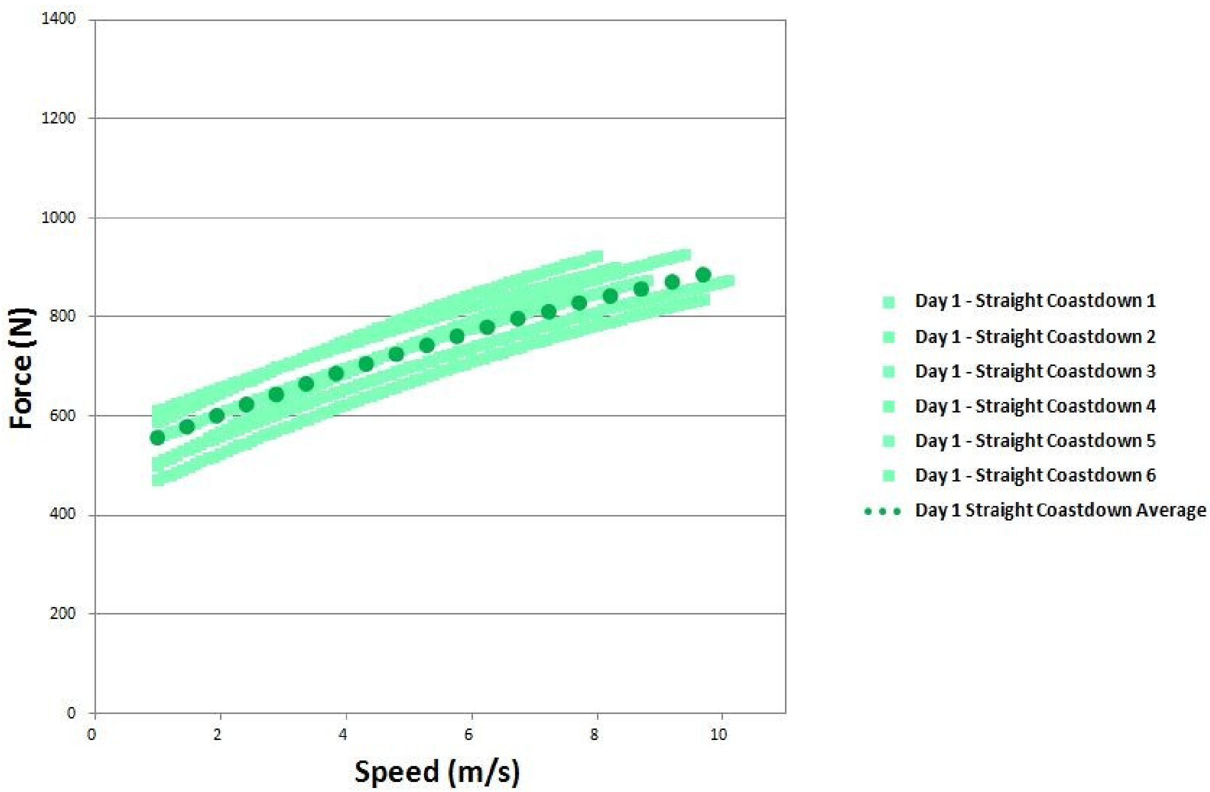

Figure 23: Day 1 Straight Line Coast Down Test Results – Force vs. Speed

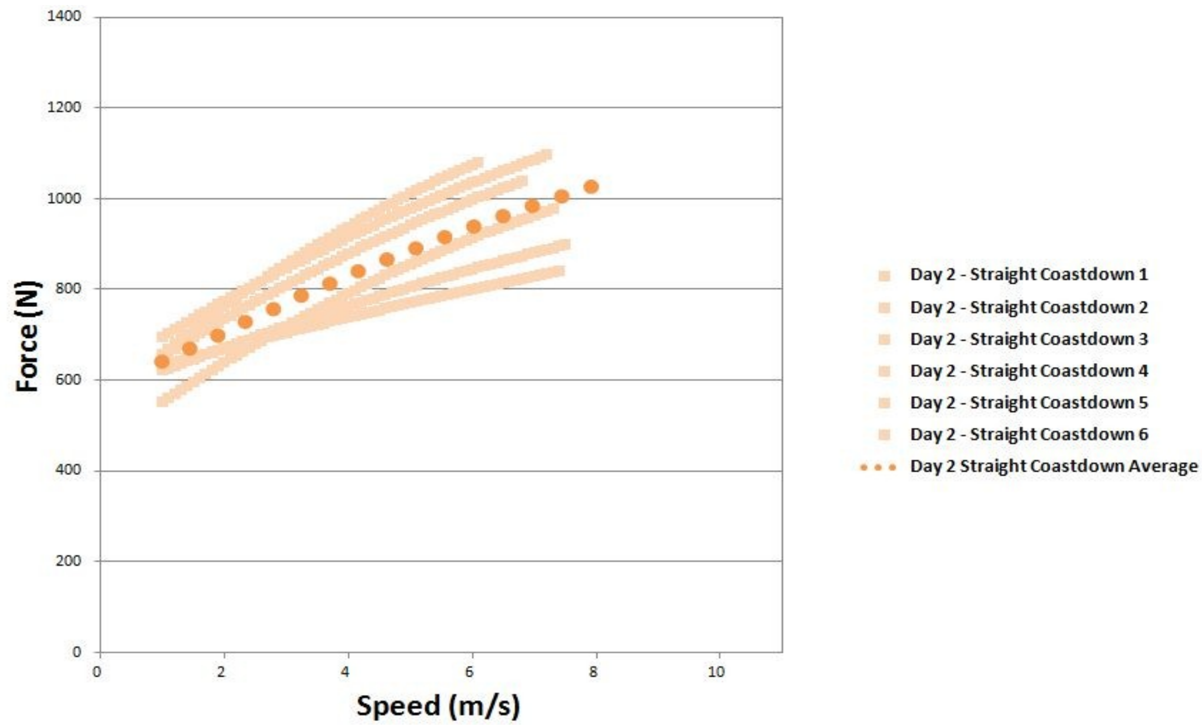

Figure 24: Day 2 Straight Line Coast Down Test Results – Force vs. Speed

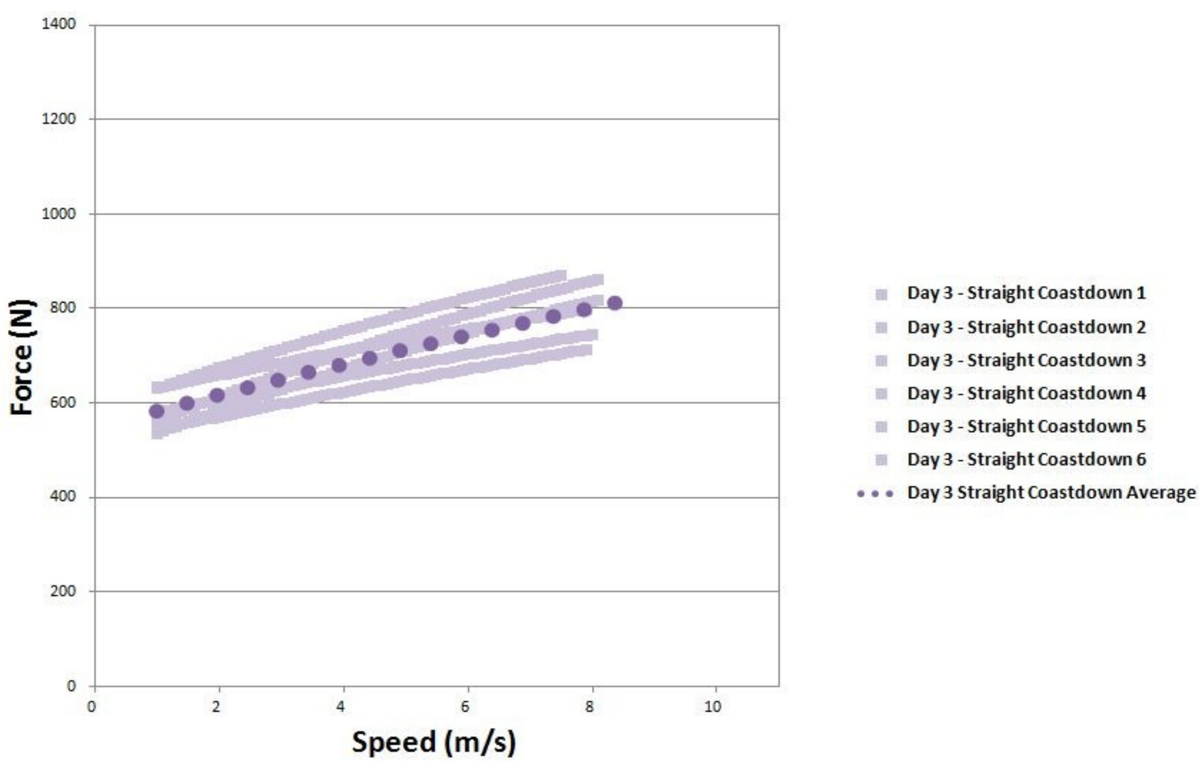

Figure 25: Day 3 Straight Line Coast Down Test Results – Force vs. Speed

Figure 26 below presents the average coast down line for each day on the same graph.

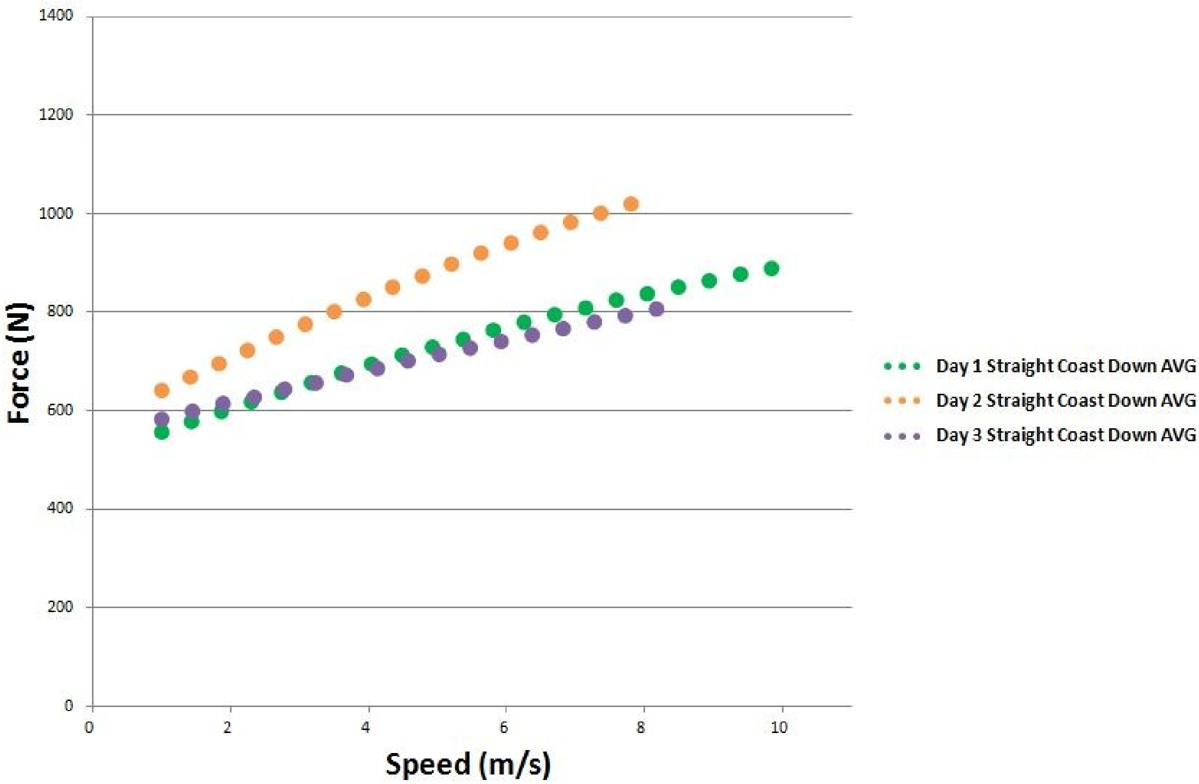

Figure 26: Daily Average Straight Line Coast Down Results – Force vs. Speed

3.3.4 Analysis of Results

The results shown in Figure 26 above clearly indicate that it is possible for the surface conditions encountered by an off-road vehicle to cause the force required at a given speed to vary significantly.

For example, at low speed, the force requirement on Day 2 is ~20% greater than on Day 1. This difference in force requirement increases as vehicle speed increases.

Interestingly, the conditions on Day 1 and 3 caused a similar force requirement at various speeds. However, despite being similar it is interesting to see that at low speed the conditions on Day 1 required less force than on Day 3, while at higher speed the conditions on Day 3 required less force than on Day 1.

The last point of interest is to quantify the greatest difference in force requirement observed at a given speed between two days. This happened between Days 2 and 3 at ~8m/s. The force required on Day 2 was over 40% greater than the force required for the same speed on Day 3. This is almost four times more than the worst cases found in the literature for road vehicles.

3.3.5 Conclusion

Section 3.3 looked at the effect of vehicle-terrain interaction on the force required to move the test vehicle at different speeds. Testing for this was performed on three different days within the same week.

The objectives of this exercise were to:

- Determine if varying snow conditions has an impact on the vehicle's force vs. speed requirement
- Quantify this impact if present

Based on the results obtained it is clear that in the case of an off-road vehicle such as a snowmobile, a common change in the vehicle-terrain interaction can yield a substantial change in the force required to drive the vehicle at a given speed.

The highest impact seen at low speed is a 20% increase. At higher speeds the largest impact observed was a ~40% increase in the required force. In must be noted that the conditions in which these tests were performed do not encompass all possible conditions the vehicle could encounter. Therefore, it is highly probable that even higher differences can be experienced between other conditions.

Snow conditions and grade are not the only aspects which can potentially vary along a given real life drive cycle. Path curvature is another aspect which can vary. Section 3.4 below looks at the effects of path curvature on vehicle force requirement.

3.4 Effects of Path Curvature

Sections 3.2 and 3.3 demonstrated how important the effect of grade and vehicle-terrain interactions can be for on-road and off-road vehicles. Section 3.4 looks at the third effect considered for this study: vehicle path curvature.

Test data for the effect of path curvature was gathered on the same three days as the data presented in section 3.3.

The objectives of this exercise are to:

- Determine if path curvature has an impact on the vehicle's force vs. speed requirement
- Quantify this impact if present

3.4.1 Literature Review

During the literature review, it was found that the difference in fuel consumption for a passenger car driving in a straight line vs. driving on a 500ft radius loop has been simulated and quantified as a function of speed from 2m/s to 30m/s. The test was performed using Gen3 PM&S software interfaced with the CarSim vehicle dynamics simulation software. [27]

The results of this study showed no difference in fuel consumption at speeds below 10m/s. Only above 10m/s did a difference start to become noticeable. The difference gradually increases from 10m/s to 30m/s. At 30m/s the estimated increase in fuel consumption when turning on this track was ~35-40%.

Another study, looking at low speed operation (0.15m/s) of a four wheeled robot on gravel, quantified the power requirement at different turning radii for two different types of wheels (rigid vs. pneumatic[3]) and two different types of turning approaches (explicit steering vs. skid steering[4]). The results of this study showed that for skid steering, power increases steadily as a function of turn radius. As a result, skid steering can require over 5x more power when doing a point turn versus driving in a straight line with pneumatic tires and 3x more power when using rigid wheels. [28]

It is clear from these examples that some types of off-road vehicles can see a tremendous impact on power consumption based on the curvature of the path they take even at very low speeds. Meanwhile on-road passenger vehicles may only start to see a measurable impact at higher speeds. These examples further emphasise why baseline Gen2 PM&S can produce relatively high fidelity results for on-road vehicles, but may only yield low fidelity results for some off-road vehicle cases.

---

[3] Rigid = Metal wheels made of an aluminum shell

Pneumatic = Elastomeric shell with an inner tube filled with air

[4] Skid steering is accomplished through the creation of a differential velocity between the inner and outer wheels. In explicit steering, a change in the heading of the wheels causes a modification to the vehicle heading. [28]

3.4.2 Effect of Path Curvature on Force vs. Speed for Test Vehicle

Given that the test vehicle for this project is a series hybrid snowmobile, a test procedure was devised to try and quantify the force required to drive this vehicle at different speeds while the steering mechanism is engaged for steering. The selected approach was to perform coast down tests with the steering mechanism fully engaged. The procedure was identical to the procedure presented in section 3.3 when measuring vehicle-terrain interaction in a straight line on different days, with the exception of the following two differences:

1- Due to space restrictions and terrain profile, the tests location differs from the test location used in section 3.3 (~500m away)

2- The vehicle speeds up in a straight line and then the steering mechanism was fully engaged prior to coasting.

Of the 6 tests performed on each day, 3 were done turning right and 3 turning left.

Figure 27 below shows the location of the sharp turn coast down testing relative to the straight line coast down testing.

Similarly, Figure 28 below shows an example of the shape of the resulting coast down path.

Both are aerial imagery taken during summer time (by DMTI Spatial Inc.) of McGill Lods Research center fields with an overlay of vehicle speed mapped in spectral colors with red being the vehicle's top speed during the test and dark blue being a speed of 0m/s.

Figure 27: Sharp Turn Coast Down Test Location within Lods Research Center Along with Straight Line Coast Down Test Location

Figure 28: Sharp Turn Coast Down Example – Speed in Spectral Colors

3.4.3 Results

The results obtained for the coast down tests on a curved path are presented in Figures 29, 30 and 31 below. Each figure presents the results obtained on one specific day of testing along with the results obtained for straight line coast downs for the same day (i.e. the results presented in section 3.3).

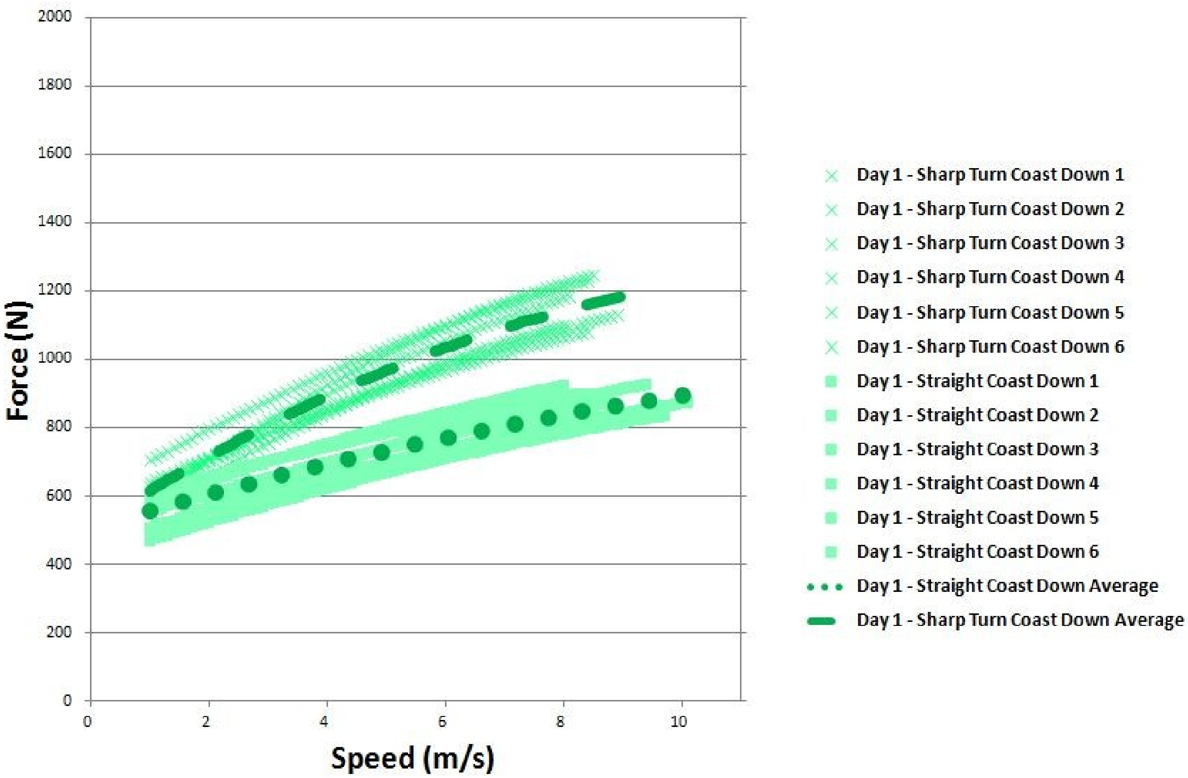

Figure 29: Day 1 Sharp Turn & Straight Line Coast Down Test Results – Force vs. Speed

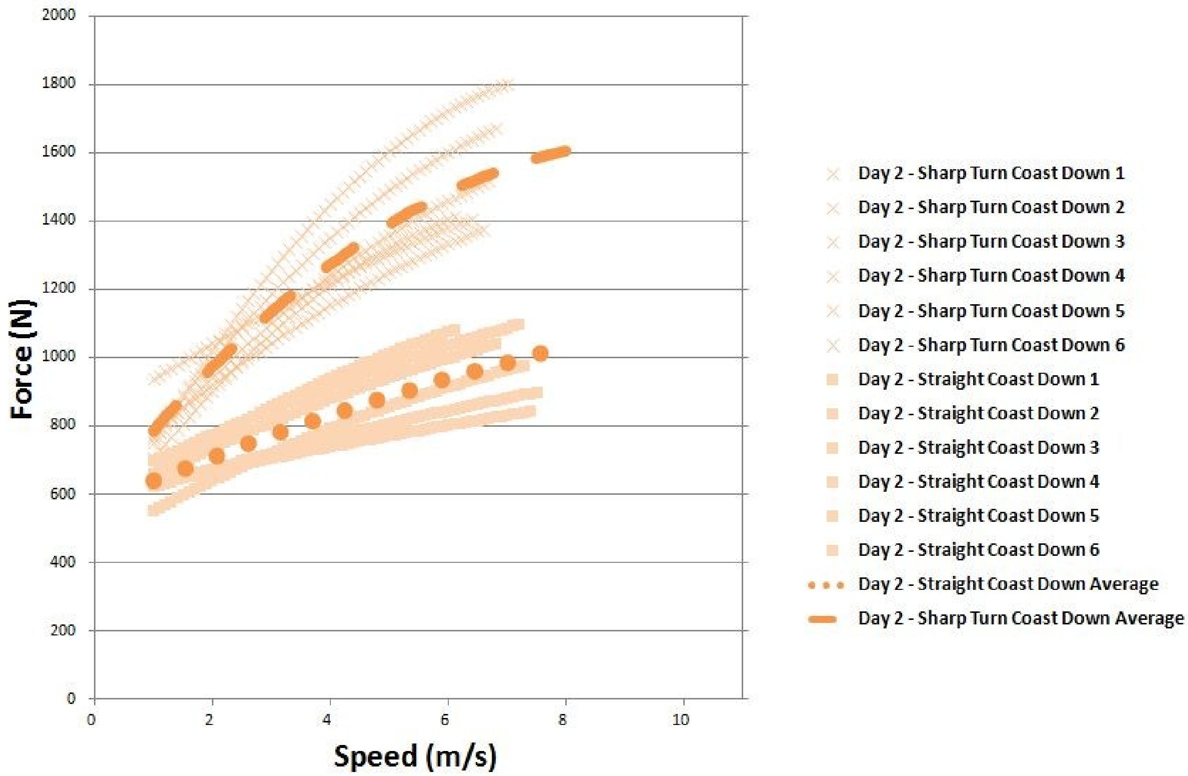

Figure 30: Day 2 Sharp Turn & Straight Line Coast Down Test Results – Force vs. Speed

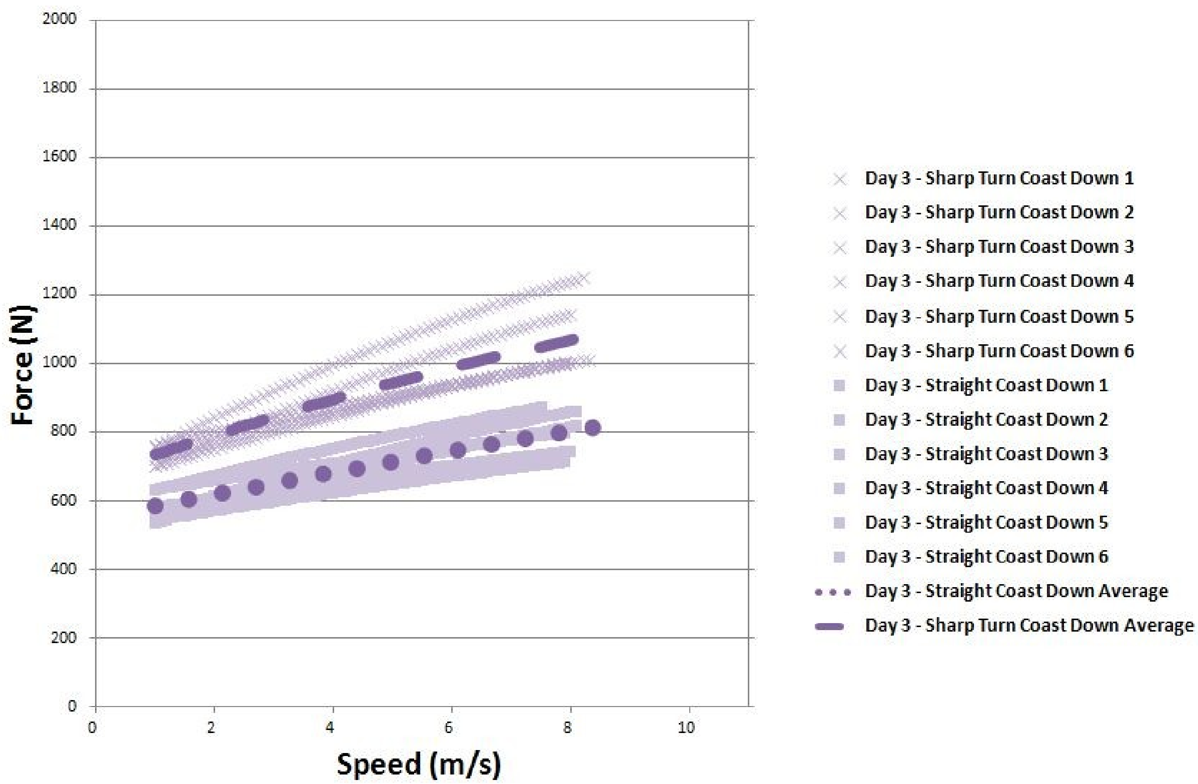

Figure 31: Day 3 Sharp Turn & Straight Line Coast Down Test Results – Force vs. Speed

3.4.4 Analysis of Results

The results shown in Figures 29, 30 and 31 clearly demonstrate that path curvature has an impact on the force required to move the vehicle at different speeds.

This difference varies depending on the snow conditions of each day. The following observations can be made:

- On Day 1, path curvature had very little effect on the force required at low speed (~5% increase).

- At the other end of the spectrum, on Day 3, even at low speed, path curvature increased the power required by about 30% over the straight line case.
- The relative difference in the force required while turning vs. while going straight on Day 3 barely increased from the 30% baseline as speed increased.
- As speed increased, Day 1 and Day 2 saw an increasing difference in the force required while turning vs. while going straight.
- The largest difference was seen on day 2 where turning required ~60% more force than going straight at higher speeds.

3.4.5 Conclusion

Section 3.4 looked at the effect of vehicle path curvature on the force required to move the test vehicle at different speeds. Testing for this was performed on three different days.

The objectives of this exercise were to:

- Determine if path curvature has an impact on the test vehicle's force vs. speed requirement
- Quantify this impact if present

Based on the results obtained, it is clear that path curvature can have impact on the test vehicle's force vs. speed requirement.

This impact ranged from a 5% increase at low speed on day 1 to a 60% increase at higher speed on day 2.

The following section presents a methodology to integrate in Gen2 PM&S, vehicle and environmental variability aspects shown, in sections 3.2, 3.3 and 3.4, to have an impact on the vehicle force vs. speed requirement.

4. Integrating Off-Road Vehicle Powertrain Models with GIS

In section 3, limitations of Gen2 PM&S software with regards to vehicle and environmental variability were explored. Also some environmental aspects of vehicle operation which can have a substantial impact on instantaneous power requirement were investigated. Furthermore, it was shown that the effect of some of these environmental aspects can potentially be much greater in some off-road vehicle applications than in typical on-road vehicle applications.

Section 4 presents the methodology used to integrate vehicle and environmental variability in Gen2 PM&S using GIS. This approach aims at expanding the capabilities of PSAT beyond the limitations shown in section 3.1 by allowing it to interact with the various aspects presented in sections 3.2, 3.3 and 3.4.

Achieving this will validate hypotheses #2 and #3 presented in section 1.2.1.

First in section 4.1, generic Gen2 PM&S models are integrated with GIS. Next in section 4.2, these new Gen2 PM&S + GIS models are initialized as off-road vehicles; in this case a snowmobile.

4.1 Integration of Generic Gen2 PM&S Models and GIS

This project aims at developing an approach which can be used by the entire off-road vehicle industry and not just on a specific vehicle type. Furthermore, ideally the results of this approach should be usable by the automotive industry as well even though the impact of environmental factors may be less than in the off-road sector. Therefore, it was deemed essential that the approach developed be vehicle type agnostic. It is with this objective in mind that the PSAT "vehicle agnostic" modeling approach with "vehicle specific" initialization was left untouched.

4.1.1 Selected Software

As previously mentioned in section 1, the selected Gen2 PM&S platform for this project is ANL PSAT.

In terms of GIS application, the QGIS 2.4.0 – Chugiak, open source GIS application was selected. A prime motivator for this choice was to see if a free GIS software add-on could provide all the functionalities required for this project.

In order for QGIS 2.4.0 to have all the required functionalities for the project, the following free plug-ins were downloaded and installed from the QGIS built in plug-in manager:

- Point sampling tool v0.4
- Points2One v0.2.14
- QChainage v0.1.3
- Interpolation v0.001

4.1.2 Experimental Setup

The ultimate goal of this project is to compare the fidelity of simulation results from two different approaches (baseline Gen2 PM&S vs. Gen2 PM&S + GIS) for an identical real life benchmark vehicle test scenario. In this sub-section, the chosen real life benchmark test scenario is described.

The chosen benchmark test scenario is a ~1.1km test path. This test path is located in field #86 of the McGill Lods Research Center. Its location was recorded using a Garmin GPS16-A unit. The recorded GPS location of the path is presented in Figure 32 below, overlaid in white on top of the DMTI Spatial Inc. aerial imagery along with the location of the coast down tests from sections 3.3 and 3.4.

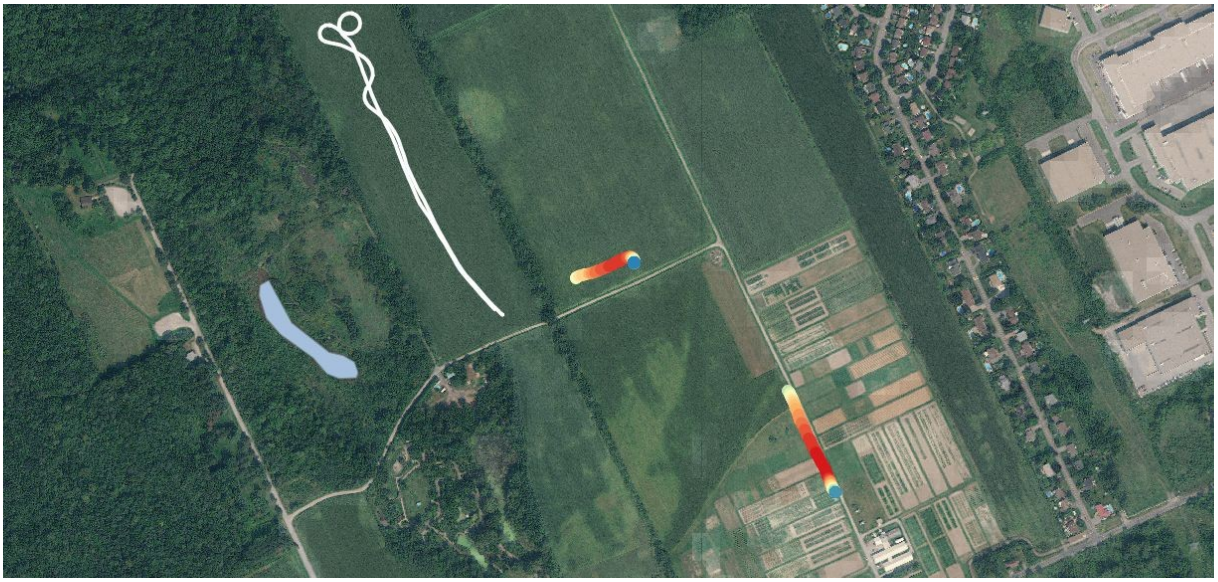

Figure 32: Location of Test Path within Lods Research Center Along with Coast Down Areas

The benchmark path was then divided into three categories:

1- Sharp turns

2- Medium Turns

3- Straights

Figure 33 below shows which segments have been associated to each category. Segments in solid orange are classified as sharp turns, long yellow dashes medium turns and white dotted segments as straights.

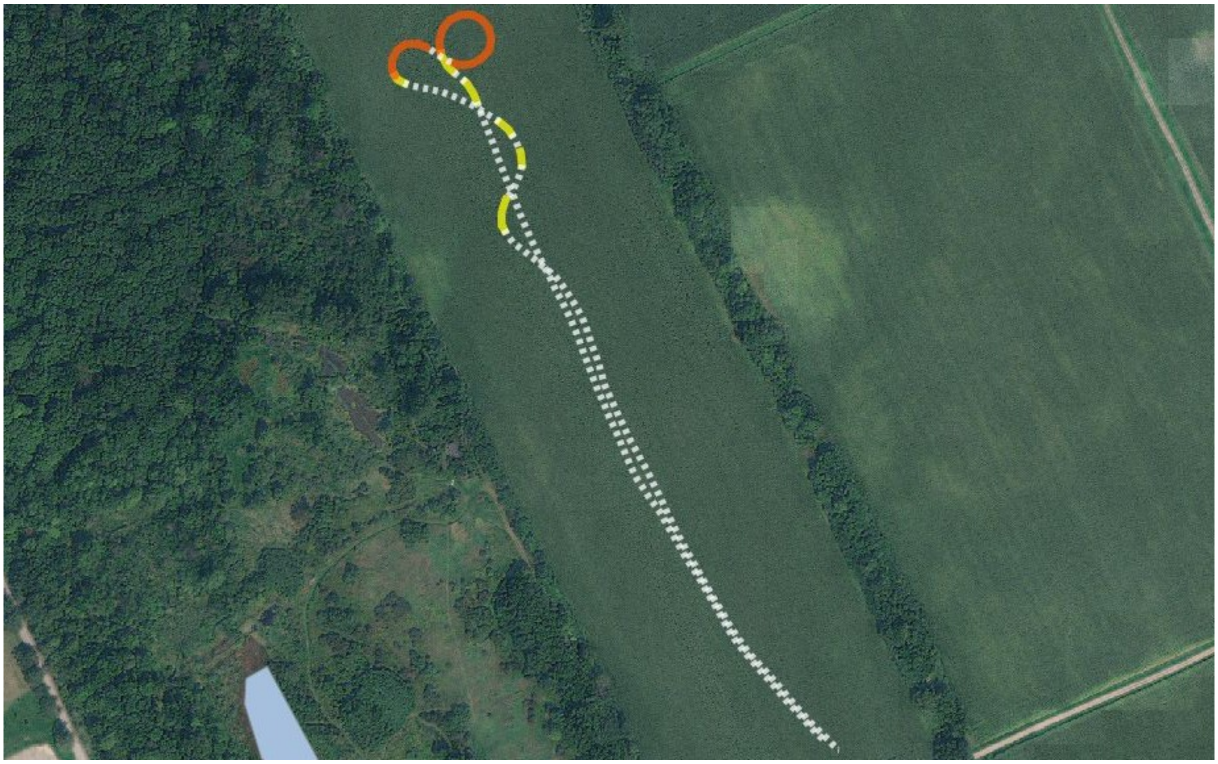

Figure 33: Test Path Segmentation

Table 5 below shows which distance percentage of the path falls under each category.

Table 5: Percentage of Total Path Distance by Classification Type

Path Section Category	Percentage of Total Path Distance
Sharp Turns	11.1%
Medium Turns	6.4%
Straights	82.5%

4.1.3 Implementation in QGIS

The benchmark test path logged with the Garmin GPS16-A was imported in QGIS as Latitude-Longitude (Lat-Long) points.

By using the Points2One Plugin, the GPS Lat-Long points were stitched together into a single line feature.

In parallel to importing the GPS Lat-Long points of the test path, geo-referenced elevation points of field #86 was obtained from the McGill Precision Agriculture & Sensor Systems Research Team[5]. They were imported to QGIS and from these points a triangulated irregular network (TIN) surface was created using the Interpolation Plugin v0.001. The resulting TIN digital elevation model (DEM) around the test path is presented below in Figure 34 along with a bare hillshade representation of the DEM and one with the DMTI Spatial Inc. aerial imagery overlay with some transparency.

---

[5] The McGill Precision Agriculture & Sensor Systems (PASS) Research Team is lead by Prof. Viacheslav Adamchuk, a Professional Agricultural Engineer who holds multiple awards in this field.

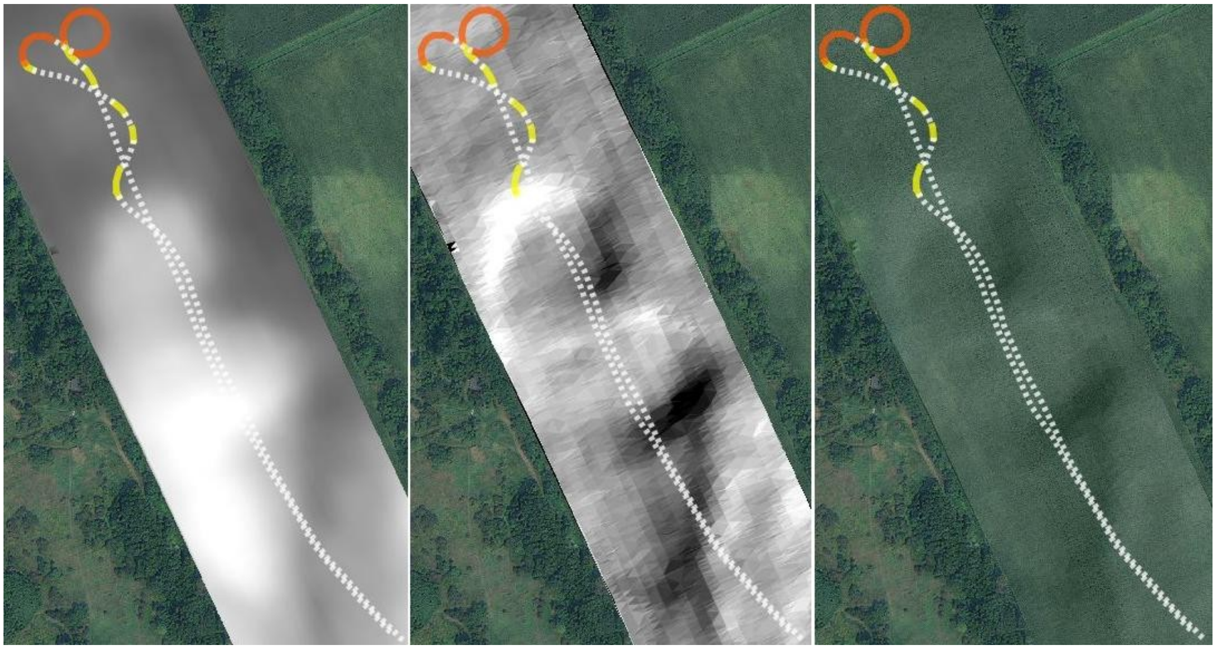

Figure 34: Test Path Overlaid on Field #86 DEM / Hillshade / Hillshade with Aerial Imagery

Using the QChainage v0.1.3 plugin, a layer of evenly spaced points (0.5m) was added along the test path. From these points, elevation from the DEM was extracted along the path every 0.5m using the Point sampling tool v0.4 plugin. Slope at any given location along the path was then calculated on a 2.5m span for the entire path.

The end result of this work is that a query to QGIS for this test path can now simultaneously output the grade and the path section classification (sharp turn/medium turn/straight) based on location along the path.

This work validates hypothesis #2 stated in section 1.2.1. Namely that: The aspects that primarily affect off-road vehicle simulation fidelity in Gen2 PM&S software can for the most part be catalogued in a GIS application, synchronized with one another, and eventually output as lookup tables.

4.1.4 Implementation in ANL PSAT - Gen2 PM&S Software

As demonstrated in section 3.1, ANL PSAT is a time-based PM&S simulation tool. In its original format, it is ill equipped to cope with variability of the vehicle model during a simulation. The one environmentally related aspect which PSAT can make a variable during a simulation is grade. However, PSAT uses time as the indexing value for grade variation during a simulation.

Given that in Gen2 PM&S the simulated vehicle's actual speed is an unknown prior to simulation (in contrast to the schedule speed), indexing slope perfectly as a function of time for a real scenario is not possible. This is especially true in the case such as the one under investigation where an extremely large step function is used as the input drive schedule in order to see what the vehicle speed and power consumption will be under maximum accelerator input conditions.

The challenge thus lies in modifying PSAT in such a way that it can:

1- Query the information from QGIS based on the virtual location of the simulated vehicle along the path.

2- Cope with multiple possible vehicle load models within the same simulation.

In order to achieve these objectives, modifications to the baseline PSAT curve fit losses (CFL) chassis model were made.

4.1.4.1 Query Information in GIS Based on Location

Since the vehicle path is known ahead of time and is already referenced in the GIS application, in order to query vehicle location in the GIS application, it is possible to define location as a distance point along the test path.

What is therefore required is to have the distance traveled along the path information present in the PSAT CFL chassis model block.

Since the PSAT CFL chassis model block already has vehicle speed information at each simulation time step available within it, it was decided that distance travelled along the test path would be obtained by passing the instantaneous speed information through a new integral block in the CFL chassis model.

Combining this with a new look-up table which is populated by the grade vs. distance information contained in the GIS application was sufficient to modify PSAT to now query grade information in the GIS based on location.

Figure 35 below highlights the modifications performed to PSAT's baseline CFL chassis model block.

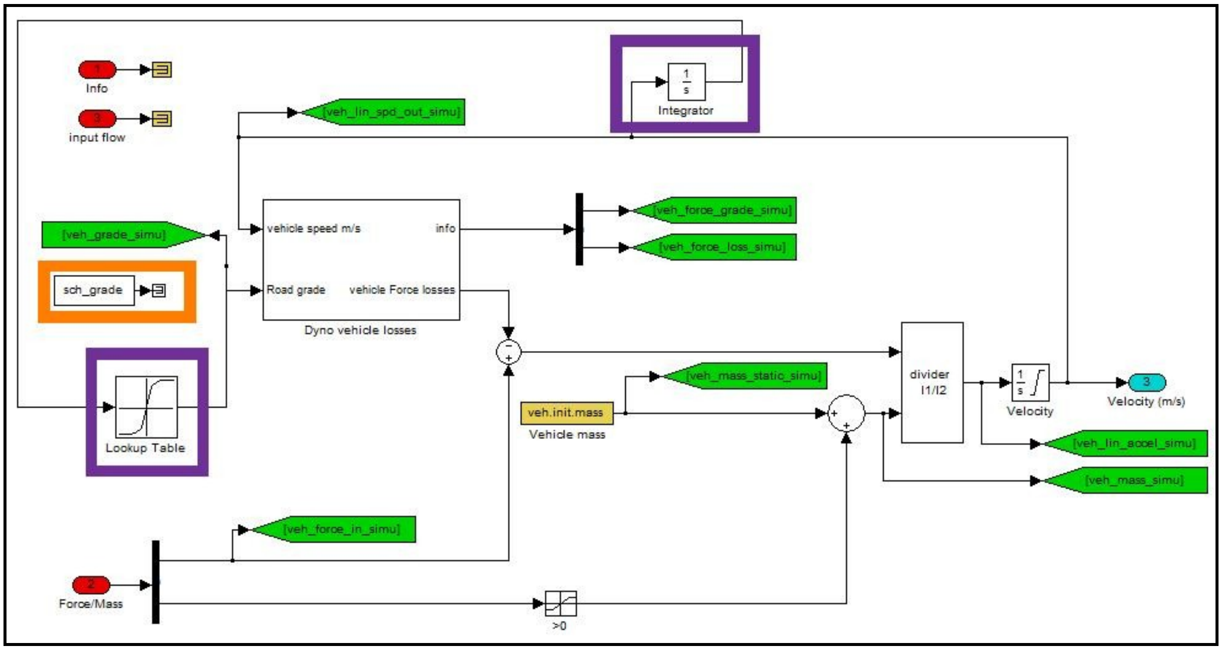

Figure 35: Modifications to PSAT's baseline CFL chassis model block.

In Figure 35 above, the blocks boxed in purple are the blocks added to the PSAT's baseline chassis model while the block boxed in orange has been disconnected from the PSAT baseline.

4.1.4.2 Coping with multiple chassis models in a simulation

The previous sub-section showed how it was possible to use the GIS grade data in PSAT. However, those modifications are not sufficient for PSAT to cope with variations in the vehicle – environment interactions during a simulation.

In order to do this, the chassis model's "Dyno Vehicle Losses" (DVL) block must be expanded and:

1- The vehicle's location must be defined within that block

2- A GIS lookup table with location as an index must be defined within that block.

3- The output of the lookup table must trigger a change in the chassis model's DVL curve fit equation.

Points 1 & 2 can be achieved by using the approach defined in 4.1.4.1 since vehicle speed is present at each time step within the PSAT CFL chassis model's DVL block.

In order to achieve point 3, the following steps are taken:

- The coefficients (F0, F1, F2) of the baseline PSAT CFL chassis model's DVL block, are disconnected from their summation block.
- A multiport switch block is inserted between each coefficient block and the summation block.
- These multiport switch blocks are connected to the GIS information lookup table and they use the information this table outputs to determine switch position.
- Different coefficient values are connected to each coefficient's multiport switch block.

These modifications to the baseline PSAT CFL chassis model's DVL block are presented in Figure 36 below.

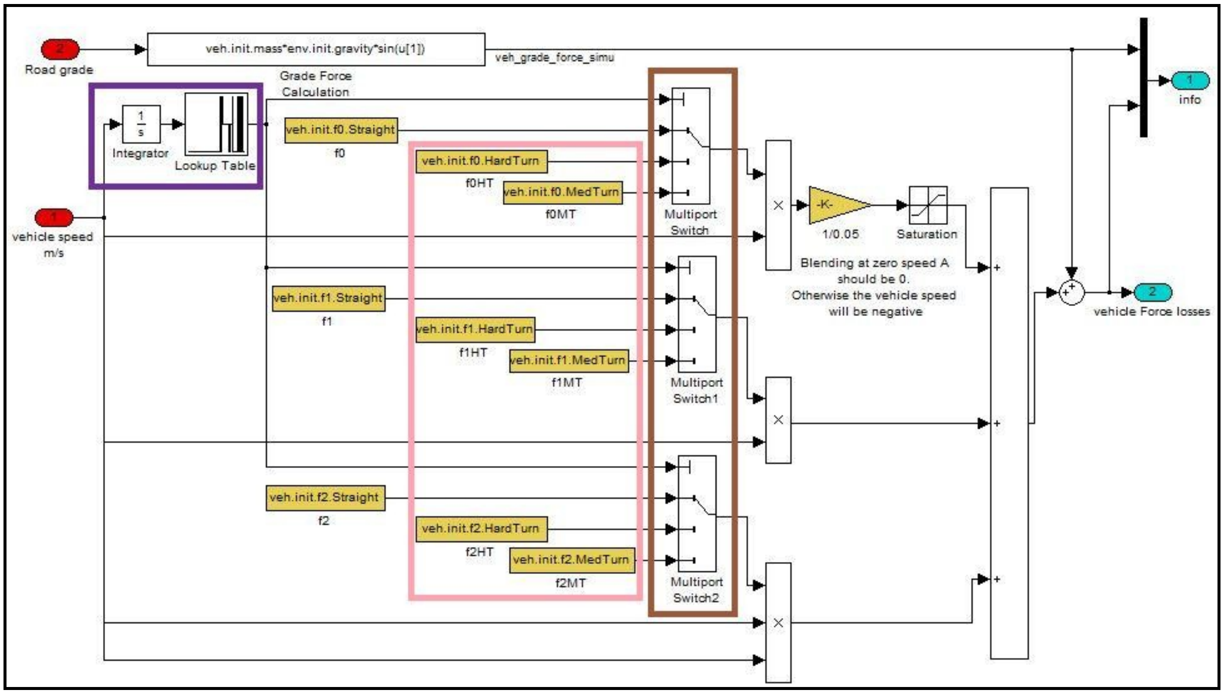

Figure 36: Modifications to the PSAT baseline CFL chassis model's DVL block

In Figure 36 above, the following changes to the baseline DVL block can be seen.

- Within the purple box are the changes implemented for PSAT to define the vehicle's location and use it as an index to output the multiport switch trigger value based on the GIS information.
- In the pink box are the new curve fit coefficients for the new supplemental vehicle-environment interactions.
- In the brown box are the newly added multiport switches that make it possible to move from one vehicle-environment model to another during a simulation.

4.1.5 Conclusion

Section 4.1, presented the methodology used to integrate vehicle and environmental variability in Gen2 PM&S using GIS. This approach expanded the capabilities of PSAT beyond the limitations shown in section 3.1 by allowing it to interact with the various aspects presented in sections 3.2, 3.3 and 3.4.

By achieving this, hypotheses #2 and #3 presented in section 1.2.1 have been validated. These hypotheses stated that:

- Hypothesis #2 - The aspects that primarily affect off-road vehicle simulation fidelity in Gen2 PM&S software can for the most part be catalogued in a GIS application, synchronized with one another, and eventually output as lookup tables.
- Hypothesis #3 - Gen2 PM&S software can be modified in such a way that it can accept and integrate, in the model and the simulation, spatio-temporally reference information from a GIS application.

The next section (4.2) describes how the newly modified PSAT vehicle model was populated with vehicle specific initialization information in order to run simulations.

Following this, section 5 gives the results of the simulations with and without the GIS information, and compares them to real life test data.

4.2 Vehicle Model Initialization

In order to run a simulation with the baseline PSAT vehicle model or the newly modified vehicle model, a number of parameters must be initialized.

Even though the test snowmobile is a series hybrid snowmobile, it is only being operated in electric mode for the purpose of this test. Therefore, the electric vehicle model structure used in previous work [3] can be used.

This section presents the information used to initialize the vehicle model for both the baseline Gen2 PM&S approach and the Gen2 PM&S + GIS approach.

4.2.1 Vehicle Model Initialization - Gen2 PM&S + GIS

With the exception of the chassis model block whose modifications have been documented in section 4.1, all other vehicle model blocks remained the same as in previous work [3].

The initialization parameters for blocks upstream of the motor controller were left unchanged.

The initialization parameters for blocks downstream and including the motor-controller had to be modified since the snowmobile being used for this test is a completely different model. Gearing ratios, effective wheel dimensions and motor power &

efficiency maps have all been measured for this new vehicle and input to the PSAT environment in the same way as in previous work. [3]

The most important differences related to the core of this project are that now:

1- Grade vs. location table must be initialized based on the GIS information

2- Vehicle – Environment interaction classification as a function of location must be initialized based on the GIS information

3- The PSAT CFL chassis model's DVL coefficients must be initialized for each Vehicle – Environment interaction classification category

The three sub-sections below explain how this was done.

4.2.1.1 Grade vs. Location

This table is populated using the grade information presented in section 4.1.3.

Field #86, the location of the test path, is usually a corn field in the summer time. Therefore, it should be no surprise that the graphic representation of grade vs. location for the test path shown below in Figure 37 does not present any major inclines over prolonged distance.

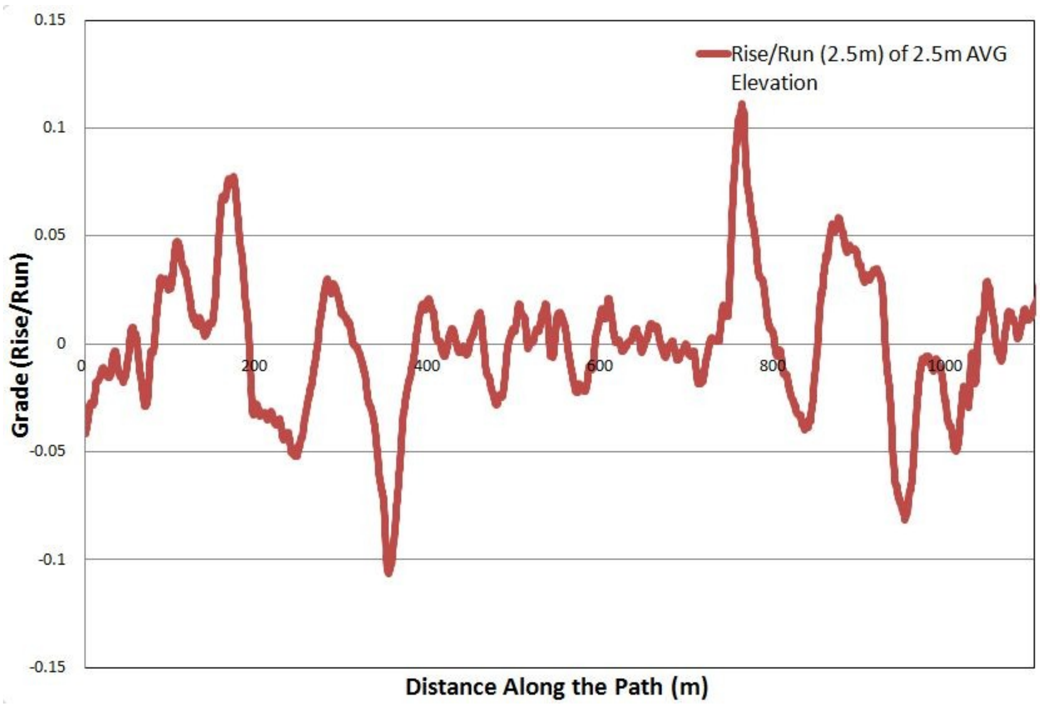

Figure 37: Test Path Grade vs. Location Along the Path

4.2.1.2 Vehicle – Environment interaction classification vs. Location

For this experiment, vehicle-environment interaction classification was divided into 3 classes as discussed in section 4.1.2. Figure 38 below shows a graphic representation of the change in classification as a function of distance for the test path.

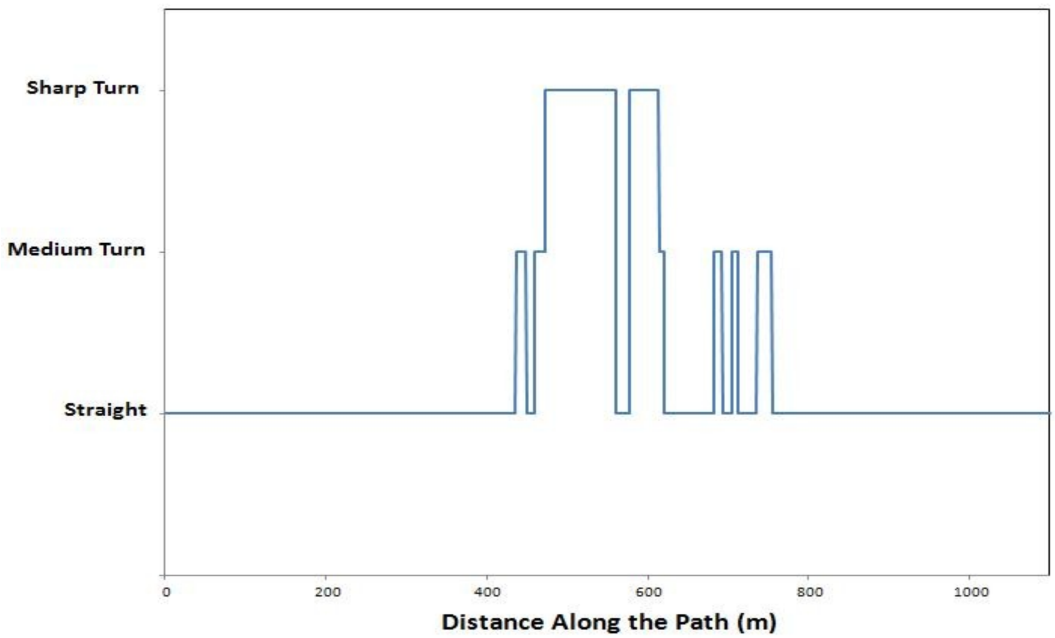

Figure 38: Test Path Classification Category vs. Location Along the Path

4.2.1.3 Defining Chassis Model Coefficients for each Vehicle – Environment Interaction Category

As defined in section 4.1.2, the vehicle-environment interactions have been classified in three categories for this test: straight driving, medium turning and sharp turning. In section 4.2.1.2 the initialization of the moment when each category comes into effect in the simulation was presented.

Now, in section 4.2.1.3, the definition and initialization of the coefficients of the CFL chassis model's DVL which come in to effect for each vehicle-environment interaction category is presented.

As explained in section 3, this project uses a curve fit equation approach to model the various loads experienced by the vehicle as a function of speed. In a standard Gen2 PM&S software, this approach requires the initialization of three coefficients under the standard automotive approach of defining vehicle loads as a second order polynomial.

In the case of the snowmobile being tested, it was deemed appropriate to use a 2nd order polynomial equation to represent the vehicle loads as a function of speed. However, given the slower test speed, this equation is different than what is normally seen in the automotive sector due to its negative 2nd order terms coefficient.

In order to fully initialize all the parameters required by the new Gen2 PM&S + GIS approach, three equations must be used to initialize the model instead of one as in standard Gen2 PM&S.

The coefficients of the first equation are the coefficients to be used when driving in a straight line. Given that the test case presented for validation in this paper was performed on Day 1 of testing, the selected coefficients are those found by performing a 2nd order polynomial curve fit on the average of the straight line coast down force results of Day 1 presented in section 3.3. Figure 39 below shows the resulting equation.

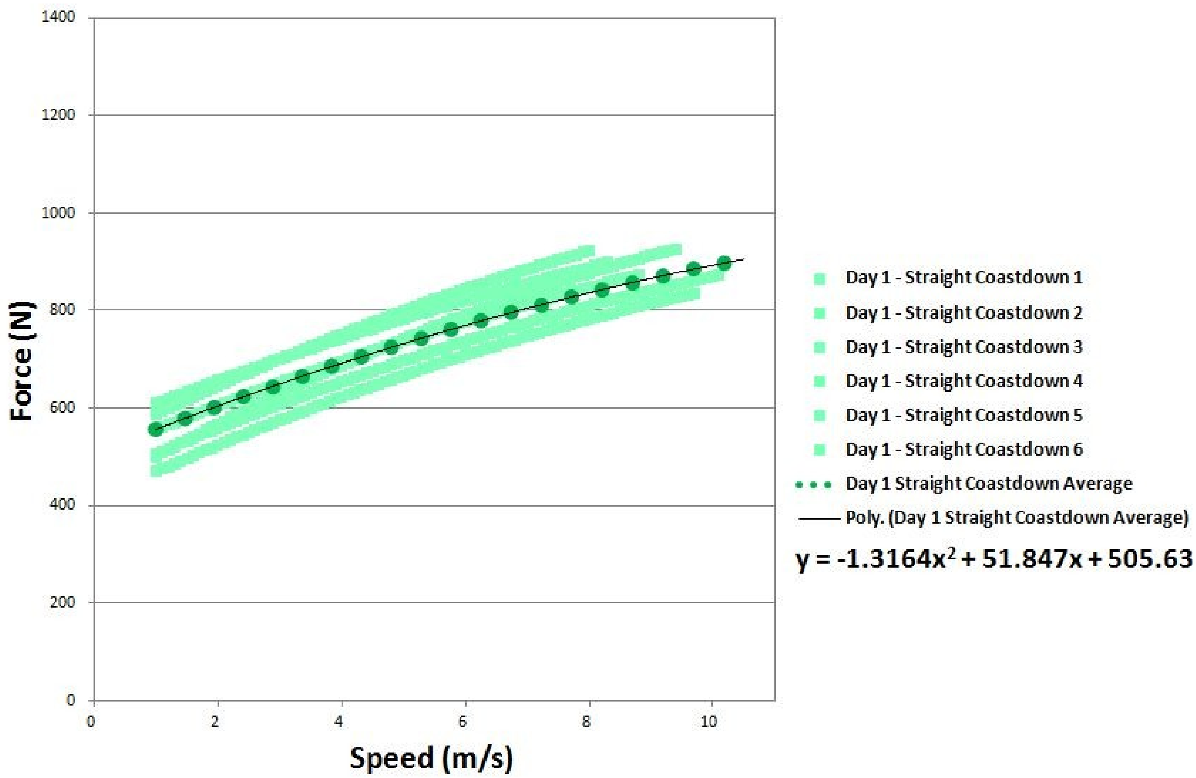

Figure 39: 2nd Order Polynomial Curve Fit of Straight Line Coast Downs on Test Day

A second set of initialization coefficients, have been obtained for when the vehicle is performing a sharp turn. As with the straight line case, given that the test case presented for validation in this paper was performed on Day 1 of testing, the selected coefficients are those found by performing a 2nd order polynomial curve fit on the average of the sharp turn coast down force results of Day 1 presented in section 3.3. Figure 40 below shows the resulting equation.

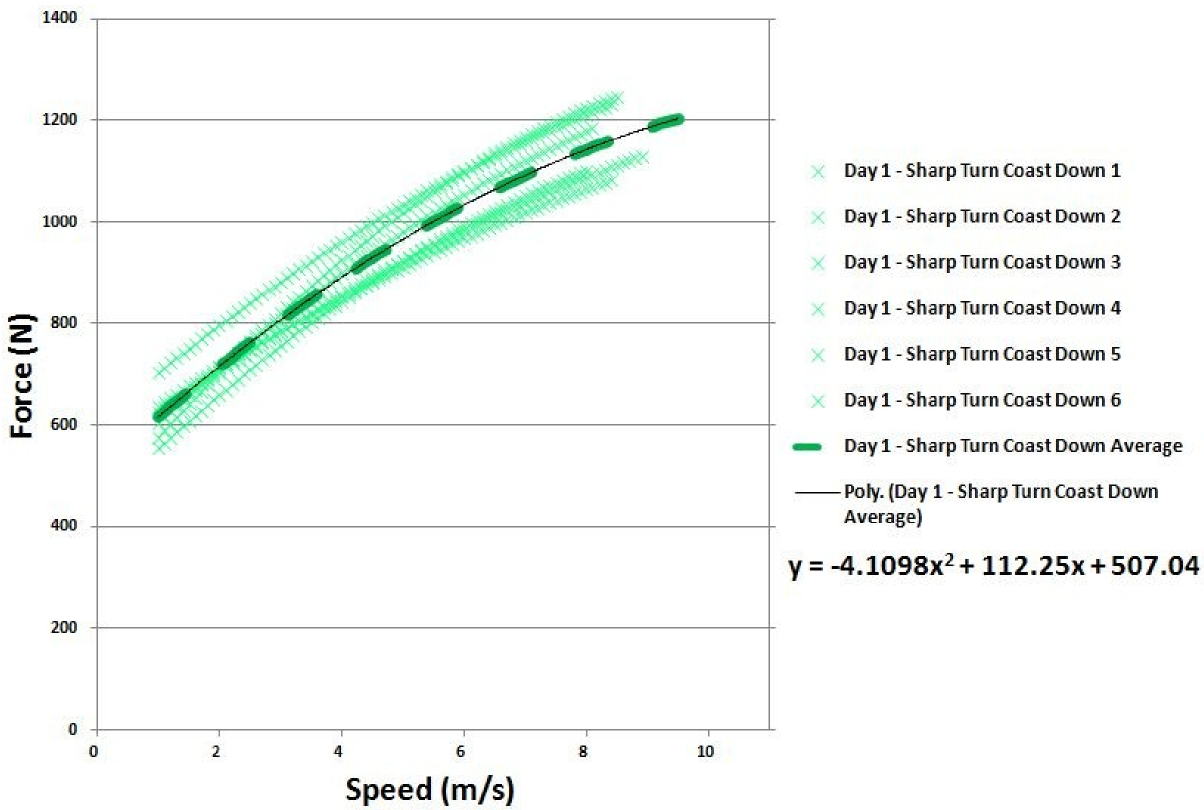

Figure 40: 2nd Order Polynomial Curve Fit of Sharp Turn Coast Downs on Test Day

Since only straight line coast downs and sharp turn coast downs were performed, it is not possible to obtain the required 3rd set of coefficients for medium turns directly from a dedicated set of coast down data. In order to obtain these coefficients, a new force vs. speed equation was calculated by finding the mid-point between the average straight line coast down curve fit equation and the average sharp turn coast down curve fit equation. The resulting medium turn force vs. speed line is presented below in Figure 41 with its 2nd order polynomial curve fit equation and the two lines and equations that were used to generate it.

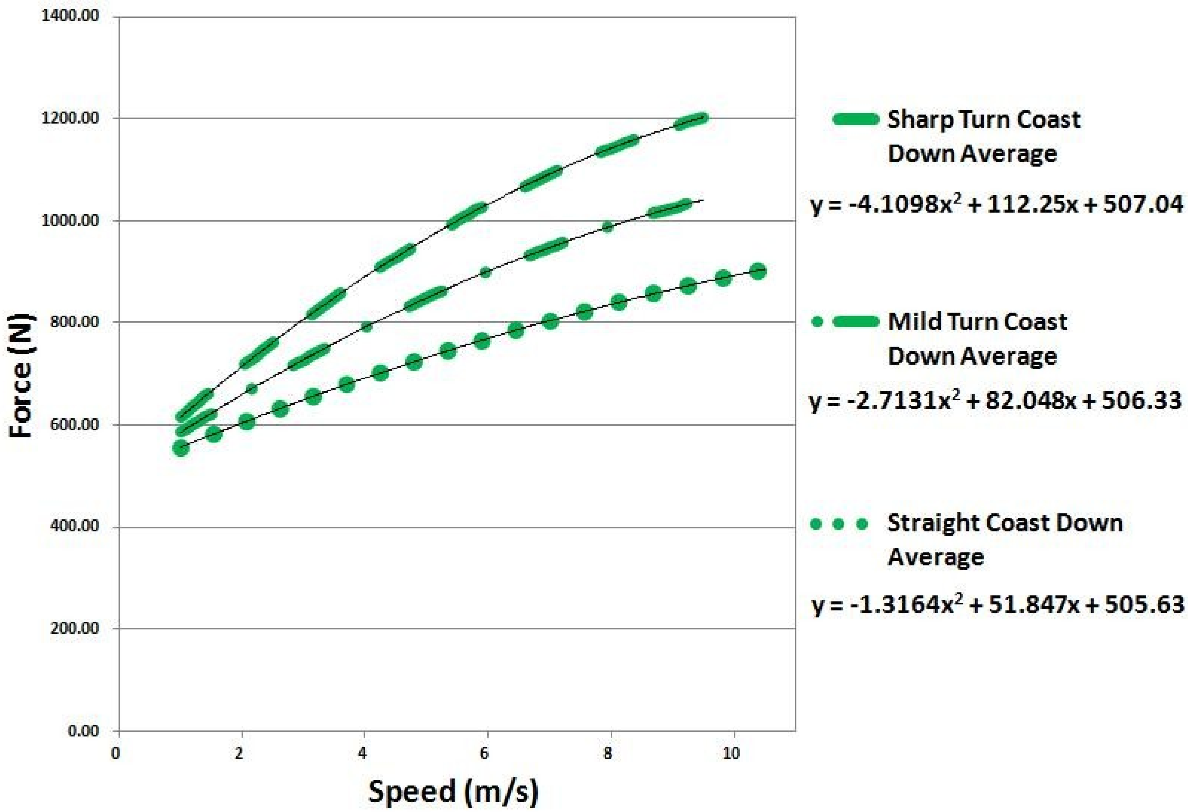

Figure 41: Sharp Turn, Medium Turn and Straight Line Force vs. Speed Coefficients Used to Initialize Test Day Vehicle Model.

By using the nine coefficients shown in Figure 41 (3 equations, each with 3 coefficients) it is possible to initialize all the parameters required by the modified version of the PSAT CFL chassis model DVL block presented in section 4.1.4.2.

4.2.2 Vehicle Model Initialization – Baseline Gen2 PM&S

For the Gen2 PM&S software baseline simulation, the model used and its initialization parameters are identical to the one described in section 4.2.1 with the exception that it uses the generic PSAT CFL chassis model. Therefore, this block is only initialized with the coefficients for the average straight line coast downs found in Figure 40.

4.2.3 Conclusion

This section presented the information used to initialize the vehicle model for both the baseline Gen2 PM&S approach and the Gen2 PM&S + GIS approach.

The baseline Gen2 PM&S approach uses a single set of chassis load parameters derived from the straight line coast down data. This is the only information which will be used by the chassis model during simulation.

On the other hand, the Gen2 PM&S + GIS approach uses the same chassis load parameters as the above baseline Gen2 PM&S approach, but it can also vary some parameters during the simulation thanks to a modified vehicle model chassis component that can query the geo-referenced information at each simulation time step.

In this project, two unrelated variables (terrain topology and vehicle turning radius) are related via GIS and this information is used to adjust the vehicle model's chassis component at each simulation time step.

At this point in the process there are two models of the same snowmobile in PSAT. They are identical except for the fact that one of them can receive information from a

GIS application as a function of location and also change the force vs. speed coefficients based on the information provided by the GIS application.

In the next section, both snowmobile models will be asked to simulate a situation where a snowmobile driver fully engages the accelerator for the entire duration of a test run. The results from each simulation will be compared to the data obtained when performing this test in real life. One key assumption being made in these tests is that the snow conditions in which the coast down tests were performed are representative of the snow conditions in which the test run is performed.

5. Testing and Validation

So far, three of the four hypotheses stated in section 1.2.1 have been validated. However, in order for this project to attain its goal, the fourth and last hypothesis must also be validated. This hypothesis states that:

Simulations from Gen2 PM&S + GIS will yield results with significantly higher fidelity to data obtained in full scale real life trials than simulation results obtained using the same Gen2 PM&S software without GIS add-on.

This section looks at the results obtained with both approaches and compares them to real life test data in order to validate the fourth and final hypothesis. By doing so, the improvement potential of this new methodology is quantified for the case example under consideration.

One key assumption being made in these tests is that the snow conditions in which the coast down tests were performed are representative of the snow conditions in which the test run is performed. This is believed to be a valid assumption since the tests are performed within a few hundred meters from one another and within minutes from one another.

The real life test scenario is described as such in section 1:

A driver mounts on a series hybrid snowmobile prototype at rest and then, promptly, fully engages the accelerator thumb lever of the vehicle. The driver keeps the accelerator thumb lever of the vehicle fully engaged throughout the test drive while using the vehicle's steering and his body positioning to keep the snowmobile on a pre-defined course.

The aforementioned pre-defined test course is presented in details in section 4.1.

5.1 Initial Results

Section 5.1 first shows the results obtained using baseline Gen2 PM&S and then those obtained using Gen2 PM&S + GIS. The results from both approaches are compared to the data gathered during real life tests. An error analysis is performed between the simulation output of each approach and the real life test data.

5.1.1 Simulation output data

The measure of success of this project has been defined in section 1.1.3 as its ability to predict vehicle speed and controller power input as a function of vehicle location along a known path.

Therefore, the simulation output variables which will be analyzed and compared to real life data in this section are the vehicle speed and the controller power input.

5.1.2 Baseline Gen2 PM&S Results

Figure 42 below shows the output of the baseline Gen2 PM&S for the two variables under consideration.

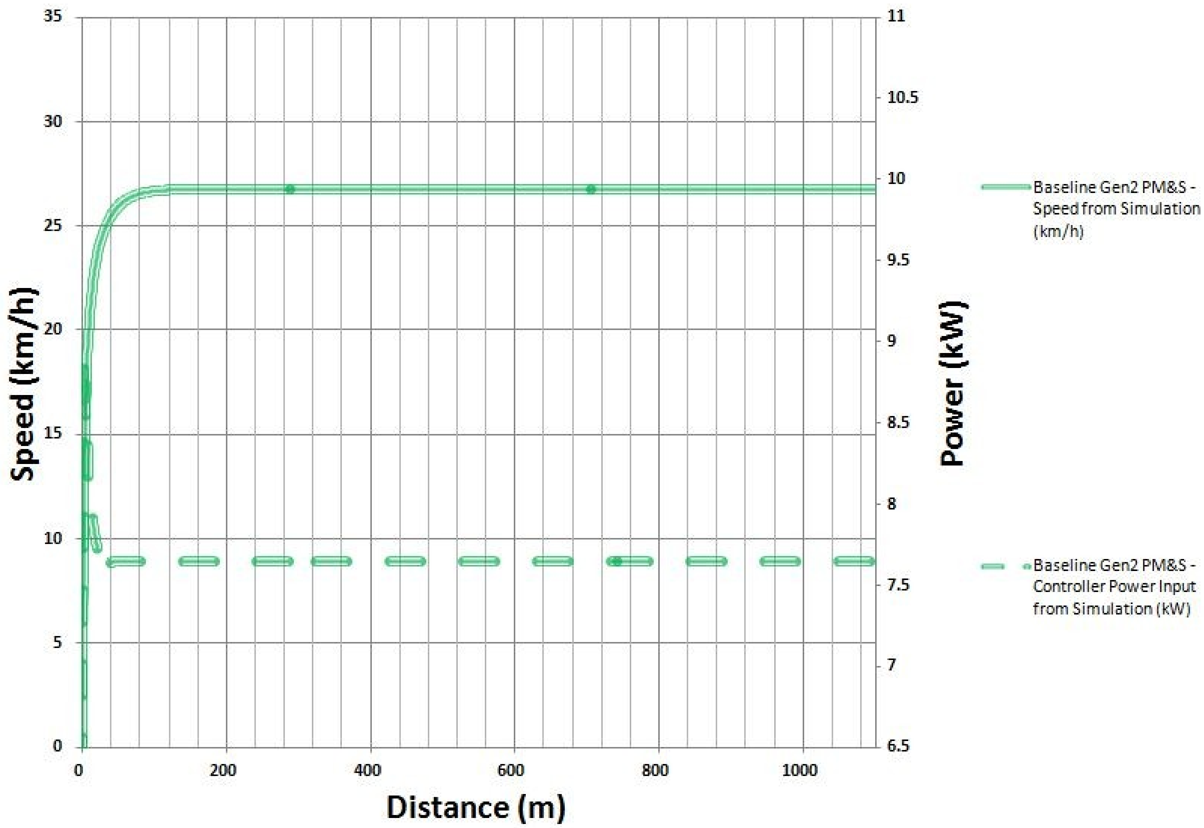

Figure 42: Baseline Gen2 PM&S Simulation Results (Speed & Controller Power Input)

Since there are no variations in any environmental factors in this simulation, as expected, the speed hits a plateau at a certain point and simultaneously, the power in to the controller also achieves steady state.

When superimposing the data recorded during real life testing to the baseline Gen2 PM&S results, the graph in Figure 43 is obtained.

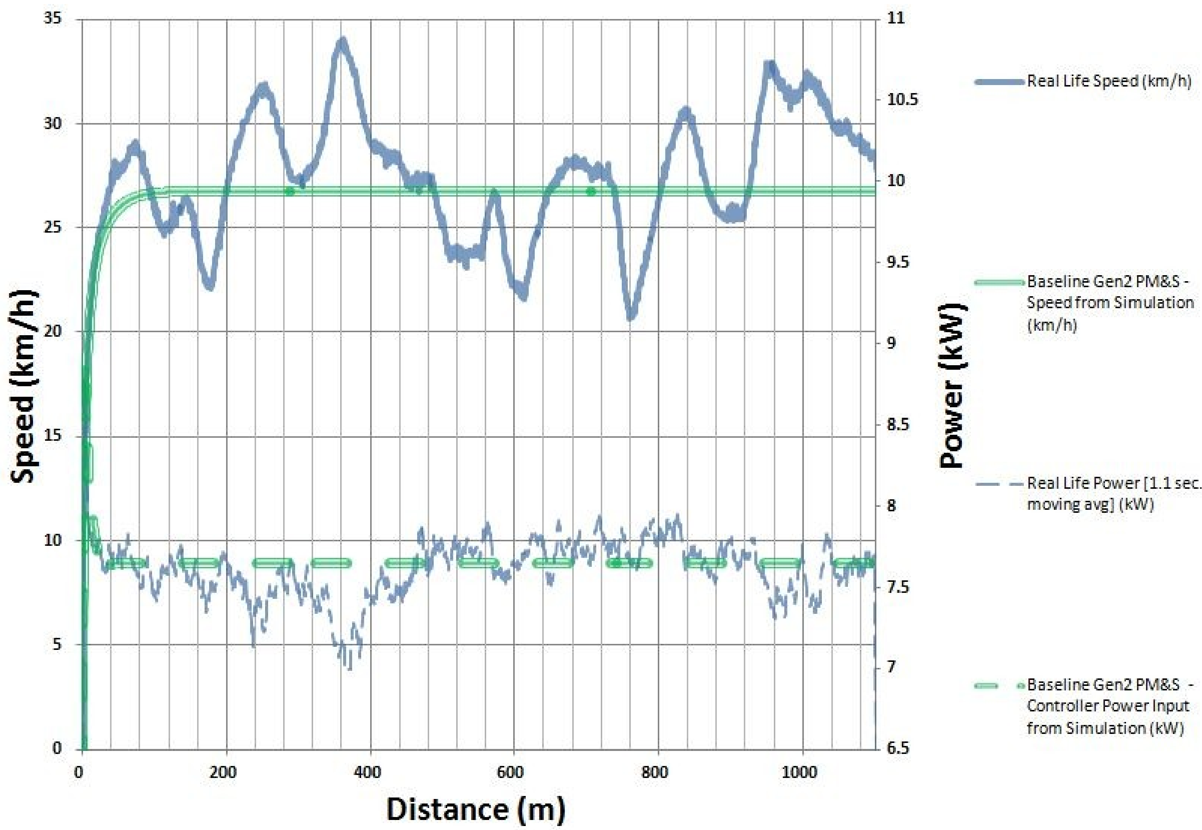

Figure 43: Baseline Gen2 PM&S Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

Table 6 below presents the mean absolute error (MAE), the standard deviation of the error and the mean absolute percentage error (MAPE) for both the vehicle speed and the controller power input for the baseline Gen2 PM&S approach.

Table 6: Error in Baseline Gen2 PM&S Initial Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

	Vehicle Speed	Controller Power Input
Mean Absolute Error	2.22 km/h	0.06 kW
Standard Deviation	2.64 km/h	0.12 kW
Mean Absolute Percentage Error	8.06 %	0.83 %

5.1.3 Gen2 PM&S + GIS Results

Figure 44 below shows the output of the Gen2 PM&S + GIS simulation for the two variables under consideration. The GIS cataloged and synchronized two unrelated variables (terrain topology and vehicle turning radius) which were used to adjust the vehicle model's chassis component at each simulation time step.

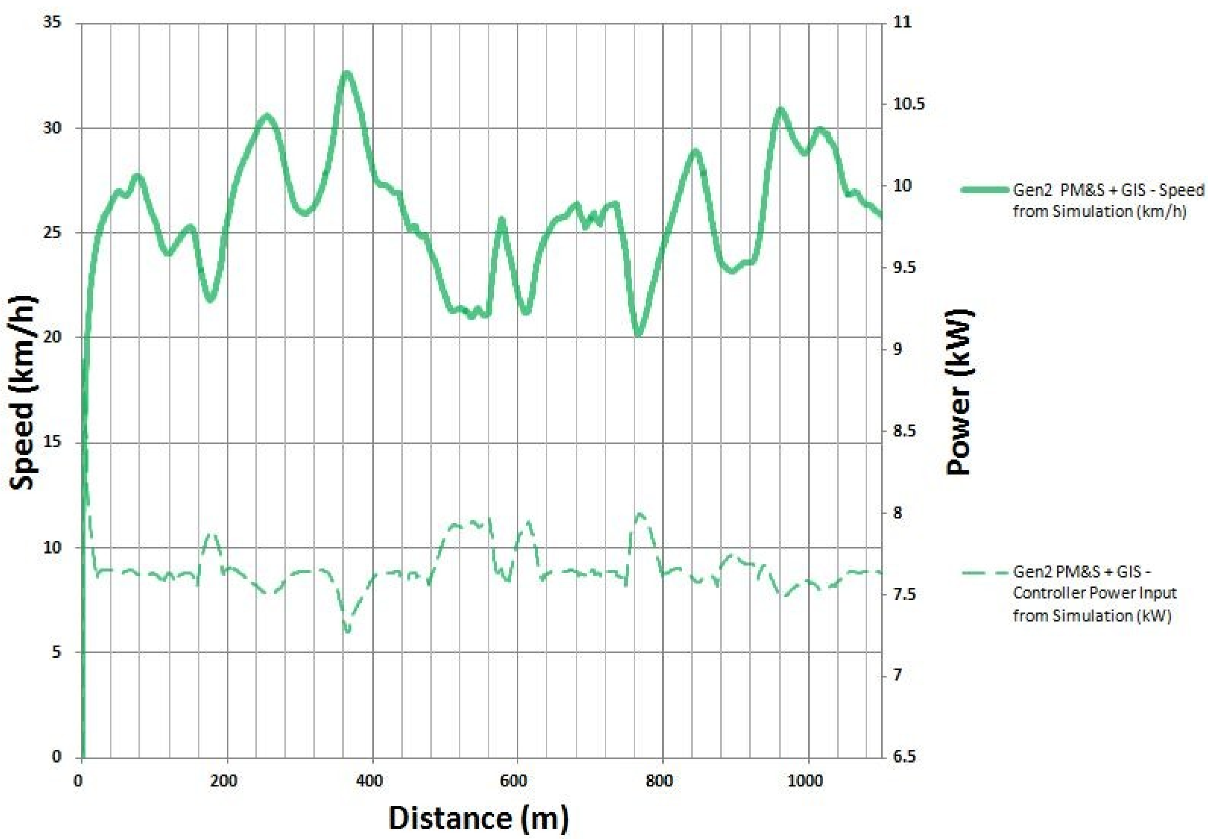

Figure 44: Gen2 PM&S + GIS Simulation Results (Speed & Controller Power Input)

Despite the driver model request being constant from beginning to end, since the grade encountered by the chassis model is constantly changed as a function of location and the chassis model's DVL coefficients are also varied as a function of location, there is variation in both vehicle speed and power input to the controller throughout out the simulation.

When superimposing the data recorded during real life testing to the Gen2 PM&S + GIS results, the graph in Figure 45 is obtained.

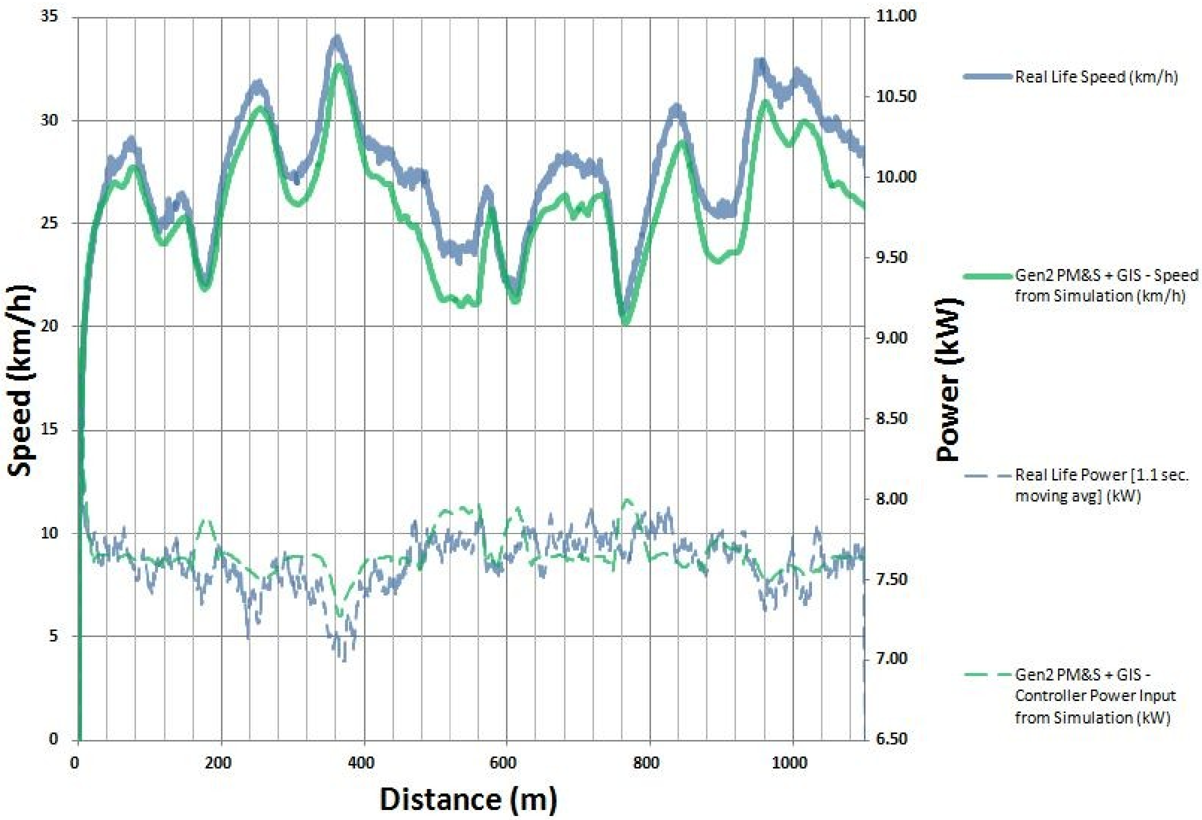

Figure 45: Gen2 PM&S + GIS Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

Table 7 below presents the MEA, the standard deviation of the error and the MAPE for both the vehicle speed and the controller power input for the Gen2 PM&S + GIS approach.

Table 7: Error in Gen2 PM&S + GIS Initial Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

	Vehicle Speed	Controller Power Input
Mean Absolute Error	1.42 km/h	0.08 kW
Standard Deviation	0.45 km/h	0.13 kW
Mean Absolute Percentage Error	5.58 %	1.00 %

5.1.4 Analysis of Initial Results

The first thing to notice when looking at Tables 6 and 7 is the error analysis on the controller power input. In both cases the error and standard deviation is very low. This is a sign that the vehicle's component models and their initialization parameters are an accurate representation of the real systems.

Having validated this aspect, the focus can now shift to the speed results. The speed results are directly related to the difference in baseline Gen2 PM&S vs. Gen2 PM&S + GIS.

When focusing on the vehicle speed results error analysis in Tables 6 and 7, it can be seen that both MAE and MAPE are lower in the case where Gen2 PM&S + GIS was used. However, since the goal of Gen2 PM&S is to accurately simulate instantaneous behavior of the system, having a low MAE and MAPE is not sufficient. They must also be accompanied by a low standard deviation. Fortunately, that's exactly where the Gen2 PM&S + GIS approach shines with a standard deviation 5.9x lower than the baseline Gen2 PM&S approach.

5.1.5 Conclusion

The initial results obtained showed significant improvement for Gen2 PM&S + GIS approach over the baseline Gen2 PM&S approach. Both approaches had good MAE and MAPE, but the Gen2 PM&S + GIS approach was significantly superior in both cases. More importantly, the Gen2 PM&S + GIS approach greatly outdid the baseline Gen2 PM&S approach by presenting a standard deviation of error almost 6x smaller.

Overall the initial results validate hypothesis #4 stated in section 1.2.1: Simulation results using Gen2 PM&S + GIS yield results with significantly higher fidelity to data obtained in full scale real life trials than simulation results obtained using baseline Gen2 PM&S.

Despite this good initial result, analysis of Figure 45 shows that there is clearly room to further improve the fidelity of the simulation. Looking at the vehicle speed, one can clearly see that the simulated vehicle almost always underestimates the real life speed and that this difference seems to increase the farther along the path the vehicle goes.

Upon a detailed review of the data and the test procedure, as well as a conversation with Camoplast, the world leading manufacturer of snowmobile tracks, it was deemed highly possible that track temperature could be playing a role in this result. Similarly to a car's tire which sees its temperature go up to a certain point as a car is being driven. A snowmobile's propelling track also increases in temperature as the vehicle is being driven. However, one difference between the two is that a snowmobile track will tend to cool down much faster at rest given its environment (cold temperature and contact with snow) and its exposed surface area.

Section 5.2 looks at the approach taken to try and compensate for this effect and presents a new set of results using this new track temperature compensated approach.

5.2 Results with Track Temperature Compensation

The initial results obtained, while being successful in validating the fourth hypothesis, still left room for improvement. This led to a search for means of further improving the results fidelity. The first step in this search was to revisit all the data gathered throughout the test campaign, including on-board video footage of the tests, in order to see what could be the main source of discrepancy between the real life test data and the Gen2 PM&S + GIS results. Based on this review of data, a hypothesis was formulated stating that track temperature could play a non-negligible role in the results and that this effect wasn't being taken into account in the original data acquisition and test procedure.

This section presents the data which led to this hypothesis, the approach taken to compensate for it and a new set of results using this new approach.

5.2.1 The Data Trend That Put Track Temperature "On the Radar"

Upon detailed investigation of the data, an interesting trend showed up in the coast down test results. After looking at coast down testing data for multiple test days, it was noticed that, as back-to-back coast downs were performed, almost without any exception, the average of any 2-way tests showed a decreasing force requirement vs. speed as the testing went on. However, if coast down testing was paused for a few minutes between tests, this effect was not present.

This observation led to the hypothesis that as the vehicle was being driven, the track would warm up and that the warmer track required less force to drive than a colder one.

This hypothesis supports the observed behavior of a lower power requirement vs. speed as the vehicle is driven more and more without prolonged stoppage. It also supports the observed behavior that stopping for a prolonged period of time between coast downs would counteract the reduction in power requirement by giving time for the track to be cooled by the large contact area with the snow surface and the cold air.

This hypothesis was further reinforced in a conversation with the Camoplast R&D department. Camoplast is the world leading manufacturer of snowmobile tracks. In this conversation, the Camoplast R&D department confirmed that in their tests, a warm snowmobile track needs less power to be driven at a given moderate speed than an identical cold track.

Based on this information, two sets of actions were taken:

1- The coast down data was revisited to try and account for track temperature.

2- The data from the test day was reviewed in order to estimate how warm the track might have been during the test course lap relative to the coast down tests.

5.2.2 Revisiting the Coast Down Data

First the straight line coast down data for the test day was revisited. Two boundary lines were derived from the data: the "Lower Limit" line and the "Upper Limit" line. These two lines define an envelope encompassing all the force vs. speed data points derived from the coast down data.

Figure 46 below shows the resulting limit lines.

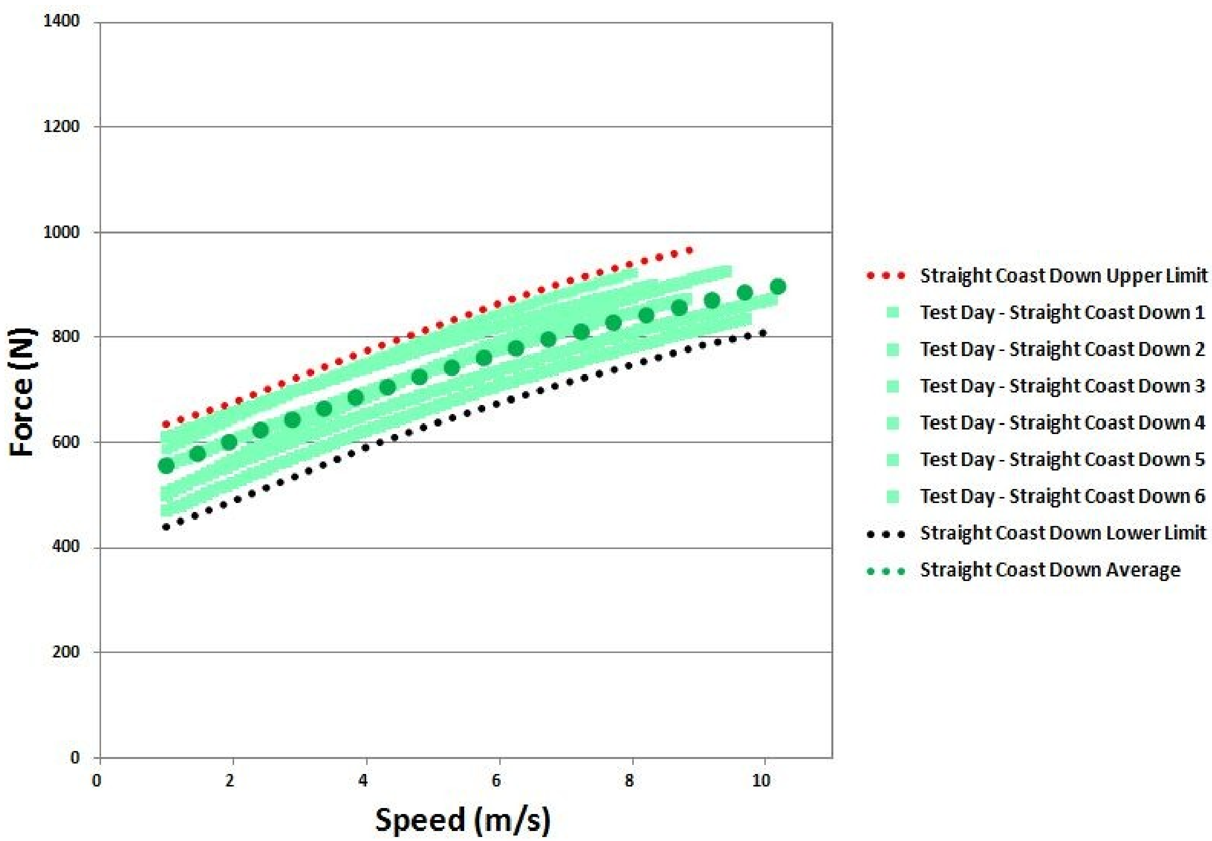

Figure 46: Test Day Straight Line Coast Down Force vs. Speed Results with Upper Limit and Lower Limit of Data Gathered

In Figure 46, the red dotted line represents the worst case scenario experienced during coast down tests on test day. Unless snow conditions change between the coast down site and the test path site or the track temperature is greatly reduced for the test course lap compared to the lowest temperatures during coast downs, this line should represent the highest force vs. speed the snowmobile model could expect to see during testing.

Conversely, the black dotted line represents the best case scenario experienced during coast down tests on test day. This line however does not necessarily represent the lowest possible force vs. speed the vehicle could experience during testing. Assuming snow conditions and ambient temperatures remained the same between the coast downs and the test course lap, it is possible that prolonged continuous operation of the snowmobile could further warm up the track and make it even more energy efficient.

The definition of an “Upper Limit” and a “Lower Limit” was also performed for the test day’s sharp turning coast down results. Figure 47 below shows the resulting envelope.

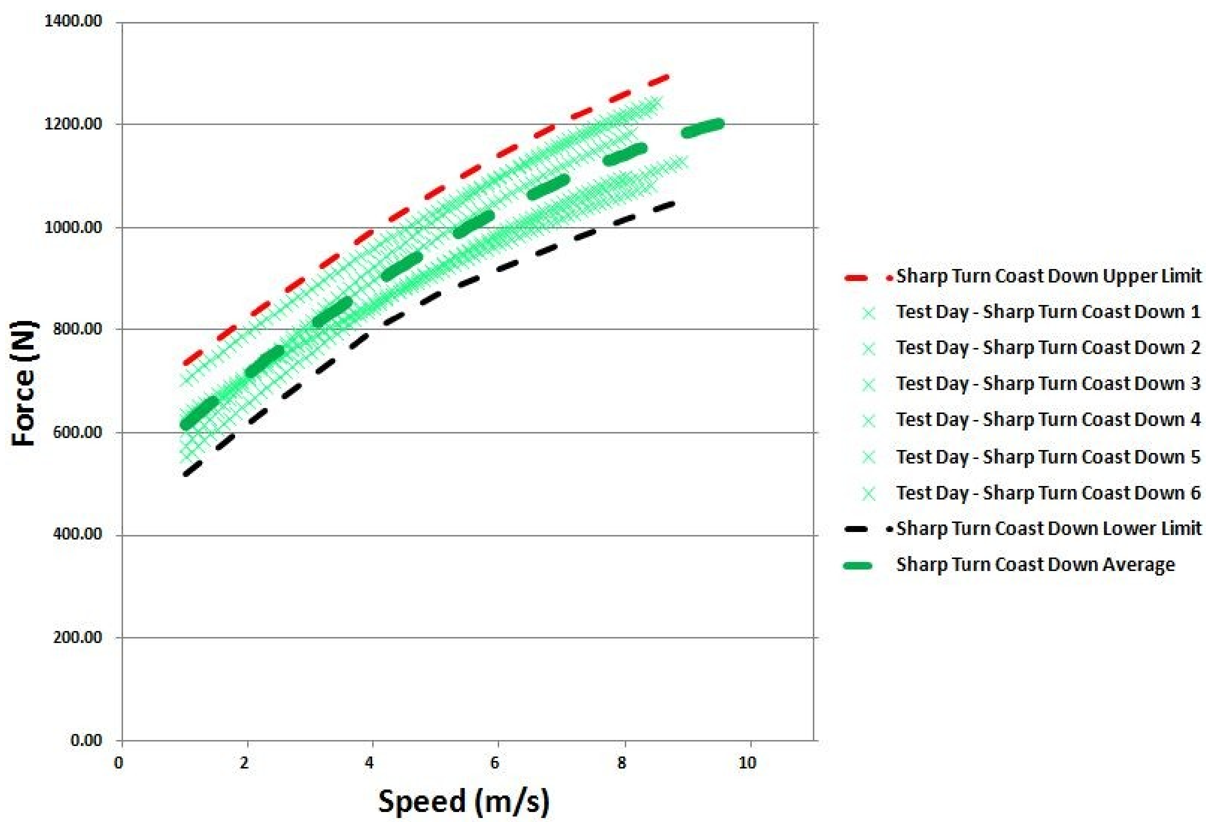

Figure 47: Test Day Sharp Turn Coast Down Force vs. Speed Results with Upper Limit and Lower Limit of Data Gathered

As performed for the average case in section 4.2.1.3, a medium turn coast down power vs. speed line was calculated based on the straight line and the sharp turn coast down results for both the “Upper Limit” and the “Lower Limit” cases.

The best fit 2nd order polynomial equation was then found for each of the three lines (straight, medium turn, sharp turn) for both the "Upper Limit" and the "Lower Limit" cases. The resulting graphs and equations are shown in Figures 48 and 49 below.

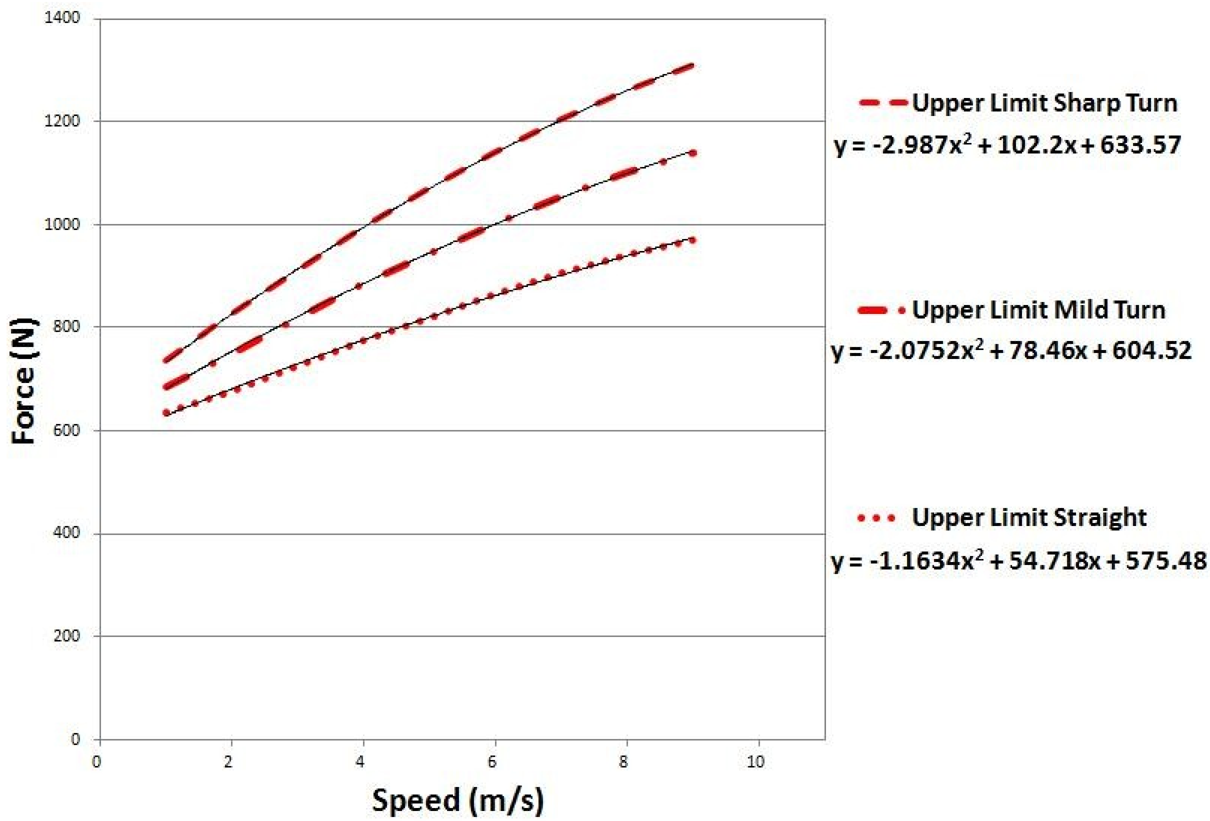

Figure 48: Sharp Turn, Medium Turn and Straight Line Force vs. Speed Coefficients Used to Initialize Test Day Upper Limit Vehicle Model.

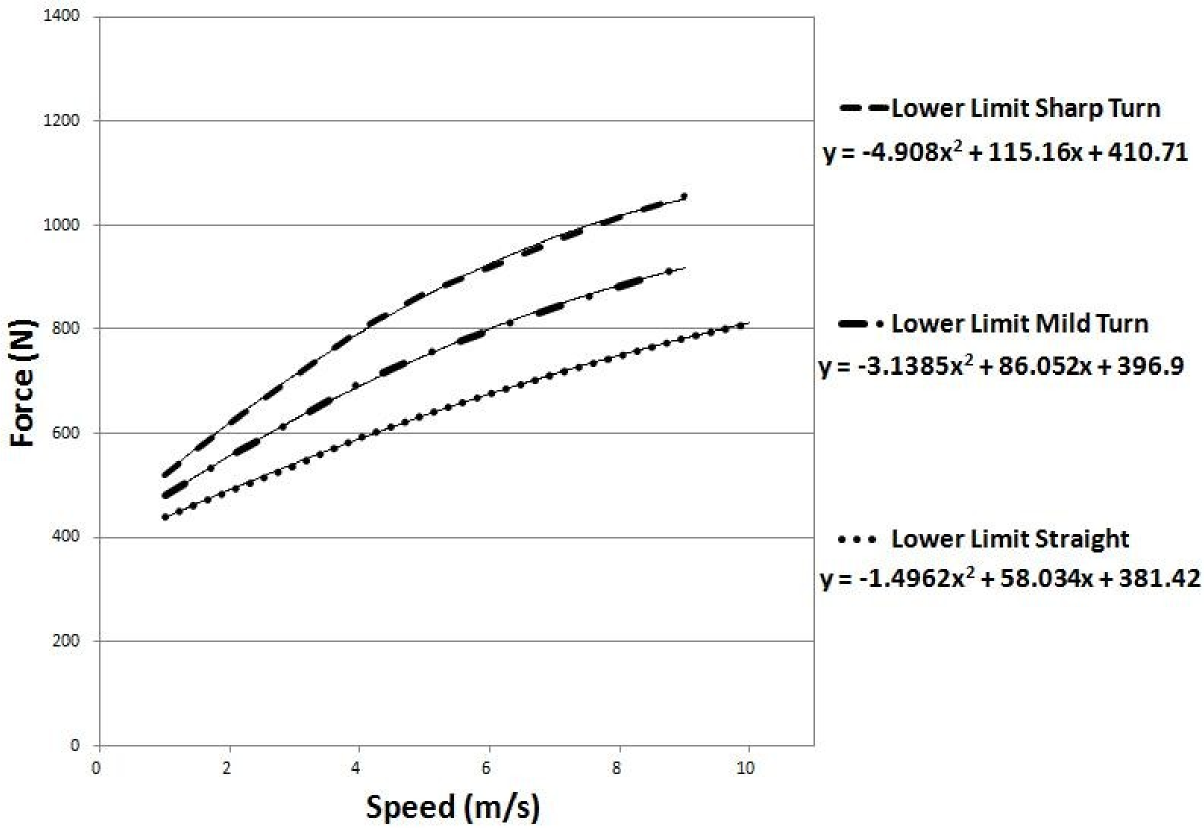

Figure 49: Sharp Turn, Medium Turn and Straight Line Force vs. Speed Coefficients Used to Initialize Test Day Lower Limit Vehicle Model.

With these two new datasets capable of more accurately representing a vehicle with a cold track and a warm track, the test data was reviewed to evaluate which dataset should be the most representative of the test course laps conditions.

5.2.3 Test Day Data Review

Video data, GPS location data and speed vs. time data was used to reconstruct the moments leading to the test under review.

Figure 50 below shows the reconstruction of the test day data on a speed vs. time graph.

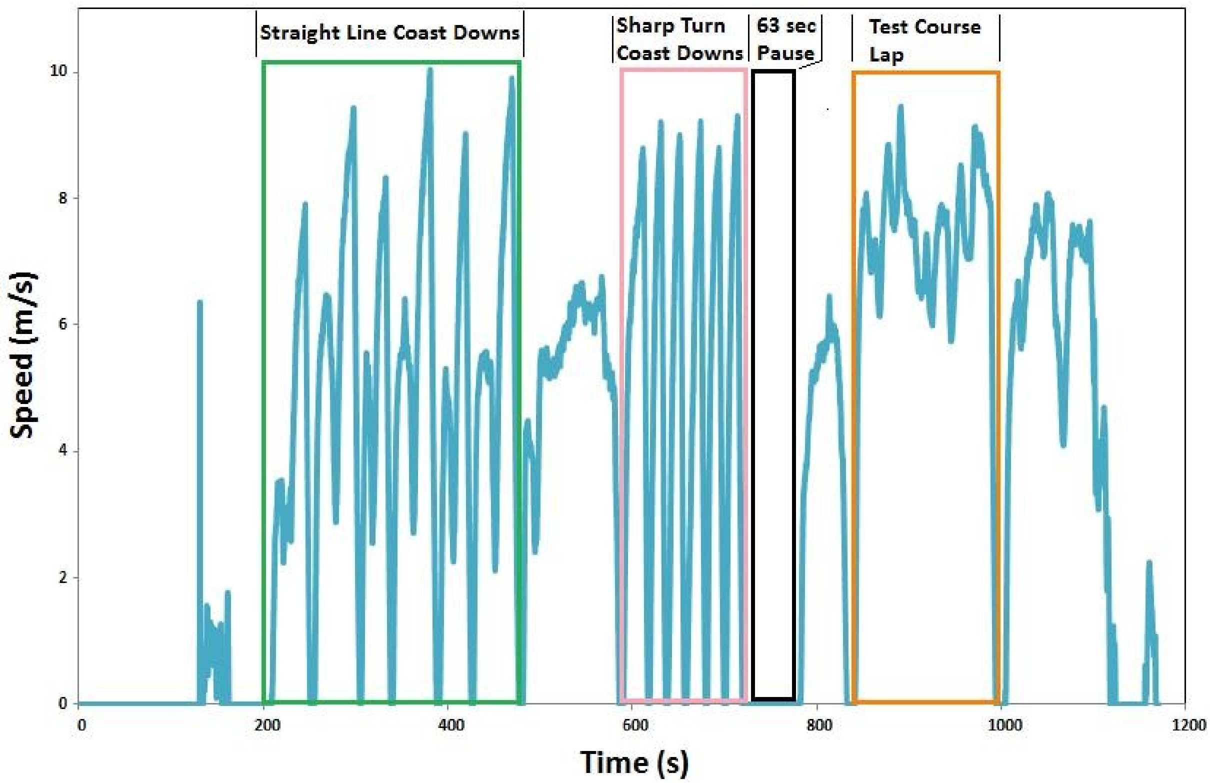

Figure 50: Reconstruction of Test Day Speed vs. Time Data

Based on previous test data, the test day data, and the timeline reconstruction, it was deemed that the 63 second pause would likely cool down the track temperature from what it was when "Lower Limit" coast downs were performed at the end of the sharp turn coast downs. However, the short drive to the test course would likely warm up the track a bit and the track would then continue to warm up throughout the test course lap.

Given this, the “Lower Limit” force vs. speed equations presented in Figure 49 were deemed to be the most representative of the likely track temperature during the test course lap. Therefore, the CFL chassis model for the baseline Gen2 PM&S approach and the Gen2 PM&S + GIS approach both had their DVL coefficients modified based on the equations in Figure 49. All other aspects of the vehicle and the simulation were left unchanged from what was defined in section 4.2.

Once this was completed, a new simulation was performed for both the baseline Gen2 PM&S approach and the Gen2 PM&S + GIS approach. The results of these simulations are presented in the following sub-section.

5.2.4 Track Temperature Compensated Results

The following two sub-sections show the results obtained with the new track temperature compensated approach. Results obtained are first presented for the baseline Gen2 PM&S approach case and compared to the initial results obtained in section 5.1.2. Then, the results for the Gen2 PM&S + GIS approach are presented and compared to the initial results obtained for that approach in section 5.1.3.

5.2.4.1 Baseline Gen2 PM&S - Track Temperature Compensated Results

Figure 51 below shows the track temperature compensated results for the baseline Gen2 PM&S approach overlaid on the results previously presented in Figure 43.

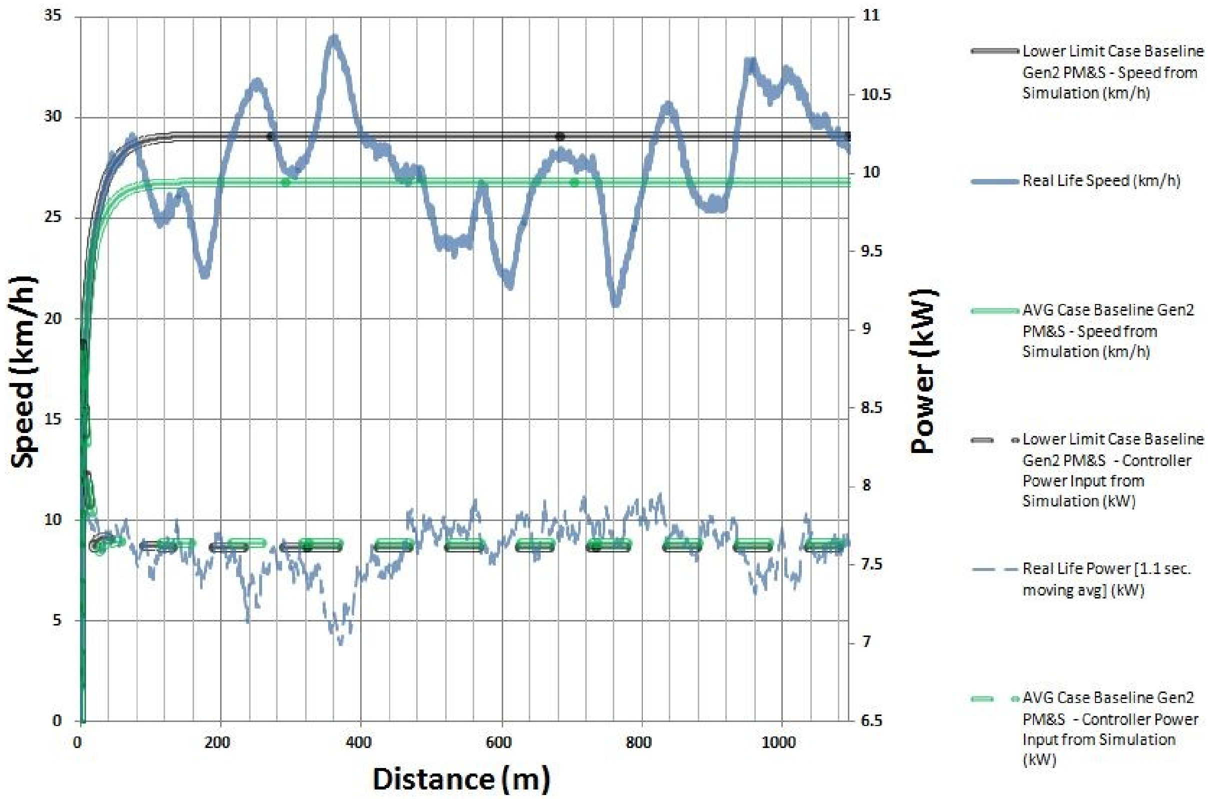

Figure 51: Baseline Gen2 PM&S Track Temperature Compensated Simulation Results Overlaid on the Initial Results

As expected, the controller power input has barely changed; however, the higher energy efficiency of the track at a warmer temperature enabled the simulated vehicle to go faster in this case compared to the previous "Average" case presented in section 5.1.

Table 8 below presents the MEA, the standard deviation of the error and the MAPE for both the vehicle speed and the controller power input for the new "Lower Limit" generated DVL coefficients using the baseline Gen2 PM&S approach vs. the real life recorded data.

Table 8: Error in Baseline Gen2 PM&S Temperature Compensated Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

	Vehicle Speed	Controller Power Input
Mean Absolute Error	2.48 km/h	0.05 kW
Standard Deviation	2.66 km/h	0.12 kW
Mean Absolute Percentage Error	9.62 %	0.74 %

When comparing error analysis table above (Table 8) with the error analysis table of the initial results presented in section 5.1.2 (Table 6), the first thing to notice is that, without any surprise, the controller power input error did not significantly change. And thus, it is safe to conclude once again that the component models and their initialization parameters which were left unchanged, performed just as well as they previously did.

However, what is more interesting to see is that the vehicle speed error also didn't change much. Furthermore, the changes observed show a greater error now that the track temperature has been taken into account.

5.2.4.2 Gen2 PM&S + GIS - Track Temperature Compensated Results

Figure 52 below shows the track temperature compensated results for the Gen2 PM&S + GIS approach overlaid on the results previously presented in Figure 45.

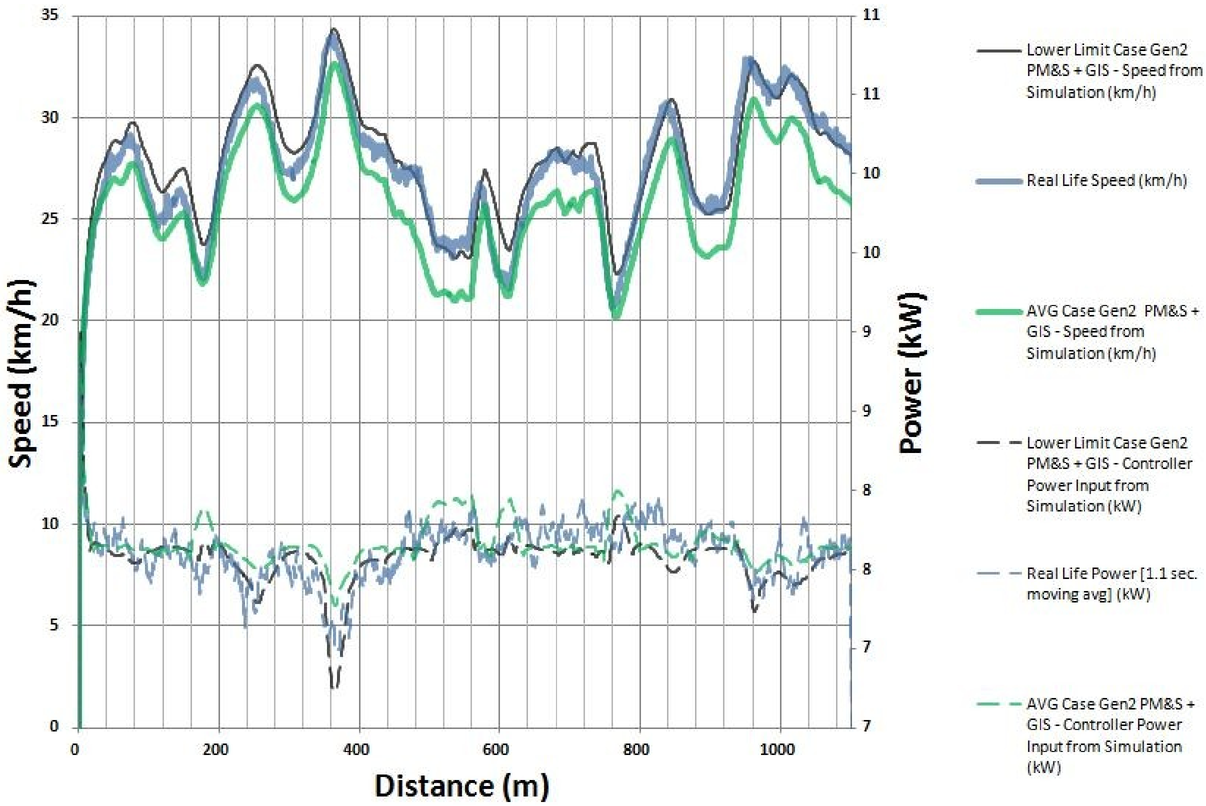

Figure 52: Gen2 PM&S + GIS Track Temperature Compensated Simulation Results Overlaid on the Initial Results

First observation: As expected, the controller power input hasn't changed much. However, in areas where it did change, it appears to be a slightly better match to the real life data.

Second observation: the assumption that the track temperature was closer to the "Lower Limit" data seems to be the correct one. As expected the real life data is initially slightly below the simulated data since the track has cooled down during the pause highlighted in Figure 50. However, very rapidly, as the snowmobile performs the test lap, the track appears to warm up and seems to exhibit a force vs. speed relationship very close to the one captured by the "Lower Limit" equations.

Table 9 below presents the MEA, the standard deviation of the error and the MAPE for both the vehicle speed and the controller power input for the new "Lower Limit" generated DVL coefficients using the Gen2 PM&S + GIS approach vs. the real life recorded data.

Table 9: Error in Gen2 PM&S + GIS Temperature Compensated Simulation Results vs. Data Acquired From Real Life Testing (Speed & Controller Power Input)

	Vehicle Speed	Controller Power Input
Mean Absolute Error	0.68 km/h	0.06 kW
Standard Deviation	0.24 km/h	0.09 kW
Mean Absolute Percentage Error	2.43 %	0.80 %

By comparing the error analysis table above (Table 9) with the initial results error analysis table presented in section 5.1.3 (Table 7), it can be seen that, the controller power input error improved slightly. However, the results were already excellent so this is not a very significant change.

When looking at the speed results however, one can see very significant change. The MEA was reduced by a factor of 2.1 and simultaneously its standard deviation was also reduced by a factor of 1.9. Meanwhile, the MAPE went from 5.58% to 2.43%.

These results are even more impressive knowing that even when temperature compensation was applied, the baseline Gen2 PM&S results didn't improve at all.

5.2.5 Results Comparison

Table 10 below compares the fidelity of the baseline Gen2 PM&S approach to the fidelity of the Gen2 PM&S + GIS approach.

Table 10: Percent Improvement of Error in Predicting Real Life Vehicle Speed - Gen2 PM&S + GIS vs. Baseline Gen2 PM&S

	Baseline Gen2 PM&S Vehicle Speed vs. Real Life Vehicle Speed	Gen2 PM&S + GIS Vehicle Speed vs. Real Life Vehicle Speed	**Percent Improvement**
Mean Absolute Error	2.48 km/h	0.68 km/h	**76.6 %**
Standard Deviation	2.66 km/h	0.24 km/h	**91.0 %**
Mean Absolute Percentage Error	9.62 %	2.43 %	**74.7 %**

It is clear from the percent improvement seen in MEA, Standard Deviation and MAPE that the Gen2 PM&S + GIS approach yields much higher fidelity results than the baseline Gen2 PM&S approach for the off-road vehicle test case studied in this project.

5.2.5 Conclusion

The initial results obtained in section 5.1 validate the fourth hypothesis stated in section 1.2.1. However, they still left room for improvement. Based on a review of available data, a new fifth hypothesis was formulated stating that track temperature could play a non-negligible role in the results and that this effect wasn't being taken into account in the original data acquisition and test procedure.

Section 5.2 presented the data which led to this hypothesis, the approach taken to compensate for it, and a new set of results using this new approach.

These new results showed no improvement for the baseline Gen2 PM&S approach, but showed significant improvement for the Gen2 PM&S + GIS approach.

Ultimately, when taking into account track temperature, the Gen2 PM&S + GIS reduced the MEA by 76.5%, the standard deviation by 91% and the MAPE by 74.7%.

5.3 Discussion

The proposed methodology has demonstrated very significant improvement for the test case investigated.

However, the work in this field should not be seen as being completed. Far from it. The work performed so far should be viewed as only a first step to lay the basis of the integration of GIS in the world of PM&S. There remains multiple means of improving this approach to broaden its application to a myriad of test cases.

The biggest limiting factor of this approach as defined so far is that, currently, it has not been yet been optimized to take into account drive cycles in which the vehicle comes to a stop before departing once again.

This comes from the fact that the approach was initially developed to test the extreme case when no “real” target speed vs time trace is available at the beginning of the simulation.

6. Conclusion

6.1 Overview

After being born from the need of NASA for an off-road vehicle, PM&S has migrated towards the automotive sector over the years. The advent of new powertrain topologies further accelerated the creation and use of PM&S platforms in the automotive sector in recent years. A similar expansion of PM&S platforms in the off-road industry has not happened in parallel. Given the lag of the off-road industry in terms of PM&S, the following question was asked:

Should the off-road vehicle industry invest in building new software tools dedicated to its advanced complex powertrain needs or can it leverage existing software developed for the needs of the automotive sector and adapt them to the needs of the off-road vehicle industry?

The author's belief is that there is merit in modifying well documented and proven automotive PM&S software tools to suit the needs of the off-road vehicle industry.

Therefore, this project was initiated with the aim of doing just that, modifying automotive PM&S software tools to suit the needs of off-road applications.

This project aimed at defining, testing and validating at full scale, an improved modeling and simulation methodology to accurately predict the power flow between components in an off-road vehicle driven in a complex real life environment in situations where the vehicle's speed is unknown prior to the simulation.

The proposed approach to achieve this goal was to improve on the Gen2 PM&S by using GIS to enable variability of parameters defining the vehicle, its environment and their interactions throughout the simulation.

In order to attain the stated goal using the proposed approach, the following hypotheses were validated:

1- A significant number of aspects negatively impacting off-road vehicle PM&S result fidelity which are not covered in sufficient detail by Gen2 PM&S software were shown to be related to the chassis model, its environment, and the interaction between the two.

2- The aspects that primarily affect off-road vehicle PM&S result fidelity in Gen2 PM&S software were shown to be apt at being catalogued in a GIS application, synchronized with one another, and eventually output as lookup tables.

3- Gen2 PM&S software was modified in such a way that it can now accept and integrate, in the model and the simulation, spatio-temporally reference information from a GIS application.

4- After validating hypotheses 1, 2 and 3, the results obtained by using Gen2 PM&S + GIS were significantly closer to data obtained in full scale real life trials than simulation results obtained using a baseline Gen2 PM&S approach. This validated the 4th hypothesis.

Given the complexity associated with the full scale validation of the Gen2 PM&S approach, the route taken to test and validate it was broken up in smaller legs. Each leg tested and validated a portion of the overall approach.

The steps taken and the related key take away points discovered along the way were as follows:

1. The role of the chassis model, its environment and their interactions in PSAT were presented (Section 3.1). From this presentation it was concluded that:
    - Only time based indexed variables can cause a change in the baseline PSAT chassis component model's output during a simulation.
    - The only time based indexed variables which can have an impact on the baseline PSAT chassis component model's output during a simulation are the time indexed scheduled speed and grade
2. The effect of grade, environmental conditions and sinuosity of path on vehicle power usage were analyzed individually. (Sections 3.2, 3.3 and 3.4). From these analyses if was concluded that:

- Baseline Gen2 PM&S can accurately integrate grade into simulations provided grade is constant throughout the simulation
- Baseline Gen2 PM&S can cope with variable grade up to a certain point provided there is as little deviation as possible between the drive schedule speed and the simulated vehicle's speed. The more the grade varies in a simulation, the more likely it will be affected by a deviation in simulation speed vs. schedule speed.
- Grade can play a significant role in an off-road vehicle simulation even if the path is relatively flat. Furthermore, even a small 1% grade added to the UDDS drive cycle can produced a significant increase in the power requirement of a passenger car.
- GIS was shown to be a valid means of acquiring path and grade data.
- Factors other than grade can affect simulation results significantly in off-road vehicles.
- In the case of an off-road vehicle such as a snowmobile, a common change in the vehicle-terrain interaction can yield a substantial change in the force required to drive the vehicle at a given speed.
- In the tests performed, the highest impact on force from vehicle-terrain interaction went from a 20% increase at low speed to a ~40% increase

at higher speeds. Test conditions were limited and it is highly probable that even higher differences can be experienced in other conditions.

- Path curvature can have a significant impact on the test vehicle's force vs. speed requirement. In the tests performed, it ranged from a 5% to a 60% increase in force depending on terrain conditions and speed. Given the limited number of test performed, it is possible that even higher increases can be experienced in other conditions

3. A representative real life test scenario was devised and integrated into a GIS application while the selected Gen2 PM&S software, was modified to interact with the GIS application's output. (Section 4.1) Based on this work it was concluded that:

    - The aspects that primarily affect off-road vehicle simulation fidelity in Gen2 PM&S software can for the most part be catalogued in a GIS application, synchronized with one another, and eventually output as lookup tables.
    - Gen2 PM&S software can be modified in such a way that it can accept and integrate, in the model and the simulation, spatio-temporally reference information from a GIS application.

4. A vehicle model was created and initialized in both the baseline Gen2 PM&S software and the new Gen2 PM&S + GIS software combination. (Section 4.2) Based on this work it was concluded that:
    - Gen2 PM&S software can be modified in such a way that it can accept and integrate, in the model and the simulation, spatio-temporally reference information from a GIS application.
5. The initial simulation results obtained for the baseline Gen2 PM&S case and the Gen2 PM&S + GIS case were compared to data gathered during real life testing. (Section 5.1)
    - The Gen2 PM&S + GIS approach was significantly superior on MAE, MAPE and standard deviation. The standard deviation of error is almost 6x smaller with Gen2 PM&S + GIS vs. the baseline Gen2 PM&S approach.
    - The initial results showed room to further improve the fidelity of the simulation. It was deemed highly possible that track temperature could be playing a role in this result.
6. Based on the initial results obtained, attempts were made to further improve the Gen2 PM&S + GIS approach. (Section 5.2) As a result, when using chassis load models (both the baseline model and the turning models) that were calibrated to take into account the expected track temperature:

- Gen 2 PM&S + GIS results showed great improvement compared to the initial results while no improvement was seen in the baseline Gen2 PM&S results.
- Gen2 PM&S + GIS reduced the MEA by 76.5%, the standard deviation by 91% and the MAPE by 74.7%. when compared to the baseline Gen2 PM&S approach

6.2 Comments

The overall approach of combining proven automotive powertrain modeling and simulation tools with the intrinsic capability of GIS applications at relating unrelated information by using location as the key index variable was shown to be valid for a complex off-road test case. This approach is generic in nature and can be applied to other vehicles.

This approach requires the modification of the baseline vehicle model's chassis component in order to query the geo-referenced information at each simulation time step. The added complexity compared to traditional automotive PM&S is that now vehicle chassis load parameters must be found for multiple situations. This however is necessary in order to obtain high fidelity results for vehicles in complex environments. In this project, two unrelated variables (terrain topology and vehicle turning radius) were related via GIS and this information was used to adjust the vehicle model's chassis component at each simulation time step. Other vehicles may benefit more from having other unrelated variables investigated. For example ad bus or a delivery truck may benefit more from having its mass catalogued in a GIS whereas a field tractor would likely benefit more from having its variable plowing depth catalogued in a GIS.

The approach and the tools used are generic and hence can be applied to different types of vehicles. It is expected that off-road vehicles would in general benefit the most from this approach of varying the vehicle model at each time step based on information contained in a GIS. Any off-road vehicle that sees its chassis loads vary significantly as a factor of location during normal use can benefit from this approach. However, on-road vehicles could also benefit from the approach, albeit to a lesser scale given that factors affecting their chassis model tend to be more homogeneous.

6.3 Future Work

Future work on this subject should be focused on two main objectives:

1- Improving the current approach in order to make it optimally compatible with situations where a “real” target speed vs. time trace is the basis of the simulation.

2- Testing the approach on different types of off-road vehicles in different settings and potentially some on-road special cases.

In both cases, no indications were found so far that would see these future courses of improvement and validation pose insurmountable challenges.

For the first point of interest in future work, the use of a “real” target speed vs. time trace instead of a single step input as was the case in this project could be achieved by adding the desired speed information to the GIS and having an extra provision to tell the simulation how long to wait if/when there are moments in the drive cycle where the vehicle comes to a stop.

In this study, only the spatial reference index of GIS has been linked to PM&S. A third aspect of interest in the field once the two aforementioned aspects have been further investigated is to also link the temporal reference index of GIS with PM&S.

LIST OF REFERENCES

1. Krasner, Jerry; COMPARING EMBEDDED DESIGN OUTCOMES WITH AND WITHOUT MODEL-BASED DESIGN, White Paper Report, Embedded Market Forecasters, www.embeddedforecast.com, © American Technology International, Oct 2010
2. Costes, N.C.; Farmer, J.E.; George, E.B.; MOBILITY PERFORMANCE OF THE LUNAR ROVING VEHICLE: TERRESTRIAL STUDIES - APOLLO 15 RESULTS, Technical Report NASA TR R-401, N73-16817, George C. Marshall Space Flight Center, Al. 35812 / National Aeronautics and Space Administration, Washington, D.C., December 1972
3. Ouellette, S.; INVESTIGATING THE DESIGN OF A ZERO EMISSION ELECTRIC UTILITY SNOWMOBILE, Thesis, © McGill University, 2008
4. Turner, J.; MODELING THE BEHAVIOUR OF NICKEL-ZINC BATTERIES IN A RECREATIONAL-SCALE ELECTRIC VEHICLE, Thesis, © McGill University, 2011
5. Fulem, Joseph; ICCT EVALUATION OF SIMULATION TOOLS, Summary Report RD 08/119502.3,RICARDO, www.ricardo.com, © Ricardo PLC, August 2009
6. PSAT (Powertrain System Analysis Toolkit). Argonne TTRDC. Accessed August 15, 2014. http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html.
7. U.S. Environmental Protection Agency, Retrieved from www.epa.gov/otaq/standards/light-duty/udds.htm, April 2011
8. FUEL ECONOMY LABELING OF MOTOR VEHICLES REVISIONS TO IMPROVE CALCULATION OF FUEL ECONOMY ESTIMATES. Washington, D.C.: Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency, 2006. (Accessed August 15 2014) http://www.epa.gov/fedrgstr/EPA-AIR/2006/February/Day-01/a451.pdf. and http://www.epa.gov/fedrgstr/EPA-AIR/2006/December/Day-27/a9749.pdf

9. 40 CFR 1051.505 - WHAT SPECIAL PROVISIONS APPLY FOR TESTING SNOWMOBILES? Accessed August 15, 2014. http://www.gpo.gov/fdsys/granule/CFR-2012-title40-vol34/CFR-2012-title40-vol34-sec1051-505.
10. US EPA; Office Of Transportation & Air Quality;. December 2006. Accessed June 06, 2014. http://www.epa.gov/otaq/carlabel/documents/420r06016.pdf.
11. Wipke, K. B.; Cuddy, M. R. ; Burch, S. D.; ADVISOR 2.1: A USER-FRIENDLY ADVANCED POWERTRAIN SIMULATION USING A COMBINED BACKWARD/FORWARD APPROACH, IEEE Transactions On Vehicular Technology, Vol. 48, No. 6, November 1999, p. 1751
12. Rousseau, A.; Deville, B.; Zini, G.; Kern, J.;Anderson, J.; Duoba, M.; HONDA INSIGHT VALIDATION USING PSAT, Conference Paper 01–FTT49,Future Transportation Technology Conference, Costa-Mesa, August 2001
13. Kim, N.; Carlson, R.; Jehlik, F.; Rousseau, A.; TAHOE HEV MODEL DEVELOPMENT IN PSAT, SAE paper 2009-01-1307, SAE World Congress, Detroit, April 2009
14. Rousseau, A.; Sharer, P.; Pagerit, S.; Duoba, M.; INTEGRATING DATA, PERFORMING QUALITY ASSURANCE, AND VALIDATING THE VEHICLE MODEL FOR THE 2004 PRIUS USING PSAT, SAE paper 2006-01-0667, SAE World Congress, Detroit, April 2006
15. Clarke, K. C., 1986. ADVANCES IN GEOGRAPHIC INFORMATION SYSTEMS, COMPUTERS, ENVIRONMENT AND URBAN SYSTEMS, Vol. 10, pp. 175–184.
16. Maliene V, Grigonis V, Palevičius V, Griffiths S (2011). GEOGRAPHIC INFORMATION SYSTEM: OLD PRINCIPLES WITH NEW CAPABILITIES. Urban Design International 16(1). pp. 1–6. doi:10.1057/udi.2010.25.
17. Cowen 1988. “GIS VERSUS CAD VERSUS DBMS: WHAT ARE THE DIFFERENCES ?", Photogrammetric Engineering & Remote Sensing Vol. 54,

No.11, November 1988, pp. 1551–1555.http://funk.on.br/esantos/doutorado/GEO/igce/DBMS.pdflast retrieved 9/17/2010.

18. Scott, C.; Urquhart, N.; Hart, E.; INFLUENCE OF TOPOLOGY AND PAYLOAD ON CO2 OPTIMISED VEHICLE ROUTING, Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) v6025 LNCS nPART 2, ©2011 Elsevier B.V., May 2010, p. 141-150
19. Tavares, G.; Zsigraiova, Z.; Semiao, V.; Carvalho, M.G.; OPTIMISATION OF MSW COLLECTION ROUTES FOR MINIMUM FUEL CONSUMPTION USING 3D GIS MODELLING, Waste Management -Pergamon Press- 29, no. 3, 2009, p. 1176-1185
20. Jazcilevich, A.D.; García-Fragoso, A.; García Reynoso, A,; Grutter, M.; Diego-Ayala, U.; Lents, J.; Davis, N.; A VEHICLE EMISSIONS SYSTEM USING A CAR SIMULATOR AND A GEOGRAPHICAL INFORMATION SYSTEM: PART 1--SYSTEM DESCRIPTION AND TESTING, Journal of the Air & Waste Management Association, 57, ISSN:1047-3289, October 2007, p. 1234-40.
21. Map Practical, Retrieved from http://mappractical.blogspot.com/, Entry: Monday January 18 2010 Cartography Tools, Accessed April 2011
22. Guzzella, L.; Sciarretta, A.; VEHICLE PROPULSION SYSTEMS INTRODUCTION TO MODELING AND OPTIMIZATION, ebook, 2nd Edition, Publisher OhioLINK electronic book center SpringerLink, © Springer, 2007, (or Guzzella, L., and Antonio Sciarretta. Vehicle Propulsion Systems: Introduction to Modeling and Optimization. Berlin: Springer, 2005)
23. Joint eapa/eurobitume task group fuel efficiency. ENVIRONMENTAL IMPACTS AND FUEL EFFICIENCY OF ROAD PAVEMENTS, March 2004. Accessed April 08, 2014. http://www.eapa.org/usr_img/position_paper/fuel_efficiency_report.pdf
24. Greene, Suzanne, Mehdi Akbarian, Frank-Josef Ulm, and Jeremy Gregory. PAVEMENT ROUGHNESS AND FUEL CONSUMPTION, August 2013.

Accessed April 8, 2014.
https://cshub.mit.edu/sites/default/files/documents/PVIRoughness_v15.pdf.

25. National Asphalt Pavement Association, David Newcomb, and Howard Marks. SMOOTHNESS STILL MATTERS. Accessed April 8, 2014. http://www.asphaltroads.org/assets/_control/content/files/Special_Report-Smoothness_Still_Matters.pdf.
26. Ardekani, Siamak A., and Palinee Sumitsawan. EFFECT OF PAVEMENT TYPE ON FUEL CONSUMPTION AND EMISSIONS IN CITY DRIVING, March 2010. Accessed April 8, 2014. http://www.rmc-foundation.org/images/UTA%20Fuel%20Consumption-Emissions%20Study%20Final%203-10.pdf.
27. Gopal, Ram V., Aymeric Rousseau, and Argonne National Laboratory. SYSTEM ANALYSIS USING MULTIPLE EXPERT TOOLS. January 21, 2011. Accessed June 2, 2014. http://www.autonomie.net/docs/6%20-%20Papers/Paper_SAE2011-01-0754.pdf.
28. Shamah, Ben, Dimi Apostolopoulos, Michael Wagner, William "Red" Whittaker, and Field Robotics Center, The Robotics Institute Carnegie Mellon University. EFFECT OF TIRE DESIGN AND STEERING MODE ON ROBOTIC MOBILITY IN BARREN TERRAIN, 1999. Accessed June 2, 2014. https://www.ri.cmu.edu/pub_files/pub2/shamah_benjamin_1999_1/shamah_benjamin_1999_1.pdf.