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Indianapolis

DESIGN EVALUATION AND DEVELOPMENT OF A VEHICLE PHYSICS MODEL FOR A DRIVER TRAINING SIMULATOR

A Directed Project Final Report

Submitted to the Faculty
of
Purdue School of Engineering and Technology
Indianapolis

by

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In partial fulfillment of the requirements for the

Degree of Master of Science in Technology

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Abstract

Due to resource restrictions and regulations limiting on-track time, driver-in-loop simulation is used increasingly in the motorsports industry. Race Like A Pro Simulators (RLAPS) is developing a simulator package to meet the needs of developing drivers looking to practice fundamental driving skills in virtual simulation. An essential element to delivering this simulation experience is a robust vehicle physics model.

As part of the development of the RLAPS Simulation Software Program (SSP) a vehicle physics model was developed around four subsystems – chassis and suspension, aerodynamics, powertrain, and tires. Tires are the most complex model, and have the most direct impact on the performance and feel of the vehicle model. A complex algorithm governing vehicle physics was presented in a generalized form to guide the programming of the RLAPS SSP. From the generalized algorithm, a practical model was implemented using Unity 3D game creation software (Unity, 2017). The simulation was tested and evaluated against data from numeric lap-time simulation software. Various parameters were opened for tuning to refine the performance and behavior of the vehicle in simulation. The tuned vehicle model performed in such a manner as to exercise the steering, braking, and throttle application skills of drivers using the simulator.

Introduction

Simulation in a virtual environment is an increasingly important training tool in many industries and pursuits. Improving technology allows simulations to improve their complexity and fidelity. This has been particularly true for motorsports applications. Several race sanctioning bodies have regulations limiting on-track testing. Beyond regulatory limitations, track testing is time-consuming, expensive, and carries the risk of damage and injury from crashes. Manufacturers, racing teams, and drivers alike are turning to simulators to address this limitation.

There are multiple potential uses for simulators in motorsports applications, and simulators can fall into several categories. Applications can be categorized into driver-in-loop (DIL), also known as operator-in-loop, or numeric algorithm simulations. The first type, driver-in-loop simulators, utilize a human driver to provide control input into the simulation program, provide an environment that mimics a vehicle driving position , and generate visual, audio, and tactile feedback of the simulated environment to the driver. The second type, numeric algorithms, numerically solve mathematic representations of vehicle dynamics over time without input from a human operator. DIL simulators can be further categorized as entertainment, human-factors, or engineering grade (Ansible, 2016). Entertainment grade simulators are frequently used in personal applications, utilizing a single personal computer or gaming console, basic controller hardware, and a cockpit environment ranging from a simple chair in front of a desk to a compact mockup of a vehicle cockpit on a motion platform. As the name implies this type of simulator is frequently used for entertainment purposes by providing average consumers the chance to experience motor racing in a safe, controlled, and affordable environment, but are also used by racing drivers, even professional racing drivers, as a means to learn cars and tracks and to practice their craft outside of on-track activity. Human factors simulators are more hardware intensive, typically requiring advanced computing resources and employing a full-scale mockup of an actual vehicle interior. The focus of simulators in this category is to provide an environment where driver behavior is studied, such as distracted driving experiments and evaluating the ergonomics and intuitiveness of controls. Finally engineering-grade simulators are the most complex category, requiring the highest level of computing resources to operate extremely detailed vehicle models. The fidelity of these simulators make them useful in vehicle development where the nuances of design details can be evaluated for their impact to the driving dynamics and performance of the whole vehicle. They are also used at the highest level of motorsports to provide the most accurate and immersive environment for training drivers and a testbed for engineers to rapidly evaluate new component designs and vehicle setups.

Race Like A Pro Simulators (RLAPS) is a motorsport simulator company with a plan to bring a different kind of simulation experience to the growing marketplace. The company is developing a simulator that will fall into the entertainment grade segment for the purpose of allowing drivers to develop and practice fundamental driving and racing skills in a virtual environment. The RLAPS simulator hardware consists of a single PC, multiple viewing screens arranged in a semi-circle, and a cockpit mockup on a motion platform offering three degrees of freedom: pitch, roll, and yaw. This hardware setup allows drivers to run several simulation software programs currently available on the market. It is also appropriately scaled to fit into a home office or small team workshop environment. In addition to hardware, the RLAPS simulator comes equipped with RLAPS' own proprietary Simulation Software Program (SSP). Other simulation programs in this category attempt to replicate real vehicles and tracks and are used by drivers to practice the nuances of particular cars and tracks ahead of real-world races with the same combination. The focus of the RLAPS SSP, on the other hand, is to train and evaluate drivers on the fundamental skills associated with driving a race vehicle. Generic cars and tracks are modeled for the simulation environment. The driver can choose from a number of scenarios related to evaluating a particular skill or set of skills. The SSP simulates the driving environment and vehicle dynamics, while recording metrics related to the driver's performance. These metrics are catalogued and evaluated against a set of standards that indicate levels of proficiency in the related skill area. Drivers and their coaches can review the metrics generated by the SSP to inform their training program, assess progress, and determine next steps. The RLAPS simulator is aimed initially at amateur or young racers, particularly those competing in stock cars on paved ovals in local and regional series. Consequently, the initial RLAPS vehicle modeled for the simulation is similar to a late model stock car-type race car, and the simulation environments are ¼ mile high banked and 7/8ths mile flat ovals, layouts typical of tracks raced on by drivers in the target market.

A significant part of the development work for the RLAPS SSP has been related to the vehicle physics modeling. Although the purpose is to model a generic car rather than a specific real world car, developing a model that would accurately reproduce the performance and feel of a typical late model stock car was important in crafting a simulation that would serve as an adequate tool for driver development. The model would have to behave in a manner that would be demanding on the driver's steering, brake, accelerator, and gear shift inputs to highlight the skills the simulator is attempting to exercise. In order to craft this model, research was undertaken to develop a complex and comprehensive vehicle modeling outline that would guide the design and implementation of the vehicle model in the RLAPS SSP.

Problem Statement

Real time, driver-in-loop vehicle simulation is computationally complex. The computational resource requirements for calculating several equations governing the dynamics and state of a multi-body vehicle, simulating computer-controlled vehicles in the environment, and tracking performance metrics are high. The RLAPS SSP must handle those three tasks using a single personal computer.

Significance

The market for driver-in-loop simulators is growing at a high rate. The range of the market is broad, from racing games on desktop computers and game consoles to professional engineering grade full scale mockups on complex motion platforms. Sanctioning bodies are further limiting allowed on-track testing time so simulators are taking on increasing importance in developing driver skills and helping drivers learn the nuances of particular cars and tracks. As this industry segment matures, the expectation for increasing realism and fidelity grows.

Improvement in vehicle modeling for simulation benefits the wider automotive and motorsports industries. Simulations, both numerical and driver-in-loop, can be used to reduce development time by allowing rapid testing and validation of design concepts. Increasing the complexity and scope of the vehicle model can allow for greater fidelity and detail in the simulated outputs, while simplifying the model through assumptions and parameterization can reduce the computing requirements. The ability to run a high-fidelity simulation with modest hardware, including a single personal computer, is crucial to expanding simulation to racers below the top-level professional categories of racing. Lower-level racers are limited in resources but need extensive practice and coaching to improve their skills, making a small-scale driver-in-loop simulator an important tool to have at their disposal.

Simulation is multidisciplinary, incorporating learnings from several areas in the motorsports engineering curriculum, including vehicle dynamics, aerodynamics, data acquisition and analysis, computer modeling and coding, vehicle control systems, and project management. This project represents a comprehensive use of the broad range of subjects studied in the course of earning a Master's of Technology degree concentrating in Motorsports. It also highlights practical experience relevant to careers in the motorsports industry. Simulation Engineers are increasingly in demand by sanctioning bodies, racing teams, constructors, and manufacturers.

Literature Review

Several technical papers, studies, research, and white papers have been published on the subject of vehicle models, or portions of vehicle models, for simulations. The scope of this literature is broad, ranging from discussions of full vehicle and track modeling techniques to detailed analysis of individual subsystems within the vehicle model. Literature also includes studies with methods of evaluating results from driver-in-loop and numeric algorithm-based simulations.

The literature review process began with a search through the Society of Automotive Engineers (SAE) technical papers archives, using search keywords such as simulation, vehicle model, and more specific search terms such as tire model. Literature found in this search included citation of related literature that was reviewed as well. The researcher signed up for distribution of literature including white papers from other companies involved in the simulation industry. Faculty in the Motorsports Engineering program in the Purdue School of Engineering and Technology at Indiana University Purdue University Indianapolis recommended relevant studies and materials. Finally, additional literature was provided by the partners within RLAPS from their own research and affiliation with simulation-oriented organizations and trade groups.

A good place to start the literature review was a high level overview of simulator options and categories, the benefits of utilizing simulation, and the equipment necessary to develop a simulator. The previously noted categories of entertainment grade, human factors, and engineering-grade simulators was reinforced by Norfleet, Wagner, Alexander, & Pidgeon (2009) as well as the range of hardware complexity from a simple desktop computer station to a full range motion platform with full scale cockpit mockup. The breakdown of the vehicle model into subsystems including chassis, engine, and transmission, as well as an environment module was proposed. The review noted higher complexity vehicle models typically require greater computing resources, with detailed multi-body models found in engineering grade and human-factors grade simulators typically requiring multiple computers to operate.

One of the primary judgments of the vehicle model created in this project would be the perception of fidelity held by the drivers operating the simulator. Literature suggests experienced operators tend to rate the fidelity of simulators poorly. In a test of two flight simulators, one simple with relatively low fidelity and one complex with high fidelity, test pilots gave higher ratings to the high fidelity simulator, but both simulators were given low marks across the board (Schreiber, Bennett, & Gehr, 2006).

Andrzej Nalecz (1989) outlined and demonstrated methods for sensitivity analysis of vehicle dynamics systems in simulation. These methods allowed the effect of changes to vehicle parameters on vehicle performance to be analyzed in time and frequency domains. Two dimensionless functions that enable the comparison and ranking of the influence of parameters on whole system performance are identified. The methods outlined were most useful for using numeric simulation algorithms to assist in the design and tuning of a real physical vehicle, but could provide useful insights for using similar algorithms to assist in the design of a virtual vehicle.

Dols and Pardo offered a comprehensive look at the development and evaluation of a driver-in-loop simulator for the purpose of driver training (Dols, Pardo, Verwey, & De Waard, 2001). This study touched on software development (in C++), hardware specification, and the deconstruction of driving into a series of tasks. The project largely mirrored the RLAPS project but within the context of general on-the-road driving rather than race driving and motorsports applications. The results of this study indicate the methods and philosophy underlining the RLAPS concept, and the software and hardware used to implement it, can be successful.

Since motorsport simulation is an established and growing industry, examination of other simulation software titles can be instructive. iRacing is one of the premier entertainment-grade driver-in-loop simulation programs commercially available, and is used by many professional racing drivers. The developers of iRacing documented the process of creating their car and track models (Kaemmer, Benwick, & Porter, 2008). iRacing has in one sense the opposite objective as RLAPS. iRacing attempts to recreate real cars and tracks to create a virtual simulation that is useful for drivers to learn the nuances of particular cars and tracks. RLAPS, on the other hand, is less concerned about exactly recreating real world cars and tracks as it is in crafting a simulation environment that emphasizes driving techniques. Still, many of the considerations in crafting a vehicle model as detailed in this paper are relevant to the development of the RLAPS vehicle model. The structure of modeling chassis, aerodynamic, powertrain, and tire subsystems and applying forces to a rigid body model is used in the RLAPS project. The testing and validation procedure, evaluating not only objective performance metrics but also subjective feel and behavior, mirrors the validation procedure of this project.

A paper outlined a comprehensive mathematical and computer model for vehicle dynamics situation (Gim & Nikravesh, 1991). The tire model component was the central and most developed part of the model. The other components such as steering, suspension, powertrain, and brakes, were far simpler, not as thoroughly developed, and were used primarily to determine the inputs for the tire model. The tire model takes into account terrain condition such as physical profile and friction coefficient, tire geometry and construction especially as relating to tire contact patch, and empirical data for forces developed related to slips (lateral and longitudinal) and camber.

In simulators intended for driver development, the ability to capture data and metrics for driver behavior is important, even in non-motorsports applications. One such study looked at methods for designing simulation software and hardware to accommodate data acquisition at sufficiently high sampling rates (Campelo, Martí, Pardo, & Serrano, 2006). As with the RLAPS project considerations for integrated hardware and software compatibility with the data acquisition method is a primary concern in the study and communication protocols throughout the system are analyzed.

The study of human-factors and engineering or vehicle dynamics-grade simulators can be useful in the development of an entertainment-grade simulator by defining an upper-limit of expectations for the fidelity of the simulator. Although it was intended for human-factors and hardware-in-loop studies, the simulator of the Korea Automotive Technology institute has many similar characteristics to those desired for the RLAPS simulator. The vehicle model is a complex multi-body model with subsystems for powertrain, transmission, brakes, and a Pacejka-based tire model with parameters tuned by comparing to real-world testing results (Yu, Lee, & Kim, 2007). This simulator also utilized a motion based and associated control software alongside the simulation software.

One of the requirements for the vehicle model was to be simple enough to allow the RLAPS simulation software program to have acceptable computational and rendering performance.

Defining acceptable performance would be necessary for designing to this objective. A study of graphically-intensive simulation performance in a cloud environment identified 18 frames per second (fps) as the minimum objective performance standard for such simulations (Benslay, Osborne, Clapis, Matthews, & Parrish, 2016). Subjective qualities of look and feel were also discussed, and the observation that more experienced operators are more sensitive to latency was noted.

Factors other than the accuracy and complexity of the vehicle model can impact the perceived fidelity of a simulator. In a motion-based simulator designed for replicating drift maneuvers, it was observed that both the type and number of degrees of freedom used in the motion of the simulator cockpit heavily influenced test driver performance and perception of accuracy (Nozaki, Shimizu, & Sakuno, 2009). The vehicle model used in this study was created in the pre-existing CarMaker simulation software. Tracking of the test-driver's gaze and eye movements was used in the study which was an interesting suggestion for further metric tracking and performance evaluation.

In most of the literature reviewed vehicle models consisted of various sub-systems, typically some combination of tires, chassis, suspension, powertrain, brakes, and occasionally aerodynamics. Universally, tires were presented as the primary system through which the vehicle model is defined. The tires are the primary form of interaction between the vehicle and track models in the simulation environment. Further study of tire models for simulation was warranted. Tire models used in driver-in-loop simulations vary from using empirically-based models such as the Pacejka model to physical models that attempt to derive tire performance from construction and materials (Heusinkveld, 2012). Brach goes further and identified complex physical models, simplified physical models, similarity methods, and empirical models. This study notes empirical models are only truly accurate in steady state conditions and do not model response lag and the popular friction ellipse concept can underestimate tire forces in combined slip conditions (Brach & Brach, 2009). Some tire models have been designed that combine physical and empirical models so that longitudinal and lateral forces and aligning torque are not only functions of slip and camber as with a typical empirical model, but tire spring rate, pressure, and physical dimensions as with a physical model (Salaani, 2007).

Purpose

The purpose of this project was to develop a vehicle model for the RLAPS simulation program that would meet the technical and marketing objectives for the simulator while working with the resources allocated to running the software program. This work would assist the programmers of the simulation software in the design of the program, then evaluate and adjust the program to achieve the desired characteristics of the simulation.

Assumptions

The assumptions underlying this project were driven by objectives for the RLAPS simulator. It was assumed simulation software would be developed in Unity 3D game development software. The simulator would be used for driver training purposes but would fall under the definition of an entertainment-grade driver-in-loop simulator. A single high-end personal computer would be used to run the simulation program, record driver metrics, and operate the hardware including motion platform for the simulator.

Scope

The specific application of this simulator is for personal driver training. It is a driver-in-loop, motion-based simulator. Although the purpose is for serious driver training, by the definitions discussed earlier it can best be categorized as an entertainment-grade simulator in terms of complexity and realism. The simulation must be run using a single personal computer that is simultaneously controlling the motion platform and providing metrics output, limiting the computational resources available for handling the vehicle dynamics model. The specifications for this computer are listed in Table 1 below. The RLAPS SSP was developed in Unity 3D using resources from an existing driving simulator for non-high-performance-driving as a basis. The specific scope of this project was to first create a generalized vehicle dynamics algorithm.

Table 1 Computer Hardware Specifications for RLAPS simulator

Includes: **CPU**	Intel® Core™ i5-4690K Processor (4x 3.50GHz/6MB L3 Cache)
Memory	16 GB [8 GB x2] DDR3-2133 Memory Module - G.SKILL Ripjaws X
Storage	240 GB ADATA SX930 SATA3 SSD
Graphics	Dual AMD R9 380 4GB
Optical	24x Dual Layer DVD±R/±RW + CD-R/RW Drive
Power Supply	850 Watt - EVGA SuperNOVA 850 - 80 PLUS Bronze
Operating System	Microsoft Windows 10 Professional
Case and Cooling	NZXT Source 210 Mid Tower Case - Blue Gigabyte GA-Z97X-SLI Asetek 550LC 120mm Liquid CPU Cooler - Standard 120mm Fan

This project developed an initial generalized vehicle dynamics framework which was then applied to a simulation program developed in Unity 3D. The limitations of the Unity 3D development software, the hardware specifications that would run the software, and the additional tasks, such as controlling motion hardware and tracking metrics, determined the complexity of the vehicle model that would be implemented. This model reduces vehicle characteristics to scalar parameters, and neglects some finer details of vehicle modeling such as camber and toe gain for wheels experiencing vertical articulation in suspension compression, or ride height, yaw, steer, and roll sensitivity for aerodynamic characteristics. The vehicle model was also designed around emphasizing skills and tasks for driver practice as part of the RLAPS training methodology, so direct reproduction of specific real-world vehicle behavior was not the ultimate objective.

The development, tuning, and evaluation of the vehicle model in the RLAPS SSP for this project was constrained by time, the schedule for RLAPS business deliverables, and resources available for testing. Versions of the simulation software with parameters open to the researcher for adjustment and displays indicating lap time and vehicle speed were made available beginning January 2017. From that time to the scheduled completion of this report it was possible for the researcher to personally test the software and evaluate it against performance estimates from numeric lap time simulation software. Real world data and professional test drivers were not available within the time frame of this project, but are anticipated for later phases of work.

The scope of work and responsibilities for the writer of this report was to advise on the development of the vehicle physics model for the RLAPS SSP. Tasks included researching vehicle modeling methods, providing governing equations, feature requirements, and parameter values to the programming team, adjust parameters in software builds, and evaluate the simulated performance of the vehicle against objective and subjective criteria.

Procedure

The timeframe and scope of this project took the vehicle model from a general conceptual framework, into implementation in a simulation program created in Unity 3D, and concluded with evaluation and fine tuning of the simulation program against estimates produced from lap time numeric simulation software. The first stage of the project consisted of providing to the programmers guidelines describing how a race vehicle behaves and how it can be mathematically modeled. The literature reviewed earlier and previous numeric vehicle dynamics simulation algorithms were used to compile and organize a list of governing equations organized as an algorithm. Accompanying this algorithm, descriptions of the interactions and relationships between components comprising a whole vehicle system were written. The algorithm and descriptions were passed on to the programming team to inform how the vehicle in the RLAPS SSP should be modeled to meet the requirements for the simulation program.

The programming team applied the provided vehicle dynamics outline to the modeling tools and physics engine in the Unity 3D game creation software. The performance objectives for the software, the hardware it would be run on, as well as the requirement to track and report various driver and vehicle performance metrics and operate a motion platform were taken into consideration. The programming team delivered to the researcher a simulation software program that featured a vehicle model based on the principles dictated to them crafted using the tools provided in Unity. The simulation program also included two oval track environments to drive the vehicle model in, graphics displaying lap time, engine speed, vehicle speed, engaged gear number, and lap number, rudimentary computer controlled opponent vehicles, and support for the Logitech G27 steering wheel and pedals peripherals for controlling the vehicle. A file containing several parameters governing vehicle behavior was included with the simulation program installation. The researcher could edit the parameters in this document to alter the characteristics of the vehicle model in the simulation.

While the programming team was developing the simulation software, the researcher developed simulation models in the Optimum Lap numeric lap time simulation software. This software uses two-dimensional track models and simple, parameter-driven vehicle models to estimate an ideal lap time in a given vehicle around a given course without using input from a human driver. The performance estimates generated by this software were used to generate a baseline figure to evaluate reasonable, realistic performance against. The researcher acted as an initial test driver and operated the simulation software. Objective comparisons of the performance of the simulated vehicle as well as subjective assessments of the feel and character of the vehicle were compared to the Optimum Lap estimates of vehicle behavior. Vehicle parameters were adjusted and the results compared again. This process continued until the vehicle performance in the RLAPS SSP was similar to the performance predicted by Optimum Lap while also behaving in a manner that would highlight and exercise the skills the RLAPS simulator was intended to test.

Model Development

The vehicle physics model for a real-time driver-in-loop simulation can be developed by integrating four sub-models: Chassis and Suspension, Powertrain, Aerodynamics, and the Tire model. The vehicle’s motion and interaction with the simulated environment is primarily acted through the tire model. All forces that govern the acceleration of a vehicle through space, except for aerodynamic drag, are ultimately resolved through contact patches formed between the tires and the track surface. As such, in the vehicle model the chassis and suspension, powertrain, and aerodynamic models determine the force and geometry inputs into the tire model, which produces the force outputs that determine vehicle state. The aerodynamic model also produces aerodynamic drag, which influences vehicle state.

The limitation of using a single personal computer to run the simulation program, including vehicle modeling, environment modeling, and metrics tacking, dictates the scope of complexity of the vehicle model. For computational efficiency it is necessary to parameterize the models to a rather high level. For example, rather than model suspension kinematics in real time to determine the orientation of the wheel for a given amount of suspension compression or extension, linear gain values can be used to compute or look up camber and toe values for a given wheel vertical translation value.

Generalized Vehicle Model

A generalized outline of vehicle dynamics governing equations and relationships was prepared to guide the programmers as they developed the RLAPS SSP. This outline can then be used as a reference when applied to specific game development software programs and physics engines. This model arranged and outlined as an algorithm can be found in Appendix A. Figure 1 illustrates the proposed vehicle model in block diagram form and specifies inputs and outputs for each sub-system. Interaction with the environment and input from the operator through controls is also modeled in the diagram.

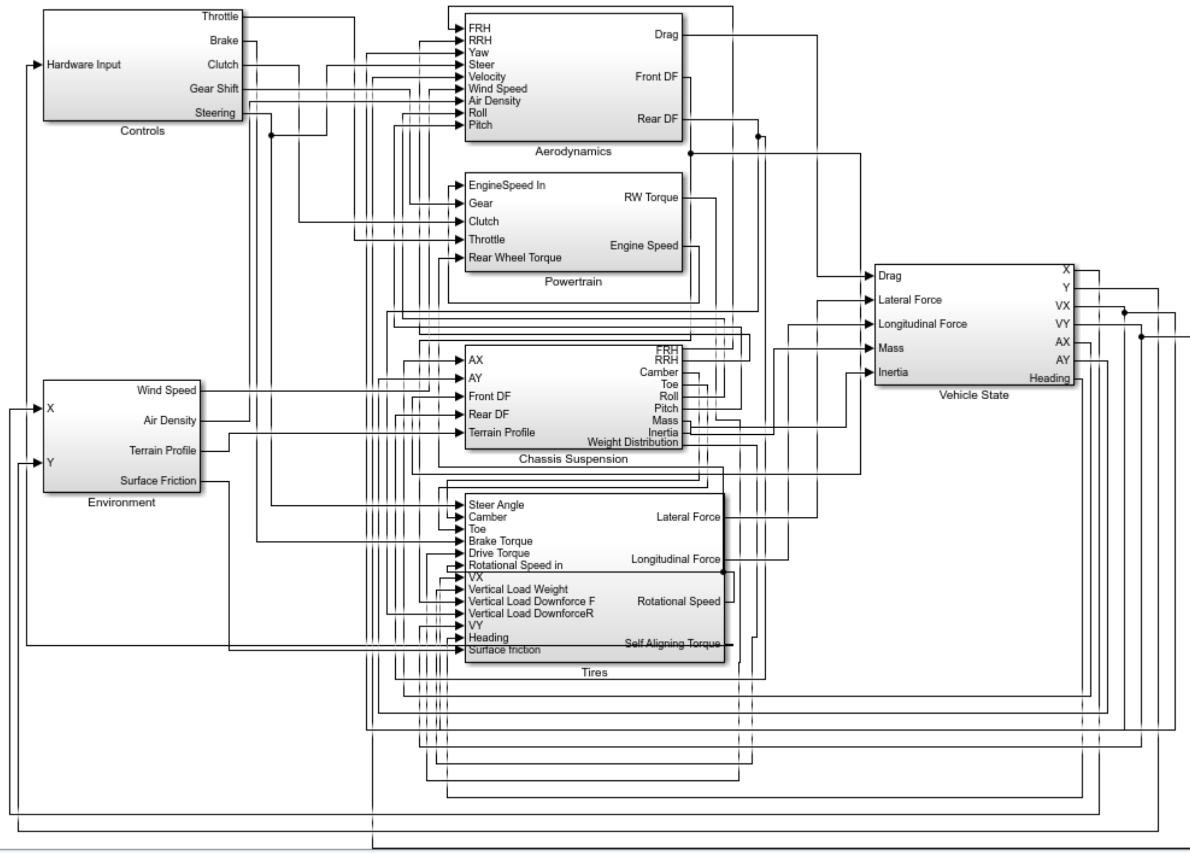


Figure 1 Block Diagram of proposed generalized vehicle model

Chassis/suspension. The chassis and suspension subsystem contains most of the parameters relating to the vehicle's physical dimensions. Mass and mass distribution (laterally, longitudinally, and vertically), front and rear track and wheelbase and rotational inertia of the vehicle body (particularly about the vertical axis) are defined here. When forces are generated by the tires and aerodynamic drag they are resolved with the parameters in the chassis model to determine accelerations of the vehicle that in turn determine its velocities, rotation, and ultimately translation in the simulation environment.

Suspension is modeled in terms of spring and damping rates, as well as functions that relate the kinematics of the suspension geometry to changes in the wheel orientation. Spring and damping rates include what is traditionally regarded as the suspension spring, whether that is in the form of a coil, flexure (cantilever) or torsion spring, anti-roll bars, third springs, the spring rate of the tire at its current temperature and pressure, and even the stiffness of the chassis itself. All of these springs are to be resolved with motion ratios so as to produce spring rates at the wheel, where wheel rate is given as $WR = \frac{SR}{MR^2}$ where SR is the nominal spring rate and MR is the motion ratio, or ratio of spring compression to wheel vertical translation. As the wheel experiences vertical translation in bump (compression) and rebound (extension) there could be corresponding changes in the wheel's camber or inclination angle and toe induced by the suspension kinematics. These changes can be quantified in terms of gain values, such as a certain degree of camber gained for every unit of suspension compression, for the sake of computational efficiency. These spring and damping forces, reacting to weight transfer in the chassis model, and the wheel orientation parameters, are sent as inputs to the tire model.

Powertrain. Powertrain is a relatively simple system to model. Maximum engine torque available is a function of engine speed and this function can be found by curve fitting results from real world dynomometer tests. The actual torque delivered can be determined by mapping throttle position to a percentage of maximum power available. A gear stack is defined by specifying a list of gear ratios. The selected gear ratio is determined from a simple control input, and this ratio is multiplied by the final gear ratio found in the differential or rear end of the powertrain. The effective combined gear ratio acts as a multiplier for the torque and rotational speed translated to the driven wheels. Efficiency ratios can be applied at the engine, transmission, driveshaft, and differential, and all losses are regarded as torque losses. Brakes can also be placed in the powertrain module, mapped as a percentage of maximum brake torque (a fixed parameter) to brake pedal position. Brake torque acts as a torque on all tires in the opposite direction as drive torque.

Aerodynamics. The aerodynamics model produces as outputs drag and lift or downforce. Drag is a force applied directly to the body of the vehicle and acts in opposition to the longitudinal forces generated by the tires in acceleration, or in conjunction with tire longitudinal forces in braking. Lift or downforce acts as an input into the tire model, combining with vehicle weight to determine the vertical or normal force on each tire. This force can be distributed on the front and rear axles as defined by a balance percentage. Aerodynamic downforce and drag are calculated, respectively, by:

$$L = 1/2 \rho C_L A_F V^2 \tag{1}$$

$$D = 1/2 \rho C_D A_F V^2 \tag{2}$$

Where L is downforce, D is drag, ρ is the air density, A_f is the frontal area of the vehicle, and V is the vehicle's velocity. Air density is determined by the simulation environment/track model, frontal area is a fixed parameter of the car, and velocity is determined from the vehicle state. Coefficients of downforce and drag can be fixed parameters but are more accurately functions of front and rear ride height, yaw, pitch, and roll, as given by the chassis and suspension model. The coefficients can be computed from lookup tables by those parameters or by a multidimensional fitting equation. The coefficients can also depend on adjustments to the aerodynamic settings of the vehicle such as wing angle and gurney flap heights, if such adjustment factors are made part of the simulation setup.

Tire. The tire model is the most complex system in the vehicle model and has the most direct impact on the vehicle's interaction with the simulation environment. The tires generate the lateral and longitudinal forces that create accelerations in the vehicle state. They also generate an aligning torque that provides feedback into the steering controls for the driver. As discussed in the literature review there are several possible methods for modeling tires. Proposed for this project is a method based off of a typical empirical model such as the Pacejka model (Bakker, Nyborg, & Pacejka, 1988). Tire forces are primarily functions of slip and vertical (normal) tire loads. Longitudinal forces are determined by slip ratio, or the difference between the velocity of the tire carcass, or the rotational velocity of the tire translated into linear velocity, and the velocity of that tire through space. Lateral forces are determined by slip angle, or the angle between the tire's heading and direction of travel. Empirical curve fits can be used to find tire friction coefficients as a function of slip angle, slip ratio, or combined slip. The product of the resulting coefficient and the normal load on the tire is the force produced. However, this coefficient can also be saturated by vertical load, so every unit increase in vertical load also results in a decrease to the friction coefficient. Toe or bump steer from the suspension model influences slip angle, while camber can be considered an additive force. Camber force can be found as a simple function of a tire's camber angle, again through an empirical curve fit, and added to lateral force produced by slip.

RLAPS Vehicle Model

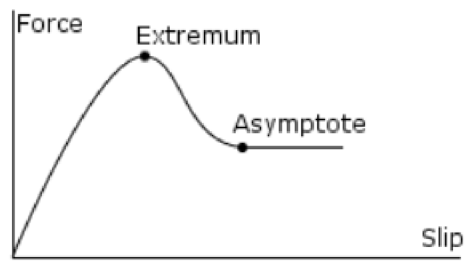
The programming team developing the RLAPS simulation software program took the proposed generalized vehicle dynamics model and attempted to implement it within the specific framework of the Unity 3D game creation software. Early on computing and rendering performance were found to be the major limiting factors in what could be accomplished with implementing the vehicle model. A complex model adhering closely to the proposed model was found by the programmers to require too much memory and slowed the simulation down to an unacceptable level. A simplified model that utilized the Rigidbody and Wheel Collider components within the unity framework and relied heavily upon Unity's built-in physics engine was found to perform acceptably. This model was heavily parameterized, and a list of the parameters made available to tuning by the researcher and their initial as-delivered values is found in Appendix B

Chassis/suspension. The chassis is modeled using the Unity Rigidbody component. This component defines the vehicle's mass, and can be offset laterally, longitudinally, and vertically. It represents a solid single mass that can be located within the dimensions of the wheelbase and track. A massless mesh collider creates the actual physical dimensions of the vehicle for collision detection purposes. The suspension allows for vertical translation of the wheels. Spring and damping rates determined at the wheel are parameterized. Each wheel is given its own mass so unsprung mass and a multibody approach can be executed. The tire also has its own damping rate, and suspension travel range is defined. The wheels articulate vertically in response to the terrain and impart forces through the springs and dampers onto the sprung body mass. Steering geometry including maximum steer angle and relation to control input are defined.

Powertrain. The powertrain model incorporated into the RLAPS SSP differs slightly from the proposed model. A maximum torque value is defined, and then ranges of engine speed are assigned a percentage of maximum torque output. Maximum and minimum engine speeds are set. A vector containing gear ratios including reverse and neutral is defined and used as a multiplier. At any given point in the simulation the torque to the driven wheels is a product of the maximum torque value, the engine speed, and the gear ratio. A top speed limiter can be set so torque to the drive wheels is interrupted at the maximum allowed speed. Traction control which limits drive torque based on wheel slip is also optional, and the degree of interference can be adjusted.

Aerodynamics. The aerodynamics model in the RLAPS SSP remains an underdeveloped area. As the intent was the model a late model stock car type vehicle, aerodynamics are not a primary driver of performance but this is an area that will need further development if more aerodynamic-dependent vehicle types are modeled. The programming team was not able to explain how the Unity physics engine models aerodynamic forces. A downforce value and drag coefficient are present in the vehicle parameters but it is not understood how these are applied to the vehicle, their dependency on any other factors. Since downforce is given as a singular value and not a coefficient, it is not known if this value is speed dependent or a constant.

Tire. Unity uses a feature called "Wheel Colliders" to model vehicle tires and it is a robust slip-based tire model combined with collision detection and wheel physics ("Unity Manual - Wheel Collider," 2017). Friction is computed separately from the rest of the physics engine, using a slip-based method similar to a Pacejka model. A tire friction coefficient is determined from a spline fit relating friction coefficient to slip, both laterally and longitudinally. This spline is defined by two developer-set points, one for what is referred to extremum, the other referred to as the asymptote point. Extremum is the point of maximum friction coefficient and asymptote is the point where the decline in friction coefficient at higher slip values begins to level off. Both points are defined by their corresponding slip and friction values. The plot begins at point (0,0) and the slope of the tangent at both extremum and asymptote points is zero. The spline curve associated with the Wheel Collider model is illustrated in Figure 2. Accompanying both lateral and longitudinal friction/slip curves is a stiffness value that acts as a global multiplier for the curve at all slip values. This value can be modified with code at run-time to have a continuously varying stiffness multiplier. This could be used to apply varying levels of track surface friction depending on the wheel's physical location on track. Attempts were made to use this feature to vary stiffness based on normal load so as to model load saturation characteristics of tires, but this resulted in unstable code so the attempt was put on hold for later development.



Typical shape of a wheel friction curve

Figure 2 Illustration of the spline fit used in the Unity Wheel Collider model

Optimum Lap Models

After the RLAPS SSP vehicle model was developed, the testing plan called for it to be evaluated against data produced by the Optimum Lap simulation software. In order to form this data, vehicle and track models were created in the Optimum Lap software by specifying vehicle parameters and track physical dimensions. The Optimum Lap software has pre-made track and vehicle models available for use so these were tested to gauge the accuracy of the software.

Optimum Lap is a mathematical vehicle dynamics simulation (OptimumG, 2017). Rather than a driver-in-loop simulation, it removes the driver as a variable, and produces an estimate of vehicle state and dynamic performance over a lap of a specified race course. This estimate can be regarded as a mathematical ideal, what would be achievable from a perfect driver operating the vehicle to its fullest dynamic potential at all times over the course of a lap.

Optimum Lap utilizes a number of key simplifications in its modeling which represent some limitations to the estimates it produces. It utilizes a point model for the vehicle, so wheelbase, track, suspension, and weight transfer are neglected. The track models are two dimensional, so elevation and banking are unable to be represented. It assumes braking is traction limited. In this assumption the brakes are strong enough to lock up the tires at any time, so the limitation to braking performance is the grip of the tires, not the capacity of the brakes. In light of these limitations, the estimates produced by Optimum Lap are regarded as being accurate to within 10% of real-world results.

After verifying the accuracy of the Optimum Lap software using existing assets, a vehicle model was made from scratch to represent the late model stock car set up for a short oval as will be used in the RLAPS Simulation Software Program (SSP). A “mass” (weight) of 2,200 pounds was specified because that is the minimum weight required by regulations in several sanctioning bodies. A drag coefficient of 0.45 is typical of a stock car, and an initial downforce coefficient of 0.55 was selected as a reasonable estimate that would minimize the influence of aerodynamic downforce. Frontal area for the vehicle is estimated at 17.8 square feet based on a straight-on front view photograph of a representative stock car used in RLAPS promotional material, imported into a CAD program, outlined, and measured. Air density of 0.078 pounds per cubic foot is representative of standard temperature and pressure.

Tire radius is about 1 foot in this category of car. A coefficient of rolling resistance can depend on inflation pressure, vehicle velocity, driving surface, and slip angle, but this software requires a single coefficient so an average value of 0.015 was selected based on data provided by Hucho (Hucho, 1998). Longitudinal and lateral friction coefficients are also dependent on several factors but since a single value is required for each and this simulation assumes maximum performance at all times, peak friction coefficients from representative tire data are selected. From sample data found in Milliken peak coefficients for short oval stock car tires can be determined to be around 1.250 for longitudinal friction and 1.350 for lateral friction (Milliken & Milliken, 1995).

Engine data is provided by specifying torque outputs at engine speed intervals. Engine dynomometer results of a typical Chevrolet crate engine were used to fill this table. Optional modifiers for thermal efficiency and fuel energy density were ignored because this level of detail is unavailable and perhaps too nuanced for this early stage of testing. A two speed sequential gearbox is initially set with a 1.26 ratio for first gear, 1.00 ratio for second gear, and 3.80 for final drive, but these ratios are typically changed as a common tuning parameter for specific tracks and conditions, so these can be revisited based on testing data. Drivetrain efficiency was set to 100%

Since banking and elevation are not considered in Optimum Lap, the RLAPS ¼ mile high banked oval track is not suitable for testing. Metrics tracking has also not yet been implemented for this track in the RLAPS SSP. The 7/8 mile flat oval is however perfectly suited to the requirements of Optimum Lap and includes some early implementation of metrics tracking at the current release build in the RLAPS SSP. This track was recreated in Optimum Lap based on specifications provided in Appendix C of the RLAPS System Design Document. The track consists of two 1,154.86 foot long straights, with one straight divided into two equal-length sections to create a start/finish line midway down the straight, and two 1,154.86 foot long corners with radii of 367.454 feet. The track is divided into four sectors, with sector one beginning at the start/finish line and ending at the midpoint of the first turn. Sector two begins at the midpoint of the first turn and ends at the midpoint of the back straight. Sector three begins at the midpoint of the back straight and ends at the midpoint of the second turn. Sector four begins at the midpoint of the second turn and ends at the start/finish line. A diagram of the track including locations of the start/finish line and sector dividers is included as Figure 3.

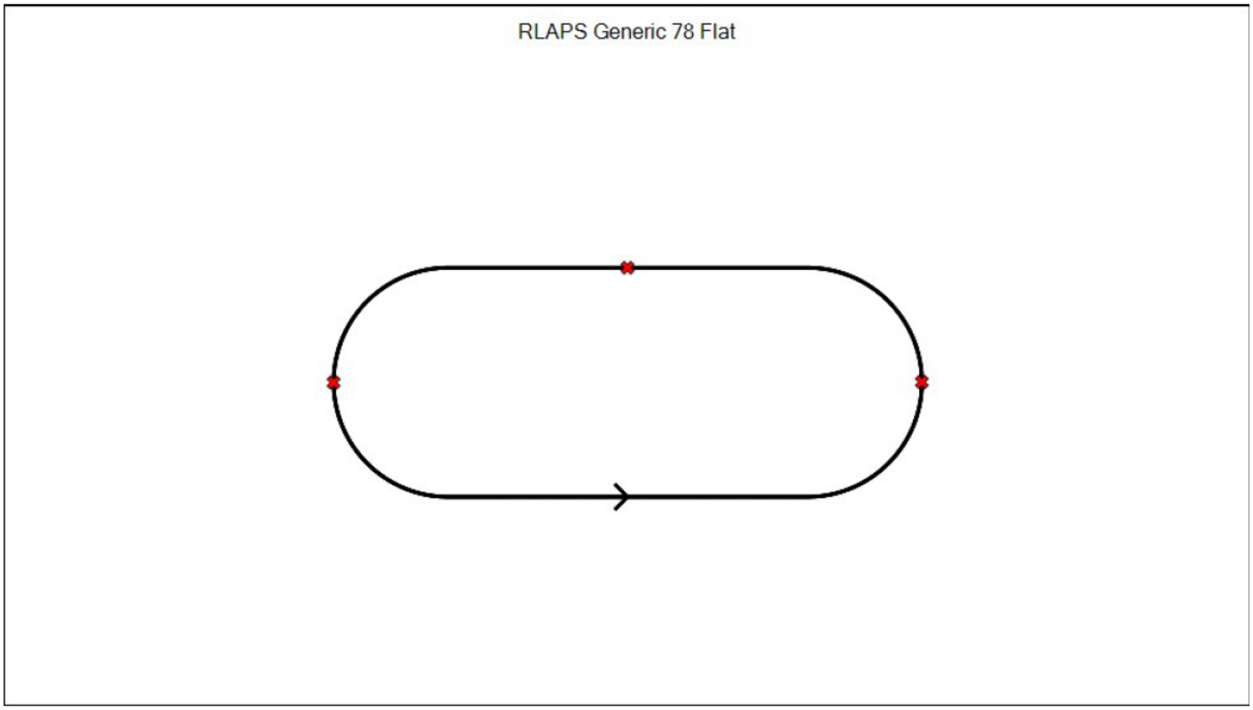


Figure 3 Diagram of Optimum Lap model representation of RLAPS Generic 7/8 mile flat oval track layout showing start/finish line and timing segments

Results and Discussion

The first step in the validation process was to produce results in Optimum Lap to serve as the target for RLAPS SSP vehicle model performance. To verify the accuracy of Optimum Lap, a test simulation was conducted with pre-fabricated vehicle and track models from Optimum Lap's library and compared to real world results. The vehicle selected was a generic LMP2 style car and the track was the Autodromo Internazionale Enzo e Dino Ferrari, also known as Imola. With this combination Optimum Lap estimated a lap time of 81.82 seconds. This was compared to qualification results from the 2016 4 Hours of Imola European Le Mans Series event. In these results the fastest qualifying time for an LMP2 car was 93.78 seconds. The difference between the two is 11.96 seconds or 12.75%. The average speed estimated by Optimum Lap is 226.89 km/hr while the real world average speed was 188.2 km/hr. This represents a 17% difference, indicating a source of error in the Optimum Lap model may be the length of the track. If the track length was accurate, the average speed would have the same margin of error as lap time.

A second test was performed to more closely match the conditions RLAPS will attempt to simulate. A generic stock car was chosen from Optimum Lap's vehicle library. The lone oval in the Optimum Lap track library, Indianapolis Motor Speedway, was selected for the location. Since Indianapolis is a relatively flat, low-banked track, the limitations of the two-dimensional constraint are minimized with this track. An initial run indicated the stock configuration of the car resulted in the car operating at its maximum engine RPM for the entire lap, an unrealistic behavior. Lowering the final gear ratio resulted in a simulation that changed engine speed over the course of the lap. With no other changes, an estimated lap time of 50.78 seconds was produced. The pole time for the most recent NASCAR Brickyard 400 race at the same venue was 48.745 seconds. The difference in lap times for this test is 4.1%. Without knowledge of the exact aerodynamic configuration, engine performance, and gearing of the pole-winning car the parameters of the car selected from the library cannot be tuned to produce a more accurate result, but this test indicates the estimate of a 10% margin of error is reasonable.

After setting up the RLAPS Stock Car and 7/8 Mile Flat Oval models, a simulation was run using these vehicle and track parameters. According to Optimum Lap, a perfect driver can achieve a lap time in this car on this track from a flying (as opposed to standing) start of 33.00 seconds. The car is in second gear for the entire lap. It reaches a top speed of 103.34 miles per hour before braking before the entry into the first turn down to a steady cornering speed of 89.66 miles per hour. It accelerates back up to maximum speed on the exit of the turn. Average lap speed is 95.89 miles per hour. A track map in Figure 4 with a color overlay indicating speed illustrates the vehicle's speed over the lap as described. These are the metrics the RLAPS SSP can currently report. Optimum Lap braking and acceleration points, as well as cornering speed, appear reasonable. The results from the Optimum Lap simulations are presented in Table 2 along with comparisons to their real-world counterpart results.

Table 2 Results from testing of Optimum Lap software and initial test of RLAPS simulation. Note: "Real World" values for RLAPS car represent performance from RLAPS SSP

Car	Track	Simulated Lap Time (s)	Real World Lap Time (s)	% difference	Simulated Average Speed (km/hr)	Real World Average Speed (km/hr)	% Difference
OL LMP@	Imola	81.82	93.78	12.75%	226.89	188.2	17%
OL Stock Car	IMS	50.78	48.745	4.1%	NA	NA	NA
RLAPS Stock Car	7/8 Mile Flat Oval	33.00	32.70	0.9%	95.89	97	1.2%

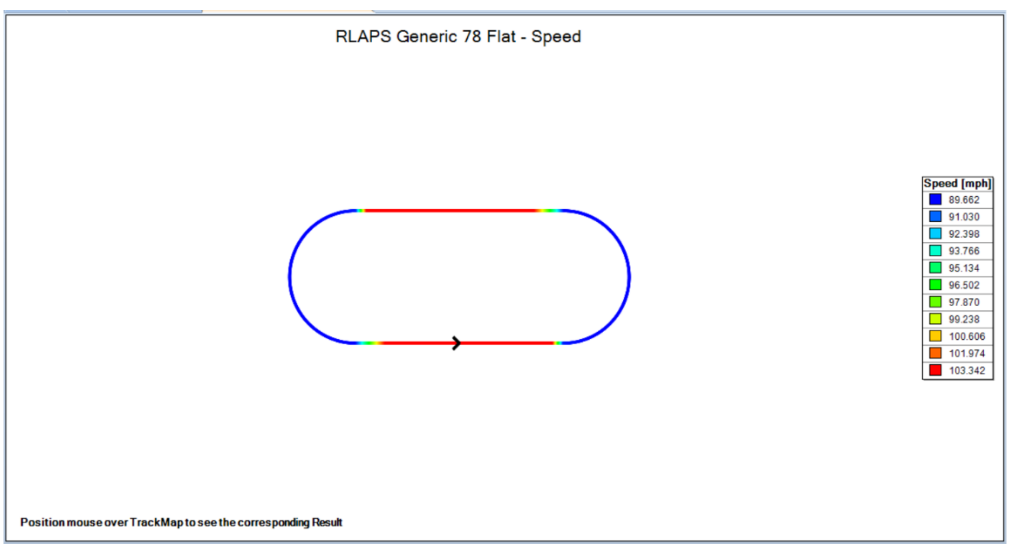


Figure 4 Track Map output from Optimum Lap with color range overlay indicating speed at any point on track.

After adjusting the vehicle model in the RLAPS SSP to match the Optimum Lap vehicle model, the researcher acted as test driver to gauge the initial match of the RLAPS SSP to the results predicted by Optimum Lap. The test driver is not a professional driver, but has competitive driving experience in karting and autocross, computer simulated driver-in-loop simulator experience, and motorsports engineering background.

In the initial test using vehicle parameters that should closely mimic the Optimum Lap model, the test driver produced lap times of 33.00, 32.66, and 32.62 seconds. Although these times compared favorably to the times predicted by Optimum Lap, the nature in which they were achieved was not similar. The RLAPS SSP did not require any braking on corner entry, nor any steering correction to manage slip. The accelerator could be fully depressed the entire time, and slight constant steering input for each turn. The initial assumption of the test driver is that the RLAPS SSP exhibits too much lateral grip, not enough longitudinal grip, and no perceptible body motion cues. During this test the on-screen simulated speedometer did not work, so no estimates of velocity at various points on the track are available. A subsequent software build included a fix for the frozen speedometer. Testing again with the new software build and repaired speedometer, similar lap times (32.52 to 32.72 seconds) were produced with the same driving character of full throttle throughout the lap and neutral handling requiring no correction to steering. The speedometer indicated a relatively constant speed between 95 and 100 miles per hour throughout the lap, with minor amounts of speed scrubbed off in the turns and regained down the straights.

From the initial impressions that the RLAPS SSP vehicle demonstrated too much lateral grip relative to longitudinal grip and forward thrust, attention turned to adjusting the parameters that would have the most direct impact on those factors. First, adjustments were made to the lateral and longitudinal stiffness values that were multipliers for the whole slip/friction spline curve. Longitudinal gain was increased from 2 to 3 and lateral gain was decreased from 10 to 8. The result was slower lap times, ranging from 33.1 to 33.3 seconds, but the same speed, handling, and controls characteristics as before. The car could still be driven at full throttle for the entire lap. The next adjustment disabled completely the steering help and traction control driver aids. Again this reduced lap times to the range of 34.1 to 34.7 seconds without changing the subjective character of the vehicle model's behavior. Further, more severe adjustment was made to the stiffness values, increasing longitudinal gain value to 6 and reducing lateral gain value to 4. This change was made to see if dramatic changes in the tire model would produce results in the desired direction. With this change lap times fell to a range of 30.9 to 31.7 seconds. The behavior changed slightly as well. The throttle was still at 100% for the entire lap, but higher steering inputs could induce slight oversteer behavior, the car in general felt edgier and more difficult to control, and the speed differential was greater, reaching a maximum of 120 miles per hour before the turns, and scrubbing speed down to 80 miles per hour in the turns without braking.

The results from the previous changes strongly indicated tire parameters had a significant influence on both objective performance measures and subjective evaluation of feel. The parameters for the Wheel Collider model were comprehensively altered from the initial values set by the programmers, setting stiffness to 1 and extremum values to 1.2 for both lateral and longitudinal. Longitudinal asymptote value was set to 0.8 occurring at slip of 0.8, lateral value to 0.5 occurring at slip of 0.5. Longitudinal extremum was set to occur at 0.2 slip, lateral extremum at 0.4 slip. These values more closely aligned with the inputs for the Optimum Lap model and with the data found in Milliken. With these tire settings lap times rose to a range of 37.3 to 38.1 seconds. Maximum speed reached 120 miles per hour. Now the throttle could not be maintained for the entire lap, and indeed significant braking down to 70 miles per hour entering the turns was required. Throttle could be applied mid-turn, raising speed to 80 miles per hour. The handling behavior of the car comprehensively changed. On power the car exhibited pronounced oversteer tendencies, while tending to understeer off power. Significant steering adjustment was required to navigate a turn, and near spins could be recovered from with generous amounts of counter-steer.

These character changes brought the car much closer to the goals the RLAPS SSP is intended to meet for driver development, but performance lagged on objective standards and the car was in a way too difficult to drive, with many spins and crashes encountered on the way to setting representative lap times. To address both of these issues, stiffness was increased globally to 1.5 laterally and longitudinally. This lowered lap times to a range of 34.8 to 35.1 and made the car easier to control. Maximum torque was increased from 200 to 300, which actually increased lap time to 35.2 to35.7 second range. The car became difficult to drive and produce clean sustainable laps. Maximum speed rose to 130 miles per hour. The lateral asymptote slip value was then moved to 0.7, broadening the usable grip curve and making the transition from grip to sliding less severe. This made the car much more forgiving, controllable, and easier to recover from near-spins. Lap time fell to a range of 31.4 to 33.1 seconds. Finally, maximum torque was reduced to 275, which lowered lap times to 32.4 to 34.9 second range. This setup produced a car that required significant braking before corner entry, modulation of throttle and steering through the corner, and smooth transition back to full power exiting the corner.

The results of each evaluation following a parameter change are summarized in the table below. The quality of the change, whether positive (better) or negative (worse), toward the objective and subjective criteria are specified. For example, a change that resulted in lap times and speeds that were closer to the values predicted by Optimum Lap than the previous test, but behaved with a less realistic feel and character would be classified as positive for objective criteria and negative for subjective criteria.

Test	Change	Objective Results	Subjective Results
1	Initial parameters as delivered	Mixed – lap time positive, speeds negative	Negative
2	Decrease tire lateral and increase longitudinal stiffness	No change	No change
3	Turn traction control and steering help off	Negative	No change
4	Decrease tire lateral and increase longitudinal stiffness	Mixed – lap time negative, speeds positive	Positive
5	Change all tire parameters to match real world data	Mixed – lap time negative, speeds positive	Positive
6	Increase lateral and longitudinal stiffness	Positive	Positive
7	Increase maximum power	Negative	Negative
8	Increase lateral asymptote value	Positive	Positive

9	Decrease power to level still greater than initial value	Positive	Positive

Conclusion

The RLAPS Simulation Software Program was intended to serve as a driver training and development tool by allowing drivers to practice and receive feedback on fundamental driving skills such as braking upon corner entry, managing a line through a turn, consistent braking and throttle points, managing wheel spin and vehicle yaw, and combining these skills to complete a fast lap without spinning out or crashing. In order to allow drivers to practice these skills while performance metrics were recorded and motion and control feedback was provided to inform the driver, the simulation program required a high fidelity but low complexity vehicle physics model. The model produced as outlined here using tools provided in Unity 3D was designed to meet objective performance requirements. After some initial tuning the vehicle performed in such a way that highlighted the exact skills that a driver using this simulator would want to exercise. The vehicle model meets the purpose for which the simulator was intended.

Evaluation and development does not end with this phase of the project. A major limitation of this study was a lack of objective real world data to measure the simulator's true fidelity against. Only one non-professional test driver was used. Further testing will involve multiple professional test drivers and real data from actual late model stock cars on representative tracks. From the existing model, beyond fine tuning based on the feedback from test drivers and data, further development can focus on renewing attempts to add details such as load saturation and camber force to increase the accuracy of the already refined tire model.

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Appendix A Proposed Algorithm to Programmers

Model Parameters

- Coordinate System for this algorithm
    - X: oriented parallel to car's longitudinal centerline, from front of car to back, positive towards front
    - Y: oriented parallel to car's lateral centerline, from left to right, positive towards right
    - Z: oriented vertically from car, positive upward
    - Origin at vehicle's center of gravity
- Aero
    - cD: 0.45
    - cL: 0.55
    - A: 17.85 ft^2
    - Aerodynamic forces act at vehicle Center of Gravity
- Drivetrain
    - Torque Curve
        - $T_e = 5 * 10^{-9} n_e^3 + 4 * 10^{-5} n_e^2 - 0.0775 n_e + 383.13$
    - Linear throttle ie Effective Torque = Throttle %*T_e.
    - Max RPM 5500
    - I_e=.7 I_a=20 (includes both rear wheels) in lb/ft^2
    - Gears:
        - Neutral: 0
        - 1st: 1.26
        - 2nd: 1.00
        - Final: 5.88
    - On/off clutch – clutch either 100% engaged, or 0% engaged if clutch depressed past some cutoff point
    - With no load (clutch disengages) engine deceleration due to friction and air pumping is 1,000 RPM/sec
- Braking
    - Max force: 4000 lbs
    - Tires have 1 ft radius, so max torque = 4000 lb/ft
    - Linear braking ie Effective force = brake%*max braking force
    - Initial Bias 60% front, 50-50% left-right
- Chassis
    - Weight distribution
        - 55% front
        - 50-50 left-right distribution
        - 20 inch height of COG
        - I_{yaw}=790 lb/ft^2
    - Dimensions
        - 103 inch wheelbase
        - 66 inch track front and rear

- Weight
  - 2850 pounds
- Geometry
  - Assume 0 degree toe and camber
  - Rigid suspension

- Tire
  - 24 inch effective diameter
  - No growth model
  - cRR – 0.055
  - I_w=9 lb/ft^2

Algorithm

Note: Any subscript "$_{xx}$" denotes a value that would be calculated for each individual wheel. For example if there was some value X that would have a value individually calculated for each wheel, it would appear as X_{xx}. If fully written out, this value would be calculated as X_{FL} for the front left wheel, X_{FR} for the front right wheel, etc.

- Determine Drive and Braking Torque to wheels
  - Engine Torque
    - Terms
      - Ne=engine speed
      - TP=throttle position percentage. Throttle pedal at least depressed position TP=0.1 (may adjust to create acceptable idle speed), Throttle at fully depressed position TP=1
      - T_e=engine torque produced
    - If ne<ne_{max}
      - $T_e = TP * (5 * 10^{-9} n_e^3 + 4 * 10^{-5} n_e^2 - 0.0775 n_e + 383.13)$
    - If ne>ne_{max}
      - T_e=0 for 0.05 sec (may adjust timeframe, see what feels like a typical real-life rev limiter)
  - Equivalent Drivetrain Inertia
    - Terms
      - I_e=engine inertia
      - I_a=drivetrain inertia including rear wheels
      - Z=overall gear ratio = selected gear (1st, 2nd, neutral) ratio * final drive ratio
    - $I_{eq} = I_e + \frac{I_a}{Z^2}$
  - Braking Torque
    - Terms
      - BP=brake position percentage. Brake pedal at least depressed position BP=0, Brake at fully depressed position BP=1

        - BD= brake distribution as a percent of braking force apportioned to the front brakes. For example, a front brake bias of 60% would result in a BD=0.6
        - T_b=braking torque produced
    - Front Brake Torque
        - T_{bFX}=0.5*BD*BP*Max Brake Torque
    - Rear Brake Torque
        - T_{bRX}=0.5*(1-BD)*BP*Max Brake Torque
- Net Torque to rear wheels
    - Term
        - T_w is the net torque to the rear wheel
    - $T_w = T_e - (T_{bRL} + T_{bRR})$
- Engine Speed and Acceleration
    - Terms
        - $\dot{n}e$ is engine speed acceleration
        - FX_R is the net longitudinal force produced by the rear tires
        - r_t is the effective radius of the rear tire
        - δt is the time frame between calculations.
        - f_e is the engine deceleration due to friction and air pumping when clutch disengaged
    - Engine Speed Acceleration
        - $\dot{n}e = \left(T_w - ((F_{XRL} + F_{XRR})\frac{r_t}{Z})\right) * (\frac{30}{\pi * I_{eq}})$
        - If clutch depressed past cutoff point, $\dot{n}e = \frac{30 * T_e}{\pi * I_e} - f_e$
    - New Engine Speed
        - $ne = ne + \dot{n}e * \delta t$

- Determine Wheel Speeds
    - Terms
        - V_X is the velocity of the vehicle in the X axis direction
        - ω_w is the wheel's rotational velocity
        - δ_s is the steering angle, the angle between the front wheel longitudinal centerline and the vehicle X axis, positive counterclockwise
        - I_w is the inertia of the individual front wheel
        - V_c = circumferential velocity of tire tread base, function of rotational velocity, defined as $V_c = r_t \omega_w$
        - a_c = circumferential acceleration of velocity of tire tread base
    - Front wheels
        - Free Rolling
            - If no braking force applied (T_{bFX}=0), assume front wheels are free rolling with no longitudinal slip
            - $V_{cFx} = \frac{V_X}{\cos \delta_s}$
        - Braking

- If braking force applied, brake torque creates acceleration (negative) for V_c
- a_{cFx} =-(T_{bFX}/I_w)
- V_{cFx}=V_{CFx}+$a_{cFx}\delta t$

  - Rear Wheels
    - If clutch engaged
      - $V_{cRx} = \frac{ne*r_t*\pi}{30Z}$
    - If clutch disengaged and brakes applied
      - a_{cRx} =-(T_{bRX}/0.5I_a)
      - V_{cRx}=V_{CRx}+$a_{cRx}\delta t$
    - If clutch disengaged and no brakes, rear wheels free rolling
      - $V_{cRx} = V_X$
      - V_{cRx}=VX_{Rx}

- Determine Wheel Slip
  - Traction
    - $s_{xx} = \frac{V_{cxx}-V_X}{V_{cxx}}$
  - Braking
    - $s_{xx} = \frac{V_X-V_{cxx}}{V_X}$
- Determine Slip Angle
  - Terms
    - α is the slip angle, the angle between the wheel's longitudinal centerline and the wheel's direction of travel. Positive counterclockwise
    - V_Y is the velocity of the vehicle in the Y axis direction
    - ω_{yaw} is the angular velocity of yaw
    - b is the distance from the front wheel centerline to the center of gravity of the vehicle
    - a is the distance from the rear wheel centerline to the center of gravity of the vehicle
  - Front $\alpha_{Fx} = \tan^{-1}\left(\frac{V_Y+\omega_{yaw}b}{V_x}\right) - \delta_s$
  - Rear $\alpha_{Rx} = \tan^{-1}\frac{Y_Y-\omega_{yaw}c}{V_X}$
- Determine tire friction coefficients
  - Terms
    - W_{xx} is the normal force load on the individual wheel
    - μ_{Xxx} is the lateral friction force coefficient developed by the wheel
    - μ_{Xxx} is the lateral friction force coefficient developed by the wheel
  - $\mu_{Xxx} = (48.685s_{xx}^5 - 139.31s_{xx}^4 + 148.85s_{xx}^3 - 73.17s_{xx}^2 + 16.17s_{xx}) - (0.25\alpha s) - (0.00105W_{xx}s)$
  - $\mu_{Yxx} = -(0.0007218\alpha_{xx}^3 - 0.02728\alpha_{xx}^2 + 0.3232\alpha_{xx}) + (0.3\alpha s) + (0.000035W_{xx}\alpha)$
- Determine Forces
  - Individual wheels
    - Longitudinal
      - Front: $F_{XFx} = \cos\delta_s\,\mu_{XFx}W_{Fx}$

            - Rear: $F_{XRx} = \mu_{XRx} W_{Rx}$
        - Lateral
            - Front: $F_{YFx} = \sin \delta_s \, \mu_{YFx} W_{Fx}$
            - Rear: $F_{YRx} = \mu_{YRx} W_{Rx}$
    - Total Resultant
        - Longitudinal
            - $F_X = \sum F_{Xxx}$
        - Lateral
            - $F_Y = \sum F_{Yxx}$
    - Aligning torque front wheels
        - $\alpha_F = \frac{1}{2}(\alpha_{FL} + \alpha_{FR})$
        - $M_z = (-17.798\alpha_F^2 + 147.68\alpha_F)(W_{FL} + W_{FR}) + (0.00001(W_{FL} + W_{FR})\alpha)$
- Determine Aerodynamic forces
    - Terms
        - ρ is the density of air
        - C_D is the drag coefficient
        - C_L is the downforce coefficient
        - A_f is the frontal area of the vehicle
    - $D = 0.5\rho C_D A_f V^2$
    - $L = 0.5\rho C_L A_f V^2$
- Determine Acceleration
    - Terms
        - a_X is longitudinal acceleration of the vehicle
        - a_Y is lateral acceleration of the vehicle
        - crr is the coefficient of rolling resistance
        - W is the weight of the vehicle
        - g is acceleration due to gravity (ie 32.2 ft/s^2)
    - $a_X = (\frac{g}{W}(F_x - (crr * (W + L)) - D))$
    - $a_Y = \left(\frac{g}{W} F_y\right)$
- Determine Velocity
    - $V_X = V_X + a_X \delta t$
    - $V_Y = V_Y + a_Y \delta t$
- Determine Sideslip
    - $\mathrm{B} = \tan^{-1}\frac{V_y}{V_x}$
- Turn Radius and yaw
    - Terms
        - l is the wheelbase
        - R is the radius of the turn
        - ω_{yaw} is the yaw angular velocity
        - $\dot{\omega_{yaw}}$ is the yaw angular acceleration
        - I_{yaw} is the yaw moment of inertia of the vehicle
    - Low Speed 15 MPH or less

        - $R = \frac{l}{\sin \delta_s}$
        - Turn Angular Velocity $\omega_{yaw} = \frac{V_x}{R}$
        - No slip angle at low speed so no lateral velocity is produced. Turn is simply a function of geometry and the changing direction of the vehicle's longitudinal velocity vector relative to the track
    - High Speed
        - Yaw
            - Torque
                - Front: $T_{yawF} = \cos \delta_s (F_{YFL} + F_{YFR})b$
                - Rear: $T_{yawR} = -(F_{YRL} + F_{YRR})c$
                - Net: $T_{yaw} = T_{yawF} + T_{yawR}$
            - Acceleration
                - $\dot{\omega_{yaw}} = \frac{T_{yaw}}{I_{yaw}}$
                - $\omega_{yaw} = \omega_{yaw} + \dot{\omega_{yaw}} \delta t$
- Vehicle position and orientation
    - Terms
        - X is the vehicle's X coordinate on the track's coordinate system
        - Y is the vehicle Y coordinate on the track's coordinate system
        - R_Z is the vehicle's rotation about the Z axis on the track's coordinate system
    - $X = X + V_X \delta t$
    - $Y = Y + V_Y \delta t$
    - $R_Z = R_Z + \omega_{yaw} \delta t$
- Weight Transfer
    - Terms
        - t is the track
        - h is the height of the center of gravity
    - Static
        - Front distribution $WS_{Fx} = \frac{Wc}{2l}$
        - Rear distribution $WS_{Rx} = \frac{Wb}{2l}$
    - Load transfer
        - Longitudinal: $\Delta W_{long} = \frac{W a_X h}{gl} + \frac{Dh}{l}$
        - Lateral: $\Delta W_{lat} = \frac{W a_Y h}{gt}$
    - Downforce application
        - Front $L_{Fx} = \frac{Lc}{2l}$
        - Rear $L_{Rx} = \frac{Lb}{2l}$
    - Final Distribution
        - $W_{FL} = WS_{FL} - \Delta W_{long} - \Delta W_{lat} + L_{FL}$
        - $W_{FR} = WS_{FR} - \Delta W_{long} + \Delta W_{lat} + L_{FR}$
        - $W_{RL} = WS_{RL} + \Delta W_{long} - \Delta W_{lat} + L_{RL}$
        - $W_{RR} = WS_{RR} + \Delta W_{long} + \Delta W_{lat} + L_{RR}$

Appendix B Parameters of RLAPS Vehicle Model From Unity

RIGIDBODY

0 Mass = 1800

1 Drag = .05

2 Angular Drag = 1

CAR CONTROLLER

3 Center of Mass Offset = 0, 0, 0

4 Max Steer Angle = 40

// 0 is raw physics , 1 the car will grip in the direction it is facing

5 Steer Helper = .2

// 0 is no traction control, 1 is full interference

6 Traction Control = 1

7 Full Torque Over All Wheels = 200

8 Reverse Torque = 500

9 Downforce = 100

// Fastest the car can go

10 Topspeed = 150

// Forward and Sideways slip limit until car starts to slip

11 Slip Limit = .3

12 Brake Torque = 20000

WHEEL COLLIDERS

13 Mass = 20

14 Wheel Damping Rate = .35

15 Suspension Distance = .001

SUSPENSION SPRING

16 Spring = 70000

17 Damper = 45

FORWARD FRICTION

18 Extremum Slip = .4

19 Extremum Value = 1

20 Asymptote Slip = .8

21 Asymptote Value = .5

22 Stiffness = 2

SIDEWAYS FRICTION

23 Extremum Slip = .4

24 Extremum Value = 1

25 Asymptote Slip = .5

26 Asymptote Value = .75

27 Stiffness = 10

GEAR VARIABLES

28 Gear Ratios = -10, 0, 9, 6, 4.5, 3, 2.5

// The Curve

// Table of efficiency at certain RPM, in tableStep RPM increases, 1.0f is 100% efficient

29 Efficiency Table = 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.85, 0.9, 0.95, 1, 1, 1, 0.95, 0.95, 0.95, 0.95, 0.8, 0.75, 0.7, 0.65

//The scale of the indices in table, so with 250f, 750RPM translates to efficiencyTable[3].

30 Efficiency Table Step = 250

31 Max RPM = 5500

32 Min RPM = 500

AUTOMATIC SHIFTING

33 RPM to Shift Up = 5000

34 RPM to Shift Downn = 1500

Appendix C Optimum Lap Track Report

Track Report

RLAPS Generic 78 Flat

Track Information

	Type of Track	Oval Circuit
	City	Country
	Track Direction	Forward Direction

Statistics

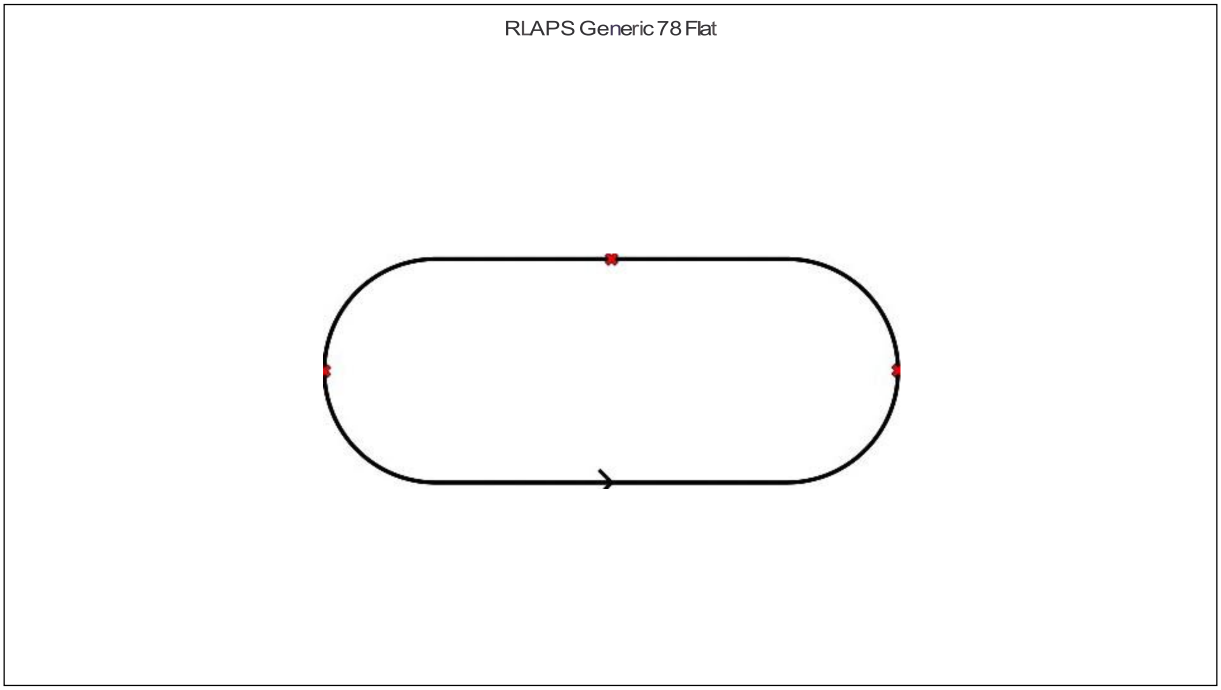
	Statistic	Value
	Total Track Length	4619.42 ft
	Percent Left Corners	50 %
	Percent Right Corners	0 %
	Percent Straights	50 %
	Average Corner Radius	367.45 ft
	Minimum Corner Radius	367.45 ft
	Longest Straight	1154.86 ft

Sectors

	Name	Distance
	Sector 1	From 0 To 1154.86 ft
	Sector 2	From 1154.86 To 2309.71 ft
	Sector 3	From 2309.71 To 3464.57 ft
	Sector 4	From 3464.57 To 4619.42 ft

Track Map

Friday, March 24, 2017



Enter your comments here...

Appendix D Optimum Lap Vehicle Report

Vehicle Report

RLAPS Generic Stock Car

Friday, March 24, 2017

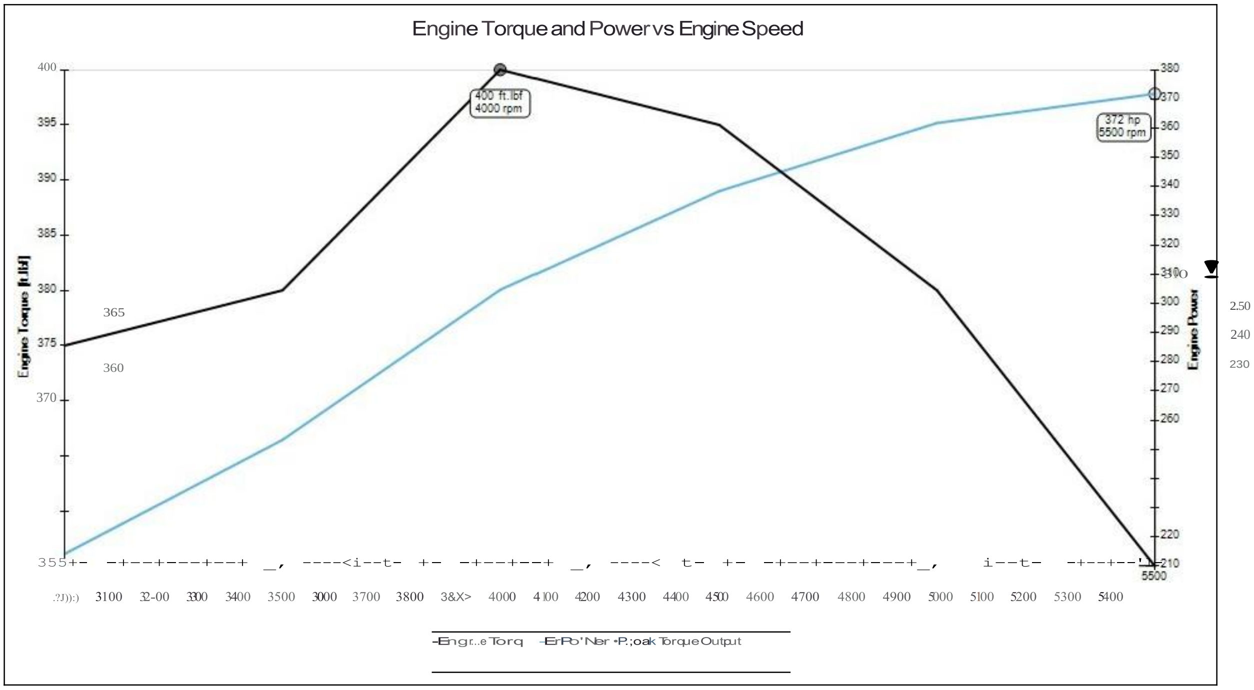
Vehicle Configuration

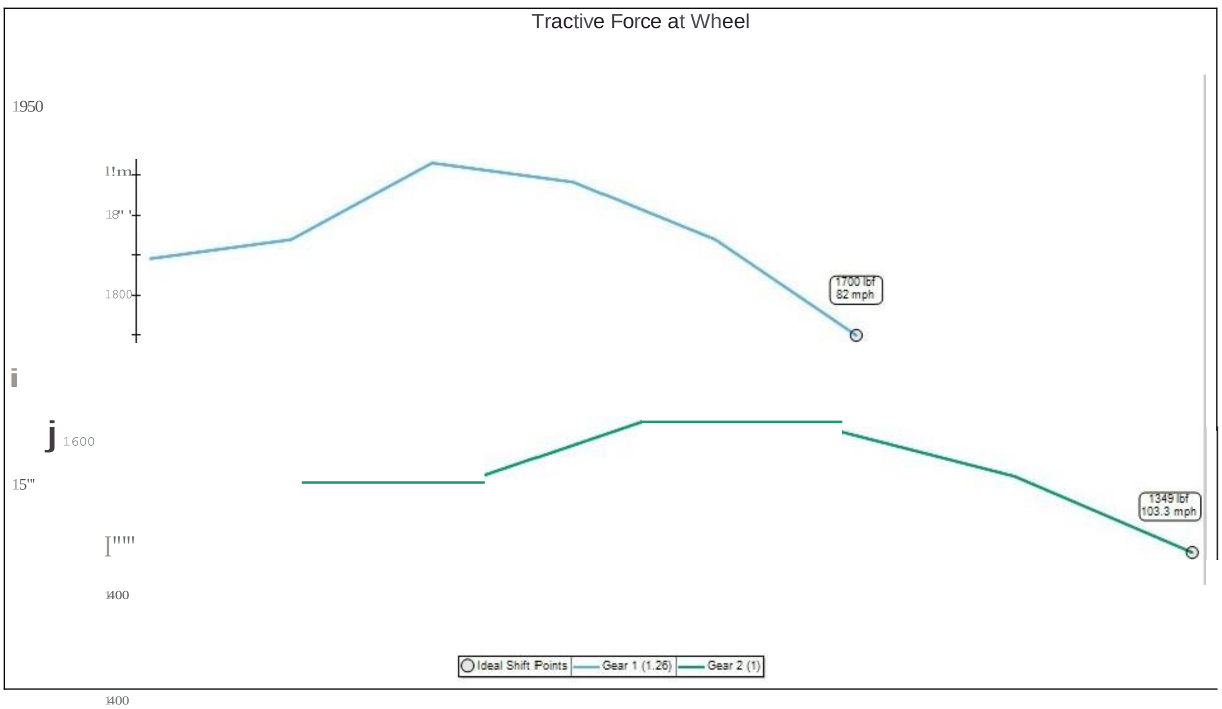
	Parameter	Value
	Total Mass	2200 lb
	Max Torque	400 ft.lbf @ 4000 rpm
	Type of Fuel	
	Type of Transmission	Sequential Gearbox
	Max Power	371.76 hp @ 5500 rpm
	Power Mass Ratio	0.17 hp/lb
	Downforce @ 62 mph	98.56 lbf
	Drag @ 62 mph	115.13 lbf

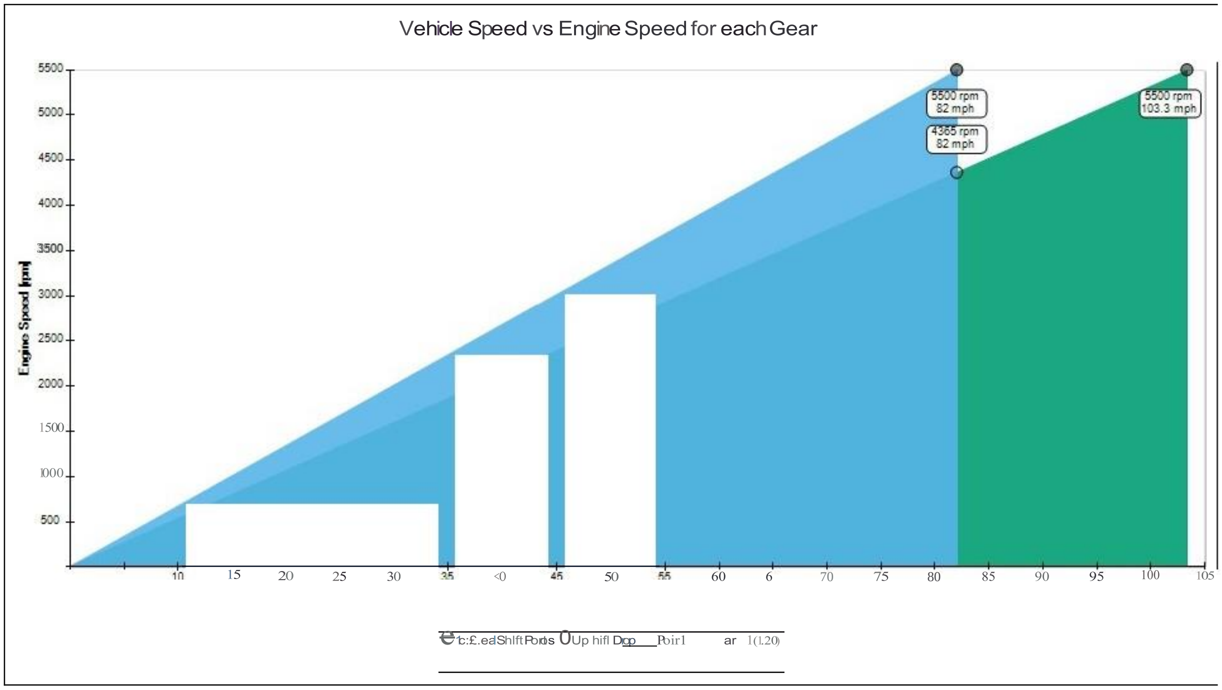
Performance Metrics

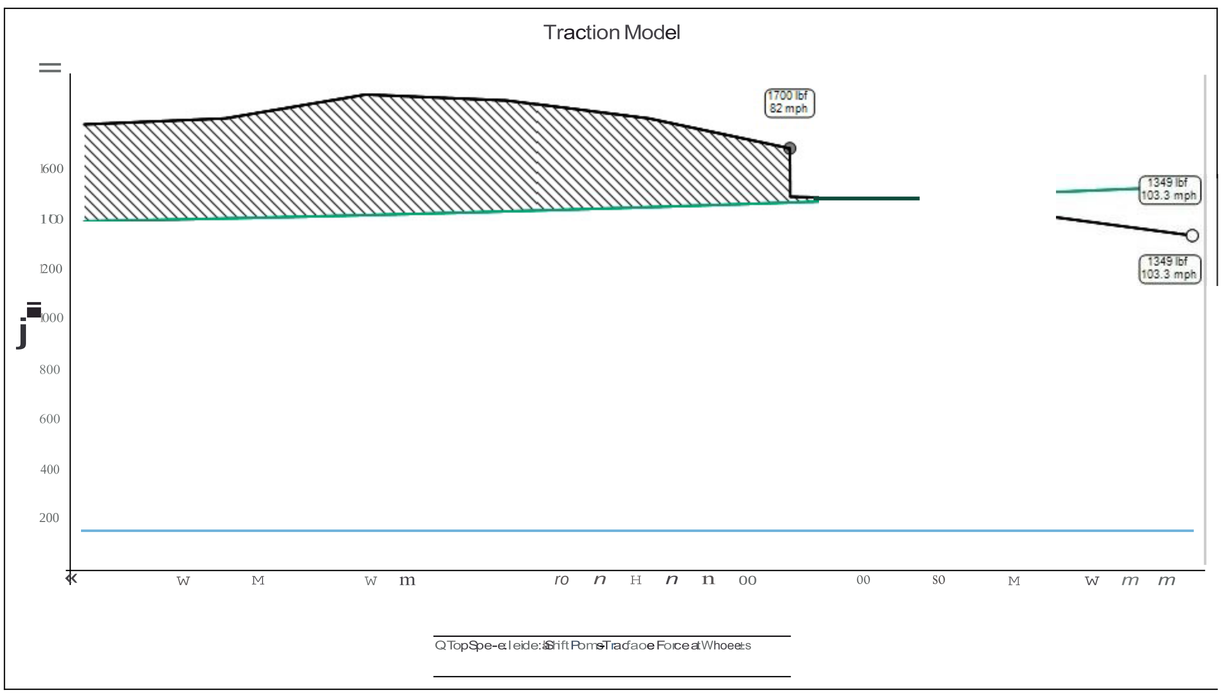
	Metric	Value
	Top Speed	103.34 mph
	Time for 0 to 62 mph	1.32 s
	Time for 62 to 0 mph	2.2 s
	Lateral Acceleration - Skidpad 164 ft	45.19 ft/s^2

Charts Summary


Engine Torque and Power vs Engine Speed
400 ft.lbf
4000 rpm
372 hp
5500 rpm
Engine Torque [ft.lbf]
Engine Power


Tractive Force at Wheel
1700 lbf
82 mph
1349 lbf
103.3 mph
Ideal Shift Points
Gear 1 (1.26)
Gear 2 (1)





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Appendix E Numeric Results from Optimum Lap Simulation

[Result Details]		
Result Name	[33.00] RLAPS Generic Stock Car	RLAPS Generic 78 Flat
Date Created	3/24/2017 13:23	
Track	RLAPS Generic 78 Flat	
Track Configuration	Closed Circuit	
Vehicle	RLAPS Generic Stock Car	
[KPI Values]		
Lap time [s]	32.99664119	
Percent in Corners [%]	53.21758813	
Percent Accelerating [%]	44.35915162	
Percent Braking [%]	55.6032351	
Percent Coasting [%]	0	
Percent 100% Throttle [%]	44.35915162	
Percent TCS Enabled [%]	53.17997485	
Lowest Speed [mph]	89.661691	
Highest Speed [mph]	103.3418636	
Average Speed [mph]	95.8930389	
Energy Spent [kJ]	3937.267136	
Fuel Consumption [lb]	âˆž	
Gear Shifts [-]	0	
Maximum Lateral Acceleration [ft/s^2]	47.54284941	
Maximum Longitudinal Acceleration [ft/s^2]	18.51476988	
Maximum Longitudinal Deceleration [ft/s^2]	-48.96683388	
Time in Sector 1 [s]	8.225972436	
Time in Sector 2 [s]	8.275053905	
Time in Sector 3 [s]	8.225972436	
Time in Sector 4 [s]	8.269642409	
Maximum Speed in Sector 1 [mph]	103.3418636	
Maximum Speed in Sector 2 [mph]	103.3418636	
Maximum Speed in Sector 3 [mph]	103.3418636	
Maximum Speed in Sector 4 [mph]	103.3418636	
Minimum Speed in Sector 1 [mph]	89.66170712	
Minimum Speed in Sector 2 [mph]	89.661691	
Minimum Speed in Sector 3 [mph]	89.66170712	
Minimum Speed in Sector 4 [mph]	89.661691	
Percent in Gear 2 [%]	100	
[Vehicle Parameters]		
Mass Longitudinal Friction [lb]	0	
Vehicle Mass [lb]	2200	
Drag Coefficient [-]	0.45	

Downforce Coefficient [-]	0.55
Aero Efficiency [-]	1.222222222
Frontal Area [ft^2]	17.8
Drivetrain Efficiency [%]	100
Tire Rolling Radius [ft]	1
Air Density [lb/ft^3]	0.078
Rev Limit [rpm]	5500
Longitudinal Friction [-]	1.25
Lateral Friction [-]	1.35
Final Drive Ratio [-]	3.8
Fuel Energy Density [J/kg]	0
Engine Thermal Efficiency [%]	0
Tire Rolling Drag [-]	0.015
Power Scaling Factor [%]	100
Aero Scaling Factor [%]	100
Grip Scaling Factor [%]	100
Mass Lateral Friction [lb]	0
Load Sensitivity Lateral Friction [-]	0
Load Sensitivity Longitudinal Friction [-]	0
Gear Ratio Data [-]	0
Gear Shift Points [rpm]	0
Torque Data [ft.lbf]	0
RPM Data [rpm]	0
[Vehicle KPIs]	
Shift Point [1 to 2] [rpm]	5500
Deceleration Time For Speed [27.778 mph] [s]	2.198707732
Deceleration Distance For Speed [27.778 km/h] [ft]	99.08136483
Top Speed [mph]	103.3418636
Acceleration Time To Speed [27.778 mph] [s]	1.318466629
Acceleration Time For Distance [100 ft] [s]	3.351095991