Chapter 1
Introduction

This chapter describes a general overview of this research. Background information related to the topic of vehicle dynamics and modeling along with research objectives are introduced. Related literature is reviewed in this section, linking relevant topics to the research presented here. Finally an outline of the thesis and a brief description on the contents of each chapter are also presented.

1.1 Motivation for Studying Vehicle Dynamics

Research in vehicle dynamics has been an on-going study for decades, ever since the invention of automobiles. Engineers and researchers have been trying to fully understand the dynamic behavior of vehicles as they are subjected to different driving conditions, both moderate daily driving and extreme emergency maneuvers. They want to apply this finding to improve issues such as ride quality and vehicle handling stability, and develop innovative design that will improve vehicle operations. With the aid of fast computers to perform complicated design simulations and high speed electronics that can be used as controllers, new and innovative concepts have been tested and implemented into vehicles [1]. This type of research is mainly conducted by automotive companies, tire manufacturers, and academic institutions.

Automotive companies are constantly improving on their chassis design and development by re-engineering their suspension systems through new technology. For example, the recent developments of traction control systems show that a marriage of vehicle dynamics and electronics can improve handling quality of vehicle [1]. Examples of such systems are anti-lock braking systems and automatic traction systems. They use a sensor to measure the wheel's rotational speed and a micro-controller to determine, in real time, whether slipping of the tire is present. This results in full traction and braking under all road conditions, from dry asphalt to icy conditions [2]. Another example of the benefit of joining vehicle dynamics with electronics is in controllable suspensions, such as those using semi-active damper [3]. Semi-active dampers enable damping characteristics of the suspension system to be set by a feedback controller in real-time, thus improving the ride quality of the vehicle on different types of road conditions [3].

A more advanced concept that is currently under research and development by automotive companies is an autonomous vehicle [4,5,6]. This concept will enable the vehicle to get from one point to another without constant commands from the driver. The idea is to relieve the burden of vehicle control and operation from the driver and also to reduce the number of accidents associated with driver operating error.

Tire manufacturers also perform a variety of research on vehicle dynamics. They are interested in characterizing the performance of their tires as a function of the tire construction component [7]. Their goal is to be able to predict or design tires for any type of applications efficiently, and to reduce the cost associated with prototyping and testing. Their efforts require developing more accurate tire models; specifically models that can predict how changing the tire compound affects the tire performance.

The use of predictive models is particularly important in applications where the tire performance is crucial, such as in race cars. The functions of tires are to support the vertical load of the vehicle, to generate the forces and moments necessary to keep the race car on the track, and to generate traction against the ground. Formula-One race cars are the most highly advanced vehicles in the world, where millions of dollars are spent on their research and development. The performance between different race vehicles are relatively the same, i.e., about the same amount of horsepower, the same amount of braking ability, and the same suspension systems. Most races, however, are decided by the tires each team puts on their car and the skills of the driver to push the car to the limits. Tire manufacturers spent tremendous amount of money and time developing the best tires for different types of racing conditions. Still, it is often difficult for the racing teams to select the tire compound that is most suitable for a particular racetrack. As a result, tire manufacturers in conjunction with racing teams are developing a simulation tool to predict the best tires for a particular racing condition [8].

Universities and research institutions are interested in vehicle dynamics for the same reasons as mentioned above. Most of their projects are often funded by the automotive industry. Another financial contributor may be the government agencies where their interest lies in preserving the road surface due to different driving conditions. Reducing the road damage caused by heavy trucks is a major concern in trying to keep the cost of infrastructure maintenance to a minimum [9].

1.2 Motivation for this Research

Similar to most engineering studies, this research is initiated by an idea. Currently track testing is conducted by using test drivers to perform repetitive maneuvers on the track; specifically to characterize the handling, ride, and other vehicle related performance of the vehicle. The objective of the test may be to do performance comparison between old and new designs of shock absorbers, suspension geometries, or tires. In order to accurately compare between different versions of a proposed designs, testing environment and vehicle input must remain the same for all test vehicles. It is quite difficult for the test drivers to be consistent, inputting exactly the same series of steering angles and longitudinal forces. If this process could be automated, the results from the performance comparison as well as repeatability of the tests can be significantly improved.

Automated track testing eliminates test drivers and replaces them with a feedback controller that follows a path. The path is not randomly generated but rather contains significant contents, depending on the application of the test. For example, if the objective of the test is to perform accelerated tire wear testing on newly designed tires, the path maximizes tire forces, and a correction factor is used to correlate the accelerated tire wear to the normal tire wear [10]. If the objective of the test is to evaluate a newly designed suspension of a racecar, the path minimizes on travel time from starting point to the finish line. These paths are often chosen heuristically by the drivers using their many years of experience. Another way to generate the paths is through the optimization algorithm using the characteristics mentioned above as objectives.

1.3 Research Objective

The objective of this research is to evaluate the applicability of optimization routines to vehicle dynamics and handling. Specifically the use of constrained optimization schemes for selecting an optimal path on a given course will be evaluated, considering the tire and vehicle dynamics. This study will help in the development of designing an automated vehicle track testing. Two scenarios will be evaluated for tire force maximization and time minimization paths. Figure 1.1 shows the diagram of the automated track-testing concept. Bold boxes are the topics that will be studied in this research.

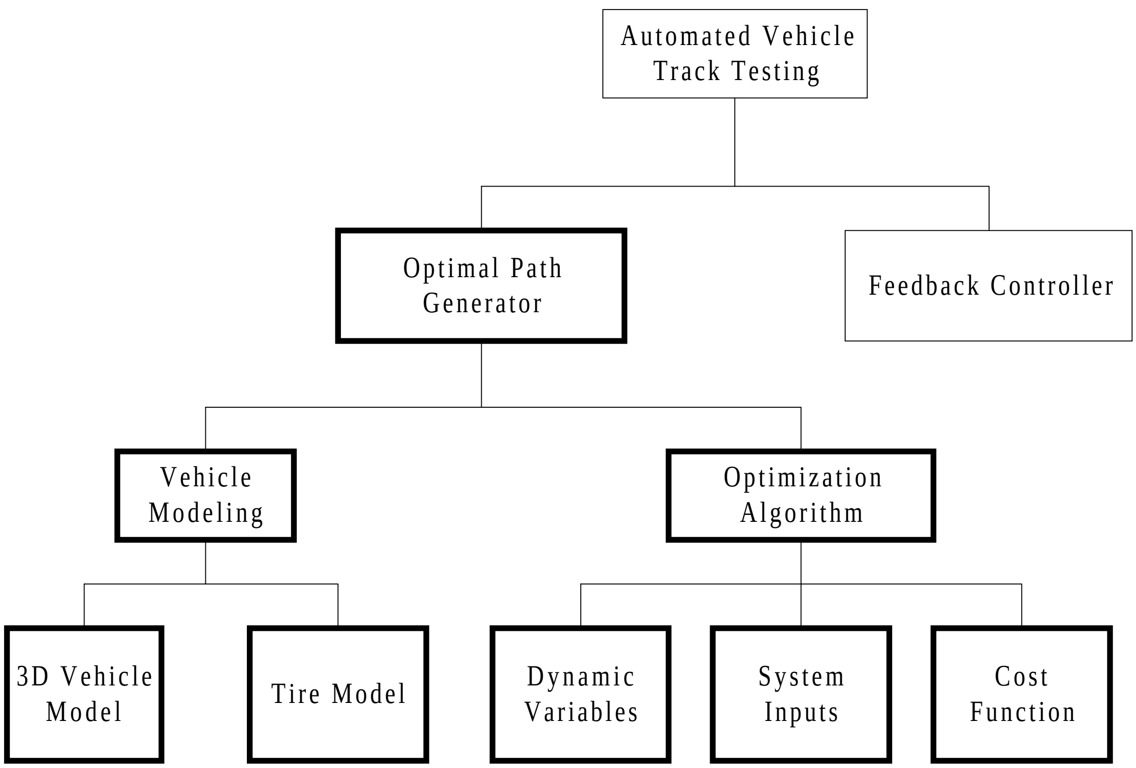

Figure 1.1 Automated Vehicle Handling Track Testing Outline

This study, which uses a relatively simple vehicle and tire model, is intended as a preliminary study of optimal path generator. More complete studies should include factors such as the dynamics of the vehicle and tire in all degrees of freedom.

1.4 Literature Review

At the beginning of this research, an extensive literature search in the area of vehicle dynamics and optimal control of vehicle was conducted. The database INSPEC, a leading source of engineering research, science, and electronics articles, the database Article1st, an index of articles from nearly 12,500 journals, and the database Proceedings, an index of conference publications, were used to complete the search. Keyword search was referenced on the following terms; vehicle dynamics, optimization, path, modeling, tire, minimum time, and friction circle. The latter two terms were used to determine if similar study of tire force maximization and time minimization had been completed. Figure 1.2 shows the results of the literature search.

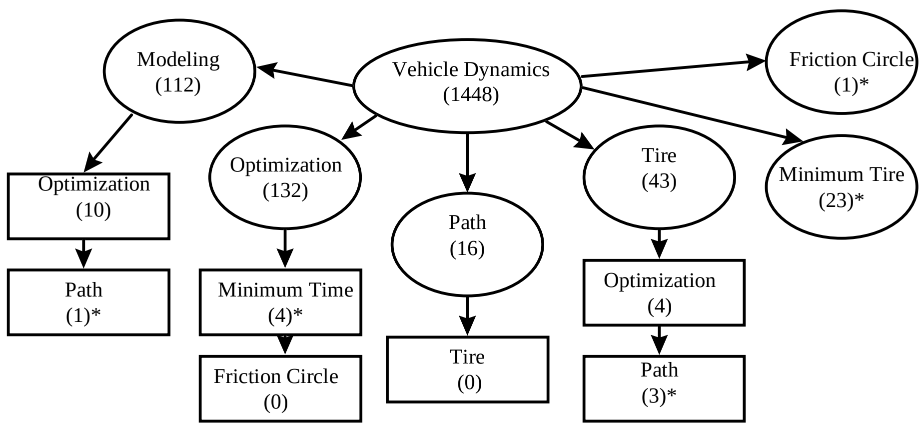

Figure 1.2 Literature Review Keyword Search Diagram

(* Irrelevant topic)

The following sections, divided into minimum time optimal path, vehicle and tire model, and autonomous vehicles sections, briefly describe the papers that were found most relevant and complimentary to this research.

1.4.1 Minimum Time Optimal Path

The research by of Hatwal, et al. [11] generated the time histories of steer angle, traction, and braking forces required to track a desired trajectory, for a lane-change maneuver. Hatwal, et al. also made a comparison of different handling performance between a front wheel drive (FWD) vehicle and a rear wheel drive (RWD) vehicle using a five-degree-of-freedom model for the vehicle. The system control variables were steer angle of the front wheel, longitudinal force of the front wheel for FWD vehicle, and longitudinal force of the rear wheel for RWD vehicle. Hatwal, et al. used optimal control approach to determine the system control vectors with an objective of minimizing time. They first assumed a free final time optimal control formulation, and concluded that it was complex. Next they used a fixed final time formulation by deriving the differential equations with respect to forward distance using the relationship between distance, velocity, and time. They noticed that the fixed final time formulation reduces the number of equations needed to be solved. They used a penalty cost function and the weighting factors tuning approach to find the desired trajectory. They concluded that FWD and RWD require similar steering angle input and longitudinal force input during low speed lane-change maneuver. At higher speeds, however, they concluded that there was a significant difference in trajectory between the two types of vehicle.

Another study by Hendrikx, et al. [12] was to determine a time optimal inverse model of a vehicle handling situation. They were interested in the driver actions, time histories of the steering rate and the longitudinal force at the road/tire contact. This optimal control problem was calculated using the Gradient Method [13]. The vehicle was modeled as a two-dimensional four-wheel model where the tire model was nonlinear. Their objective was to determine the vehicle trajectory for a lane-change maneuver, with minimum time. A parametric study comparing the optimal trajectories between FWD and RWD vehicles was also performed. As a result, they concluded that optimal control could be applied to optimize car handling for a specific lane-change maneuver by means of inverse vehicle model simulation, and FWD and RWD vehicles required different driving strategies.

1.4.2 Vehicle and Tire Modeling

Smith, et al. [14] performed a study on modeling accuracy between different vehicle models and tire models. Specifically, they compared three models; the first was a bicycle model with yaw and side-slip degrees of freedom using a linear tire model. The second model was a five-degree-of-freedom model with additional longitudinal and wheel rotational degrees of freedom, using a nonlinear tire model. The third was an eight-degree-of-freedom model, with additional roll and wheel rotational degrees of freedom for the other two tires using a nonlinear tire model. The equations of motion were integrated using the Runge-Kutta method [15]. The results shown in their paper indicated variations in accuracy between these models. They suggested that the bicycle vehicle model could not be used accurately in the high lateral acceleration maneuvers due to the lack of lateral load transfer and body roll dynamics. With these results, they concluded that the tire lag information must be included in a lateral controller for high speed maneuvers, in order to accurately predict the desired and safe trajectory.

Maalej et al. [7], performed a study on various types of tire models which were used to characterized the effects of slip ratio and slip angle on lateral force. They investigated four different models, Dugoff, Segel, Paceijka, and proposed polynomial, comparing the accuracy and the computational time between them. For the comparison, they investigated the lateral force, longitudinal force, alignment moment, and combined braking and steering performance of each model. They found that each model had its own advantages and disadvantages, Paceijka scored highest in the accuracy category while Segel scored the highest in the computational time category.

1.4.3 Autonomous Vehicles

Freund et al. [6], investigated the use of a feedback controller to automatically guide vehicles on desired trajectories. They used a four-degree-of-freedom model (yaw angle, yaw rate, longitudinal velocity, and sideslip) to describe the vehicle motion with the inputs as the front wheel lateral force and the rear wheel longitudinal force. The lateral force was derived as a function of sideslip angle, which was estimated using a pole placement method. They concluded that feedback controllers can be used to automatically guide vehicles along the desired trajectories with a certain level of accuracy.

Niehausk et al. [16], performed a study on the concept of automated highway system that uses an intelligent automotive guidance system to determine the trajectory of the vehicle during highway traffic. The intelligent automotive guidance system uses the rule-based (*if-then*) expert system to perform situation assessment and decision-making to be applied to the controller. The controller consists of sensors, actuators, and a controller that are capable of controlling the steering, longitudinal acceleration, and lateral acceleration of the vehicle in real-time. Their concept was tested on a highway traffic simulator with a traffic situation, the expert system successfully assessed and decided an action. Niehausk et al. concluded that their concept of intelligent automotive guidance has advantages in the development aspect where the code can be easily programmed, debugged, and broken up for different driving tasks. Also with further development, more highway situations will be implemented.

Kageyama et al. [17] investigated a design of the control algorithm for an autonomous vehicle using risk level as the performance criteria. The autonomous vehicle is consisted a track preview image processor that recognizes the road profile and traffic condition. A feedback controller is used to drive the vehicle to the desired position controlling the steering angle and the longitudinal acceleration of the vehicle. The cross section road profile, once captured, is divided into small sections assigning each one with a risk level. The objective of the control algorithm is to determine the optimal trajectory, in real-time, that minimizes the risk level. The objective function is defined as a function of human heart rate, which exponentially increases as the vehicle approaches the edge of the road. They tested their design using a simulated driving condition. From their results, they concluded that the control algorithm using the risk level concept could be implemented in the autonomous vehicle.

1.5 Thesis Outline

Chapter 2 describes the axis system used throughout this research, which is the standardized SAE vehicle axis system. This section also explains the derivation of the three-degree-of-freedom vehicle model and the tire model. It then describes the transformation of equations of motion to the state space form. Discussions on the third order Runge-Kutta method which is used to integrate the first order differential equations, and the step size required to make the simulation more accurate are also presented in this chapter.

The background information on constrained optimization is first presented in Chapter 3. Definitions of variables associated with this particular approach for solving the optimal control problem are discussed, followed by a comparison between two algorithms that can be used to solve the problem. The logic of the simulation program and the structure of the source code are also provided in Chapter 3.

Chapter 4 summarizes the results of this research and presents findings from the parametric study. Finally, the conclusion of the research and recommendation on future research are provided in Chapter 5.

Appendix contains the major Matlab m-files used to perform the optimal path generator simulation.