Chapter 1

Introduction

1.1 Background and History of Stability and Handling Analysis

Handling and stability analysis of automotive vehicles started as an experimental study of steering stability only. Trial and error hardware iterations were used as an economical means of refining designs. Even at moderate speeds early steering systems tended to be unstable. Some were even inherently unstable, like rear steer vehicles.

After a very short time, more regimented tests were devised. A series of skid pad tests were, and still are, used to study vehicle directional stability. The "max lat" test demonstrates the lateral adhesion capabilities of an automobile. The vehicle drives around a constant radius circle at increasing speeds until it can no longer maintain the same radius. Then an accelerometer indicates the maximum lateral acceleration that is attained. The random steer test is another test used to excite the lateral natural frequencies and measure the lateral response time to a given steering input. As these tests are performed, the limits of lateral road adhesion and force generation are tabulated. By using these types of tests, vehicle designers soon discovered that pneumatic tires influence vehicle lateral dynamics more than any other vehicle component.

A concise description of directional control is a formidable task for any vehicle analyst or designer. The complexity of the components that make up the vehicle system make analytical simplification difficult. The pneumatic tire has the most important influence over vehicle handling. For this reason models generated in the early years of vehicle design evaluation (or design analysis) had very simple sprung mass and suspension equations and complex equations for the tire.

The complexities in tire force/moment-generating mechanisms made empirically based tire models most common. Even with these simpler empirical models, the number of parameters that directly affect the lateral force generation properties necessitated in either piecewise solutions or huge matrices of tabulated data.

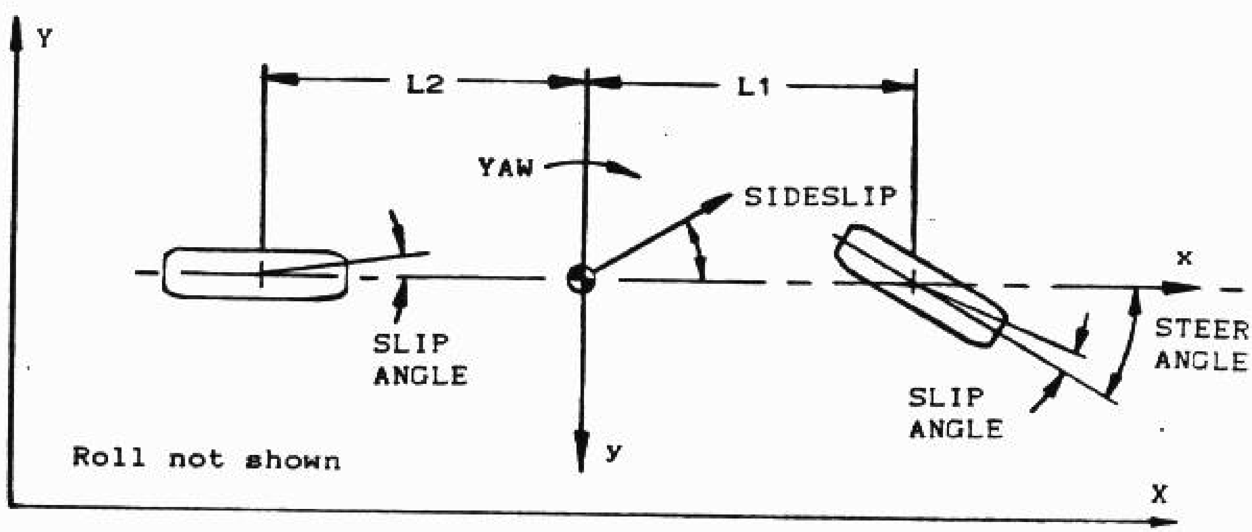

Figure 1-1: A typical "bicycle model" of a rubber tired vehicle

The rest of the vehicle model usually included a laterally symmetric and suspensionless representation of lateral dynamics. Variations of this three degree-of-freedom (dof) "bicycle model" contained coordinates like: sideslip, yaw, roll, and steer angle, see Figure 1-1. These bicycle models were based on the roll axis assumption. This assumption states that the sprung mass rolls about a stationary axis which was fixed in the unsprung mass; when the roll axis is now known to move during roll. The main use of these models was to determine how weight distribution and tire properties affected yaw attitude and yaw velocity of a vehicle during cornering or transient maneuvers. Practically useful versions of these bicycle models are used in standard chassis design today. These models (and extensive experimental development techniques) are used in the design of state-of-the-art suspensions.

About twenty years ago the Calspan Corporation, under the support of General Motors, developed and verified a full four-wheeled vehicle model. This model was never used in industry because it was input heavy and very complex. Other full vehicle models have been developed in the research community but also have not been used in industry for similar reasons. For a full vehicle model to be continually useful to the auto industry it must be developed with industry use in mind [1].

1.2 Problem Statement: Combined Maneuver Analysis as an On-line Design Analysis Tool

When a vehicle is simultaneously cornering and applying tractive/braking effort it is executing a combined maneuver. To expand the state-of-the-art in suspension design analysis the combined maneuver must be considered. As with the early development of the bicycle model, combined maneuver analysis has been left to researchers and academic investigators. But now many improvements in overall performance of pneumatic tires have made the suspension the weak link in the vehicle system. Therefore, there is a need for a combined maneuver analysis tool to optimize the use of pneumatic tire technology in suspension design. This work initiates the creation of such a tool.

Because there are many types of suspensions it is difficult to create a comprehensive design analysis tool. Four wheeled models that have been developed are either too general or too specific. Many four wheeled models use the roll axis assumption which generalizes too much and others use a specific suspension type which limits the models applicability. This happens because the progression of the design process is not considered when a model is generated to do a research study. A typical suspension design process is outlined below:

1.) The ride frequencies are selected based on historical data for the desired image of the vehicle.
   - <u>bounce frequency</u>- can be used, with an estimate of mass, to get the wheel rates of the suspension.
   - <u>pitch frequency</u>- is used to define anti-features which is a measure the pitch gain in deg/G (anti-features are defined in chapter two).
   - <u>roll frequency</u>- is used to define the roll stiffness goal (or roll gain in deg/G).

2.) Based on the ride frequencies some of the suspension geometry can be established once the following are also defined:
   - ·total vehicle mass;
   - ·mass distribution;
   - ·center of gravity height;
   - ·wheel base;and
   - ·track width.

   i.e. Wheel travel can be predicted based on ride stiffnesses (or gains) needed to meet the ride frequency target. So limiting conditions of roll, hop, and pitch with minimum legal ground clearance can be found.

3.) Finally, dynamics are considered (at this point suspension geometry and compliances must be completely defined). This would be the time when a vehicle design analysis package would be used to predict:

- roll gain (deg/G);
- total vehicle understeer (deg/g);
- lateral acceleration response time (sec);
- yaw velocity response time (sec);
- steering gain or steering sensitivity; and
- maximum lateral acceleration (G's).

The analysis done in step three is presently done either experimentally or with analytical "bicycle models". Step three is the design analysis stage used to find out if the specifications laid out in steps one and two were attained. This inquiry is less expensive if done analytically rather than by building prototypes; especially in suspension design.

When designing a vehicle to optimize its performance during a combined maneuver, a new set of constraining relations must be used. The bicycle model and roll axis concepts are unjustified because suspension motions are no longer symmetric. The best way to decide what constraints can be used is to ask the kinds of questions that can be answered by a combined maneuver analysis. For example:

- What kind of camber and toe curves should a suspension have to best handle combined maneuvers?
- How do the roll-center and roll-axis move under combined loading and what effect do these have on the adhesion limit of the vehicle?
- How do the normal loads at each wheel change under combined loading?
- How do normal loads change with varying amounts of anti-features?
- How does TLLTD (total lateral load transfer distribution) or roll couple distribution change under combined loading?

By creating an analytical model to answer these questions, and assuring compatibility with the design process, the combined maneuver analysis tool is derived. The model derived in Chapter Three is the basis for a practical tool which can be used to aid in suspension design from start to finish.

1.3 Review of Previous Work

1.3.1 Tire Modelling

In the area of tire modelling Nordeen in a paper "Analysis of Tire Lateral Forces and Interpretation of Experimental Tire Data" simplified the description of lateral force capabilities by defining the "f", "g", and "h" functions [2]. These functions were introduced to eliminate the use of large look-up tables, but only dealt with lateral loading. One of the earliest representations of a tire under combined loading is the "tire ellipse" which is discussed briefly by Wong [3].

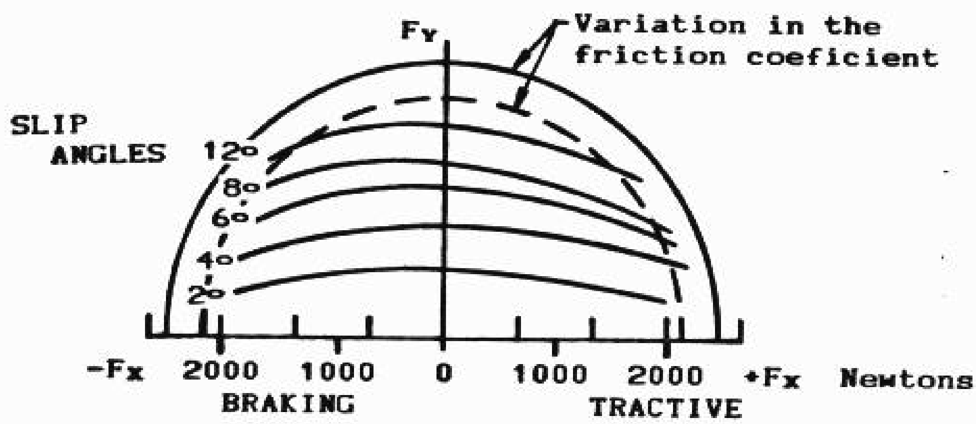

Figure 1-2: The tire ellipse plots combined effort by the tire

A tire ellipse, Figure 1-2, is an analytically or experimentally derived plot of lateral force at a given amount of tractive or braking effort. Another model by Dugoff [4] uses experimental results to generate empirical expressions for the prediction of lateral and longitudinal tire forces. The Dugoff tire model was used in the current research as a test of the vehicle model, see section 3.8 for further discussion. In a four part paper Sakai performed a very comprehensive study relating tire cornering properties to conditions of braking and traction involving both experimental and theoretical considerations [5]. In a recent paper Milliken and Radt reviewed the earlier works of Fiala and Sakai and then proceeded to derive a set of non-dimensionalized equations for tire side force, self-aligning moment, and brake force [6]. These equations simplify the characteristics to one curve for many operating conditions.

1.3.2 Suspensions and Their Effect on Handling

The impact of suspension characteristics on the most common driving maneuvers are discussed by Uffelmann [7] and Cole [8]. These works lend insight into the art of producing desired handling properties by varying suspension parameters. Similarly Bachrach and Wilson discuss how various computer models are used in the vehicle design process [1]. Finally, of general interest is Jacobson's paper on "Safe Car Handling Factors" [9]. This paper indicates how a suspension design affects the safe handling of a vehicle.

1.3.3 Vehicle Models

Chapter Five of Wong [3] uses a single-mass three dof bicycle model to describe the effect of weight distribution, tire properties, and various forward speeds on the steady-state response and dynamic stability of an automobile. Under steady forward speeds Segel [10] uses a two- and four-mass four-wheeled three-dof model with a fixed roll axis to study the dynamic stability of an automobile under fixed and free control inputs from the steering system. Killian [11] modifies Segel's model to do a quasi-steady-state combined-maneuver analysis of the three dof car. Killian's investigation was a prelude to this work and uses the same "rotating inertia vector" as input to vary the respective amounts of cornering and tractive/braking acceleration, see section 3.2. A fully-dynamic four-wheeled six dof model by Ellis [12] is used to study a vehicle with all six rigid body modes of the sprung mass. Ellis does not assume a roll axis and represents the suspension by equivalent "gear ratios"; so the suspension action is directly related to motion of the sprung mass. This model is useful in design analysis once the equivalent suspension gear ratios are calculated.

1.3.4 Handling Analysis Techniques

Several different analysis techniques exist for studying the handling and stability performance of an automobile. A good introduction to this field are given by chapter five of Wong [3] and a paper by Topping [13]. Wong does a brief steady-state and dynamic analysis as described above. Topping does "A Primer on Non-Linear Steady-State Vehicle Turning Behavior" in which he lists some fundamental equations and constraining relations for vehicle modelling. Some of these relations involve: roll couple distribution, roll axis constraint, the kinematics of turning, and relations for suspension compliances. Getting a little more complex, Nordeen [14] develops the full dynamic equations and constraining relationships of a four-wheeled vehicle with an inclined roll axis. This development uses Euler Angles to relate position from the inertial frame to the sprung mass frame. The above references introduce the relations necessary to peform a standard stability and equilibrium analysis on the automobile as a dynamic system. The techniques discussed below use non-standard methods.

Leffert and Bundorf [15] combine many vehicle design parameters to simplify the description of steady-state and transient response. They define two terms, the front and rear cornering compliance, and correlate them to automobile engineering properties. The latest design analysis technique is described in a paper by Milliken, Dell'Amico and Rice [16]. The "moment method" has been used in the analysis of aircraft statics. The current method, as described in [16], analyzes the static stability and control of an automobile based on the concept of tethered vehicle testing using a yaw constraint. The use of "performance plots" is also introduced in which well-known steady-state performance parameters, as well as a new one, defines static stability quantitatively. In a subsequent paper Rice and Milliken [17] apply the moment method to emphasize the interpretation and utility of the method in evaluating automobile stability and controllability.

1.4 The Present Approach to Combined Maneuver Analysis

This research endeavor started out to study the interaction between certain design parameters and the handling performance of an automobile; more specifically, to answer some of the questions posed at the end of section 1.2. Also a strong desire to end up with a practical and useful design analysis model was indicated by the engineers that prompted this study. A current model that would meet both of these criteria could not be found. So the major effort was centered around modelling, documenting, and laying groundwork for a usable model. With this in mind a model was created.

A quasi-static analysis is sufficient to get most of the information necessary to design the dynamic response of a vehicle. This approach is much simpler than a fully dynamic analysis. Therefore, the vehicle is modeled at an instant in time when all the loading on the center of gravity (C.G.) is known. By applying d'Alembert's principle the problem is of the non-linear non-time-varying type. An eleven dof lumped mass system* was used with an input that could be easily related to real life, see section 3.2. Care was taken to align the model for use throughout the design process. This was done by requiring a minimum amount of input for initial engineering estimates. Displacements and forces at the wheel spindle and C.G. were used as coordinates. This allows existing experimental and analytical models for tires and suspensions to be used with the main vehicle model. In this way the tire and suspension equations can be completely separated from the main vehicle equations. This type of "plug-in" compatibility is possible because spindle displacements and forces are commonly used design analysis variables and often occur in other models.

*The eleven dof's are explained in chapters 3 and 4.

Although modification will be necessary to use different tire/suspension routines, provisions have been made to make this as simple as possible. The program is documented and constructed in a modular fashion so changes are localized. In this way the model can grow in complexity with the design. The suspension routine only has to interact with the tire model and the periphery of the main model. This is because the suspension model is only used to:

- change the tire/road orientation for the tire model;
- output other suspension parameters; and
- implement suspension anti-features.

Finally, the raw system equations were left as close to original form as possible in the computer program so updates would be easier, see Chapter Four.