

High Fidelity Quasi Steady State Aerodynamic Model Development and Effects on Race Vehicle Performance Predictions

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ABSTRACT

Presented in this paper is a procedure to develop a high fidelity quasi steady state aerodynamic model for use in race car vehicle dynamic simulations and its application in a race vehicle multi-body full lap simulation. Developed to fit quasi steady state (QSS) wind tunnel data, the aerodynamic model is regressed against three independent variables: front ground clearance, rear ride height, and yaw angle. An initial dual range model is presented and then further refined to reduce the model complexity while maintaining a high level of predictive accuracy. The model complexity reduction decreases the required amount of wind tunnel data thereby reducing wind tunnel testing time and cost. The quasi steady state aerodynamic model for the pitch moment degree of freedom is systematically developed in this paper. This procedure is extended to the other five aerodynamic degrees of freedom to develop a complete, high fidelity, six degree of freedom quasi steady state aerodynamic model. This high fidelity model reduces the QSS aerodynamic fit error compared to conventional aerodynamic model development. Both the newly developed high fidelity aerodynamic model and a conventionally derived aerodynamic model are implemented in a NASCAR Truck multi-body, full lap QSS simulation to determine the effects of the high fidelity QSS aerodynamic model on the simulation results. Performance metrics are calculated from simulation results and compared to assess the effects of the aerodynamic models on the performance predictions. The increased accuracy of the high fidelity aerodynamic model is found to have discernable effects on the vehicle performance predictions resulting from the QSS simulation.

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INTRODUCTION

Race vehicle simulation is broadly and frequently utilized in the motorsports industry to predict vehicle handling and performance across every race track. Given the high stakes for race vehicle performance, the accuracy of the vehicle simulation is paramount, requiring accurate modelling of all the vehicle subsystems, i.e. chassis, powertrain, tires, and aerodynamic subsystems. This paper focuses on the development of the latter, an accurate QSS aerodynamic model, composed of a mathematical model of the aerodynamic forces and moments acting on the vehicle as a result of the vehicle orientation which includes the front ground clearance, rear ride height, and yaw. In the motorsports industry, vehicle simulations are conducted prior to race events to select the starting vehicle setup for each track event, and then trackside simulations are utilized during race events to adjust the vehicle setup for race day track and weather conditions. Pre-race and trackside simulations focus on analyzing the interchangeable components of the vehicle which affect the suspension characteristics, i.e suspension geometry, spring and sway bar rates, damping characteristics, etc. Modifying the suspension characteristics will result in vehicle orientation changes that will affect the predicted aerodynamic forces and moments acting on the vehicle. The change in the aerodynamic forces

and moments will in-turn affect the vehicle orientation. To understand the effect the suspension changes will have on the aerodynamic forces and moments, and vice versa, both an accurate vehicle model and accurate aerodynamic model are required in the simulation.

Historically, aerodynamic models have been developed and applied to vehicle models with increasing degrees of complexity. Original steady state models used constant aero forces or coefficients with no vehicle orientation dependencies [1][2]. These aerodynamic models only included three degrees of freedom: front lift, rear lift, and drag. Additional degrees of freedom were then added to these models to include side force and yaw moment [3]. As wind tunnel testing of vehicles furthered, the effect of yaw on the aerodynamic forces and moments was documented [4, 5, 6] and incorporated into aerodynamic modelling of vehicle simulations [7][8]. The final degree of freedom, the roll moment, was finally added to vehicle models for complete modelling of all aerodynamic forces and moments acting on the vehicle [7].

The next step in quasi steady state model development came with the inclusion of front and rear vehicle travels as dependencies of the aerodynamic model [9]. More recently, the effect of individual race

vehicle body components, such as wings, have begun to be characterized independently and modeled in vehicle dynamic simulations [10].

Limited testing at each race event leads the race engineers to rely on vehicle simulations to help analyze additional vehicle setups that cannot be physically tested during the event. The utilization of simulation in pre-race and especially track side analysis demands minimal run time of accurate simulations. Quick simulation with high levels of fidelity can be utilized by race engineers to run through a large number of potential setup variations to help optimize their vehicle setup for race day. Implementing an aerodynamic model of an empirical nature within the simulation can meet the track side run time requirements as opposed to a solution utilizing computational fluid dynamics, CFD. Generating a CFD solution is slow and does not lend itself to the quick turnaround time required of race vehicle simulations; thus, industry practice has trended toward incorporating empirical, mathematical aerodynamic models.

Mathematical models used to calculate the QSS aerodynamic forces and moments were first developed in the Aerospace industry [11]. Second order polynomial fits were applied to the model's independent variables to compute the aerodynamic forces applied to an aircraft. This concept was later applied to automobiles by modelling the aerodynamic forces as second order fits of front and rear ride heights [12]. To the authors' knowledge, little other documentation exists on the evolution of this modelling technique; however, industry practice now develops QSS aerodynamic models using full or partial second order fits of the independent variables, typically front travel, rear travel, and yaw.

Recent race vehicle setup trends travel the front of the vehicle close to the ground to capitalize upon aero advantages of maintaining a vehicle at this orientation. For instance, in all of the three official racing series, viz. Sprint Cup, XFINITY and Camping World Truck Series, managed by America's National Association for Stock Car Auto Racing, popularly known as NASCAR, the current setup trends attempt to minimize the front ground clearance of the vehicles such that the leading edge of the vehicle can intentionally make contact with the track. In these conditions, as the authors' have observed, the QSS aerodynamic forces and moments become highly nonlinear and can no longer accurately be modeled by unified second order fits applicable over the entire range of front travel. A new mathematical model is proposed in this paper to accurately model the QSS aerodynamic data.

Creating QSS aerodynamic models for force and moment data requires an adequate amount of test data spanning the full range of the independent variables. Wind tunnel testing and CFD are both methods that can be employed to create the test data, but the processing time and cost required by CFD, about 100 hours on a 96-Core computing cluster for a single vehicle orientation will make the CFD approach a more costly option. Computing the forces and moments at 40 vehicle orientations, a standard number with which to fit a conventional QSS aerodynamic model, 400,000 CPU hours at a rate of \$0.10 per CPU hour, results in a \$40,000 CFD cost.

Wind tunnel testing is less expensive than CFD but is still a costly alternative. Acquiring data for aerodynamic mapping can take up to five hours of wind tunnel time. Of the two wind tunnels readily available to the NASCAR industry, AeroDyn charges \$1895 per hour [13], costing almost \$10000 for a five hour shift, and Windshear charges new customers \$35000 for a one-off 10-hour shift [14]. Decreasing test time has large cost advantages, so developing a methodology to limit the required amount of the wind tunnel testing is desirable. In addition to developing a high fidelity QSS aerodynamic model, an aerodynamic model term reduction procedure is also presented in this paper to minimize the amount of test data required to develop the QSS aerodynamic model. This will minimize the cost of physical testing while maintain a high accuracy of the aerodynamic model fit. To facilitate the forthcoming analysis and discussion, the final reduced parameter high fidelity QSS aerodynamic model is abbreviated as MUAM. In addition to the development of a high fidelity aerodynamic model, the MUAM aero model is applied to a standard race vehicle full lap QSS simulation to quantify the results of the MUAM compared to conventional aerodynamic models on the predicted performance metrics resulting from the simulation.

Past research has shown a significant influence of the aerodynamic model on vehicle simulation results [10][15, 16, 17, 18]. The effect of lift and front-to-rear lift distribution has been studied for high speed and braking conditions [15]. Initial limit handling analysis calculated the effects of aerodynamics on additional lateral acceleration potential and the resulting vehicle balance [16], and the effect of aerodynamics on transient vehicle handling has been analyzed with smoothed step steer simulations [17][18]. More in depth studies have analyzed the effects of aerodynamic and active aerodynamic models on the vehicle performance potential, as well as analyzed the vehicle model in a steady state constant radius turn simulation and analyzed the transient response in a step steer maneuver [10]. In all studies, the influence of the aerodynamic forces and moments applied to the vehicle model resulted in predicted handling changes in the simulation results.

No standard simulation experiments are documented in literature to quantify the predicted vehicle handling and performance results, especially for race vehicle analysis. However, a standard simulation experiment does exist within the NASCAR industry. A full lap QSS simulation is commonly used to predict the vehicle performance around the race track. A full lap QSS simulation is independently implemented with two vehicle models, one modeled with the MUAM and the other modeled with the conventional aerodynamic model. This simulation inputs are generated from a representative NASCAR 1.5-mile oval track, Homestead-Miami Speedway, and performance metrics calculated from the simulation results are compared.

AERODYNAMIC MODEL THEORY AND SIMULATION METHODOLOGY

Aerodynamic Model Theory

The conventional QSS aerodynamic model used in the NASCAR industry is a full second order polynomial fit of three independent

variables, front ground clearance, z_f , rear travel, z_r , and yaw angle, β , described by the equation:

$$C'_a(z_f, z_r, \beta) = \sum_{i=0}^2 \sum_{j=0}^2 \sum_{k=0}^2 D_{i,j,k} (z_f)^i (z_r)^j (\beta)^k \quad (1)$$

where C'_a is the predicted aerodynamic coefficient (force or moment), and $D_{i,j,k}$ is the parametric fit coefficient for each term of the model.

The high fidelity aerodynamic model is developed to capture the highly nonlinear trends observed in the wind tunnel data when the leading edge of the vehicle is traveled close to the ground. Figure 1 contains the plots of the aerodynamic pitch moment coefficient, C_{Mx} , vs. the front ground clearance of the race vehicle at a constant rear travel and yaw angle that illustrates the nonlinearity of this dependence. This data was collected as part of wind tunnel QSS aerodynamic model development test conducted at AeroDyn using a 2007 NASCAR Truck.

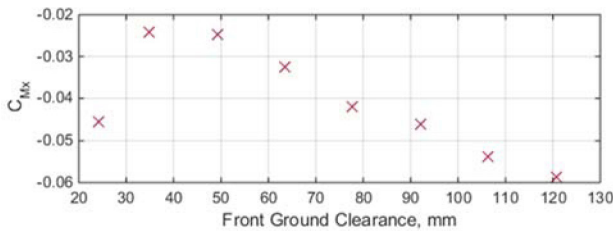


Figure 1. Aerodynamic pitch moment coefficient vs. front ground clearance at a constant rear ride height and yaw angle.

To address the nonlinearity that occurs at the lower front ground clearance, a more complex aerodynamic model is proposed. It is hypothesized, that utilizing an additional mathematical model term applied to one section of the front ground clearance data will capture the additional nonlinearities unable to be accurately modeled using the conventional approach. Thus, an aerodynamic model composed of two mathematical model terms is developed. One math model term applies to the entire range of the front ground clearance input and the other math model term is weighted to be applied to only the high ground clearance data. The proposed aerodynamic model equation is:

$$C'_a(z_f, z_r, \beta) = f_1(z_f, z_r, \beta) + W(z_f) (f_2(z_f, z_r, \beta)) \quad (2)$$

where f_1 is the unweighted mathematical model, f_2 is the weighted mathematical model, and W is the weighting function that is a function of the front ground clearance. The weighting function has the form:

$$W(z_f) = \frac{1}{2} + \frac{1}{2} \tanh(w_1(z_f - z_{fc})) \quad (3)$$

and is displayed in Figure 2 with three regions, A, B, and C, illustrated to describe the effect of this function. This weighting function drives the weighting of f_2 to 0 at low front ground clearance values, Region A, below a cut-off value of z_{fc} , and maintains the

weighting of f_2 at 1 for the higher ground clearance values, Region C. The other variable in the equation, w_1 , influences the width of the transition section, Region B. The weighting function is designed to allow for f_2 to operate as a high ground clearance deviation function. The unweighted math model, f_1 , is effective over the entire range of the front ground clearance, but the weighted math model, f_2 is only effective when the weighting function becomes non zero. The weighting function increases the influence of the f_2 throughout Region B until the f_2 function has the maximum influence on the aerodynamic model through the high ground clearance range of Region C.

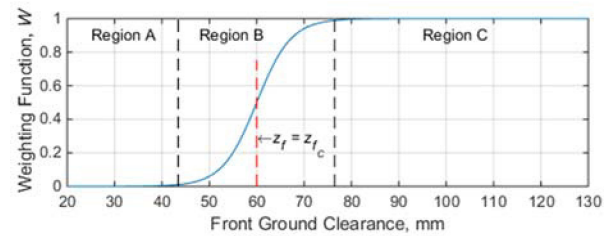


Figure 2. Weighting function

Each mathematical model term in Equation 2 is proposed to be a function of front ground clearance, rear ride height, and yaw. The first math model term, f_1 , has no weighting and thus must remain valid over the entire range of z_f inputs, so only a linear dependency of z_f will be included in this math model. The other independent variables will be implemented with a second order dependency consistent with finding in literature [4, 5, 6, 7, 8, 9] and current industry modelling practices. The function f_1 is thus defined as:

$$f_1(z_f, z_r, \beta) = \sum_{i=0}^1 \sum_{j=0}^2 \sum_{k=0}^2 A_{i,j,k} (z_f)^i (z_r)^j (\beta)^k \quad (4)$$

where $A_{i,j,k}$ is the parametric fit coefficient for each term, and 18 terms are present in this equation. This will result in 18 model coefficients in the f_1 fit.

For the higher ground clearance f_2 fit, the z_f input range is limited and the front ground clearance input can thus be modeled with more nonlinearity, so f_2 is modeled as a second order function of each independent variable and can be defined as

$$f_2(z_f, z_r, \beta) = \sum_{i=0}^2 \sum_{j=0}^2 \sum_{k=0}^2 B_{i,j,k} (z_f)^i (z_r)^j (\beta)^k \quad (5)$$

where $B_{i,j,k}$ is the parametric fit coefficient for each term of the model, and 27 terms are present in this equation. This will result in 27 model coefficients in the f_2 fit.

In total, including the weighting function, there are 47 parameters that must be determined to generate the aerodynamic model given in Equation 2. An iterative least squares approach is applied to calculate these parameters. First, a reasonable starting range for w_1 and z_{fc} is evaluated for the fitting process. For each of the coefficients,