

Virtual Motorsports as a Vehicle Dynamics Teaching Tool

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ABSTRACT

The paper describes a 'virtual motorsports' event developed by the University of Windsor Vehicle Dynamics and Control Research Group. The event was a competitive project-based component of a Vehicle Dynamics course offered by the University's Department of Mechanical, Automotive, & Materials Engineering. The simulated race was developed to provide fourth year automotive engineering students with design and race experience, similar to that found in Formula SAE® or SAE Baja®, but within the confines of a single academic semester. The project, named 'Formula463', was conducted entirely within a virtual environment, and encompassed design, testing, and racing of hi-fidelity virtual vehicle models. The efficacy of the Formula463 program to provide students with a design experience using model based simulation tools and methods has been shown over the past two years. All of the software has been released under a General Public License and is freely available on the authors website. While the software has been developed primarily as a teaching tool, it is expected that future applications include general motor vehicle design, analysis, and performance evaluation.

INTRODUCTION

Studies have shown that many typical undergraduate engineering curricula emphasize mathematics and engineering science, while the underlying need to acquaint mechanical or automotive engineering students with design experience is in many cases being ignored [1]. In an effort to combat this trend, the Mechanical, Automotive & Materials Engineering program at the University of Windsor offers several courses that emphasize the design aspect of engineering through project-based learning.

At the outset of this project, there were already existing examples of project-based course elements in the undergraduate curriculum. For the past several years, the second year dynamics class has challenged students with a group project requiring the design, analysis, construction, testing, and demonstration of a small scale 'Popsicle Stick Trebuchet'. Construction materials have typically been very limited, and various design constraints are enforced to challenge the student design teams and inspire innovation. One important feature of the project is that the scoring is based on objective, measurable results, using a relative scale based on demonstration performance [2]. With the success of this project, the project-based format has recently been incorporated into the senior level Deformation and Fracture class within the Engineering Materials curriculum.

At a higher level of complexity, the Society of Engineers offers an excellent series of annual competitive collegiate events, namely the Formula SAE®, SAE Baja®, SAE Supermileage®, and others. In the current curriculum these projects typically form a part of a two semester final year Capstone Design course, where the objective is to provide students with a real-world engineering design experience. The Capstone course completes the undergraduate curriculum, where students should use all their previous experience to develop a solution to a design problem within a team environment. Project-based courses have been shown to reinforce the direct link between course knowledge and application, while providing an opportunity for immediate response and objective evaluation, and relative comparisons to the results of peers.

The project described in this paper is associated with a required senior level Vehicle Dynamics course within the Automotive Option in Mechanical Engineering at the university. Topics covered in the course include tire behaviour and modeling, longitudinal dynamics, lateral dynamics,

effects of trailers, suspension analysis and ride dynamics, with an emphasis on vehicle modeling and analysis using numerical techniques. Various required and suggested texts have been utilized for this course including the works of Dixon [4], Gillespie [5], and Reimpell and Stoll [6], Genta [7] and Milliken [8]. The project, termed 'Formula463', has been developed to provide students in this course with a semester-long virtual design experience using model based simulation tools and methods, to reinforce the topics discussed within the course syllabus. This project has also afforded graduate level students with an opportunity to research and develop advanced simulation techniques and analysis tools. This paper details the development of the necessary computer based tools, and evaluates the efficacy of the Formula463 virtual grand prix project to aid in student learning within an undergraduate course environment.

METHODOLOGY

The initial goal of the Formula463 project was to economically provide the students with a competitive and iterative design project, allowing senior students to apply theoretical knowledge. Within this project, race teams of two students were to design, evaluate and race virtual vehicles against their peers. The students were provided with some advanced analysis tools developed by the Vehicle Dynamics and Control Research Group (VDCRG), and were expected to develop additional model based simulation and evaluation tools throughout the term using Matlab, Simulink, MathCAD or similar software. The races were to be conducted within a high-fidelity simulation environment and provide students with opportunities for practice and testing. After each event, students were given performance data as feedback to allow design improvements over the duration of the project.

To ensure that all student teams were competing on an equal level, a number of the basic vehicle dimensions were pre-determined and not allowed to be modified by the design team. These included mass, center of mass height, choice of drive axle, tire choice, wheelbase, and track width. The fixed specifications from the 2008 calendar year are shown in Table 2. However, a number of the vehicle parameters were adjustable, including the front/rear weight distribution, choice of engine, transmission and final drive ratios, suspension kinematics, spring rates, roll stiffness, and damping rates.

The teams were required to choose between two engines with approximately equivalent performance, but slightly different characteristics as shown in Figure 11. The teams were restricted to a five speed transmission, but with an unlimited choice of drive ratios in all five ranges, and a choice of three final ratios. The teams were free to define spring rates, but were limited in the selection of damping rates. The corner weight of the vehicle was determined by the location of the center of mass and the static compression of the spring was determined by the spring rate as the ride height was fixed. It was the responsibility of

the design teams to ensure the the available travel of the spring was appropriate to accommodate the static spring compression, while leaving sufficient allowance for suspension compression and rebound. All teams were also required to design a double A-arm type suspension for the front and rear of the vehicle by defining the locations of the upper and lower ball joints, the inner and outer tie rod ends, and two points defining the chassis mounting points of each of the upper and lower A-arms. As a design constraint the suspension was to accommodate a minimum suspension travel of ten centimeters in each of compression and rebound, measured at the tire.

In the past offerings of the course, the students were required to submit four reports, based on the material covered in class. Each report entailed preparing a numerical simulation using Matlab or some similar software, detailing the findings of the simulation, and answering a set of posted questions regarding the model. The Formula463 project was designed to encompass these reports, while providing a deeper understanding of the interconnectedness of vehicle system design. However, the subject matter for the final report was expanded to include the design process conducted over the entire semester. Additional preliminary 'data sets' associated with elements of each of the first three reports were assigned to allow evaluation of individual sub-systems. The following is the list of deliverables, with some description of each item.

Report #1: Drag Strip Simulation: Model based simulation and analysis using a one degree of freedom longitudinal dynamics model in the time domain, as given in Equation 1 [7]. The powertrain model included a no slip clutch, wide open throttle, and simple stick-slip tire model. Students are free to choose parameters to model a vehicle of their choice, as well as increase the complexity of the simulation if they desired.

Data set #1: Students were required to provide an engine choice from a predefined list, and transmission ratios for evaluation in a simulated drag strip test run of the benchmark race vehicle.

$$\sum F_d + \sum F_r = ma_x \quad (1)$$

Report #2: Handling Dynamics Simulation: Model based simulation and analysis using a yaw-plane 'bicycle' model with two degrees of freedom as shown in Equation 2 and 3 [7, 9]. This model incorporated a linear tire model and was to be utilized for analysis in both the frequency and time domains. Students were free to choose parameters to model a vehicle of their choice, as well as increase the complexity of the simulation if they desired. This report explored understeer/oversteer characteristics, as well as, steady-state and transient vehicle response including eigen analysis to determine characteristic speeds.

Data set #2: Students were required to provide refined engine and transmission data, as well as a center of gravity location and roll-stiffnesses for a simulated skid pad type

test run of the prototype race vehicle, with both longitudinal and lateral acceleration tested.

$$\begin{bmatrix} \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v \\ r \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \delta_f \quad (2)$$

$$\begin{aligned} a_{11} &= \frac{(C_f + C_r)}{mU} & a_{12} &= \frac{(l_f C_f - l_r C_r)}{mU} + U \\ a_{21} &= \frac{(l_f C_f - l_r C_r)}{I_z U} & a_{22} &= \frac{(l_f^2 C_f + l_r^2 C_r)}{I_z U} \\ b_1 &= \frac{C_f}{m} & b_2 &= \frac{l_f C_f}{I_z} \\ g_1 &= 0 & g_2 &= \frac{1}{I_z} \end{aligned} \quad (3)$$

Report #3: Ride Dynamics Analysis: Model based analysis of vehicle ride behaviour using a four degree of freedom bounce-pitch model described using Equations 4 and 5, in the frequency domain [7]. Students were free to choose parameters to model a vehicle of their choice, as well as increase the complexity of the simulation if they desired.

Data Set #3: Expanded the previous requirements to include engine and driveline data, center of mass data, and full suspension spring and damping data. This was used in a simulation of the prototype race vehicle with fixed suspension kinematics where the ride performance was stressed, combining lateral and longitudinal acceleration on a track with a sinusoidal elevation profile.

$$\ddot{\vec{q}} = \begin{bmatrix} 0 & I_{eye} \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \dot{\vec{q}} + \sum F \quad (4)$$

$$\dot{\vec{q}} = [z_s \quad \theta \quad z_f \quad z_r \quad \dot{z}_s \quad \dot{\theta} \quad \dot{z}_f \quad \dot{z}_r]^T \quad (5)$$

Report #4: Suspension Kinematics and Formula463 Event: Primarily focused on the design and analysis of suspension kinematics, and selection of spring and damping rates for a double A-arm suspension configuration (i.e., the Cartesian coordinates of the ball joints, tie rods, spring endpoints, etc.). Students were free to model suspension designs on their own or use a provided suspension kinematics solver. The defined race vehicle was tested in this configuration over a single time-trial lap of a full racecourse. The report emphasized the design choices made in the suspension, but included the overall design of the vehicle. It was submitted after the final series of simulations, in order to allow the students to discuss the feedback from the race event.

Data Set #4: Submitted on two separate occasions, once for an optional 'practice' event, and again for the 'race' event. Only the race results were graded, but results data was made available after the practice event for evaluation and design changes prior to the race event.

In the first three reports, the students were expected to generate their own simulation code, typically using Mat-

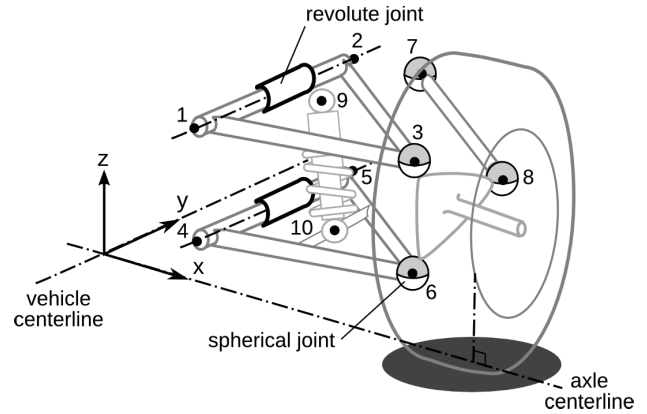


Figure 1: KINS Suspension Diagram

lab. The final report involved selection of suspension geometry, and required simulations that have been shown to generally be outside the capability of undergraduate students to reliably prepare on their own. In order to accommodate this, a suspension analysis package (KINS), has been developed and made available to the students. Within this code, the suspension kinematics problem was defined using a series of points and parameter values as shown in Figure 1 and solved by casting the problem as a set of differential equations as in Equation 6.

$$\dot{\vec{q}} = [A(\vec{q})]\vec{g}(w, p) \quad (6)$$

$$\vec{q} = [x_G, y_G, z_G, \psi, \theta, \phi]^T$$

In this form, the linear and angular speed of the suspension components ($\dot{\vec{q}}$) depends on their location and orientation ($\vec{q}$), given a fixed vehicle bounce or roll speed (w, p). The advantage of using this rate based approach was that the equations were linear when expressed in this form, as opposed to the nonlinear algebraic equations that result when forming the equations in terms of positions. The differential equations were then solved to an acceptable level of accuracy in a very short time using the 4th/5th order 'ode45' integrator in Matlab. The output from the simulation includes not only the typical suspension curves, e.g., camber vs. jounce, toe change vs. roll, etc., but also includes data regarding the suspension loads. The tire normal force, spring force, and motion ratio are found as part of the simulation. Animation of the motions are produced using the ISO standard graphics format X3D [10]. Because the code was entirely open source, the students were encouraged to investigate the numerical methods used, and experiment with the solver as they wished.

Both the provided and student developed analysis software was complimented with a user interface (F463pre), which is a plug-in based simulation and evaluation package. The students were encouraged to convert their simulation code into the defined plug-in format, allowing for the quick modification of vehicle parameters over several design iterations. This package also checked for errors and prepared the data sets for submission to minimize the