Virtual Vehicle Analysis and Simulation Environment

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Preface

This project was conceived in December 2004 when I was in my third year of college. I was on Drexel University's Formula SAE team, and we were in the middle of a year-long project in which we were to design, build, test and take to competition a small formula-style racecar. It was winter break, and the team was taking advantage of the days off from class, working hard to push various components of the car closer to completion.

Around this time, although I think all of us were anxious to get dirty and cut some metal, the team was also putting some thought into the Design Report — due in March as part of the annual competition — since we did not want to leave it to the last minute as had been done in previous years. I was the team's "suspension guru," and was spending some time thinking about the justification and reasoning behind of some of the team's design decisions.

This being my second year on the team, and the design of the car being "evolved" from the previous year's entry, some of the decisions were easily justifiable — almost copied word-for-word from last year's report. But some of the new features and changes were a bit harder. Did we really change this part because it was hard to maintain and it took too long to remove and rebuild? Was the decision maker aware that changing this part could have a negative impact on performance? How much of an impact would it have? What other options were considered? How do you balance maintainability, reliability, performance and cost on so many different components in such a complicated machine?

Some Excel spreadsheets were revived, or created where they were missing, and MATLAB was fired up to aid with the analysis. In the end, I felt like we had succeeded in justifying the design we had chosen. But I also felt like this was completely backwards from a proper design process. Does the smart engineer not *start* with the analysis? Why had we done it backwards? How did we let ourselves get away with that? We *knew* better!

The first obvious response to this (that does not include us being lazy, incompetent or apathetic) is that we assumed the analysis had been done in a previous year (which perhaps makes us lazy, incompetent *and* apathetic). But where was the proof? Even parts of the vehicle that were designed by students as part of a Senior Design Project — where it is required to generate a report — were seemingly never documented.

Long before I was involved with the team, it was clear that knowledge transfer between graduating seniors and underclassmen was required to keep a team competitive. The system is just too complicated for a small team of students to start from scratch every year and produce a well-designed competitive vehicle. This was a large part of the motivation for evolving the design of the racecar over a period of years, rather than allowing the clean-sheet approach. But it was becoming more and more apparent that this would not be enough. Drexel's team was very lucky to have some alumni (of the school and the team) continue to come to team meetings or to stop in when they were in the area. These alumni were able to provide a large part of this missing information about previous year's design decisions. Of course, this information was entirely qualitative, may or may not have been biased (depending on who's pet project made it onto the final version of the car and who's pet project was canned due to team inter-personnel issues), and may or may not have been correct. What assumptions were made? What alternatives were considered? Was this solution selected because the bracket for Widget A was in the way? If widget A is gone now, does that make another option the better solution?

Now it should be obvious that not only is knowledge transfer necessary, but it is very helpful (again, probably a requirement for the team to be competitive), but this knowledge transfer needs to be complete and accurate. It should detail not just proof that the selected solution does work, but it should show what solutions don't work, which solutions are better or worse, and it should explain why. And this knowledge transfer should be written down.

Some of the Formula SAE alumni also served on what was referred to as the team's "Executive Board." This was another device created with the intention of aiding the knowledge transfer between current students and experienced alumni. Just a few months into each school year, team members were invited to watch the seniors present their Senior Design Project ideas to the Executive Board. In many cases, the alumni provided some good advice on technical aspects of the project, but I think I took the most benefit from hearing their take on the design process and identifying the "best option" from a list of possible solutions. Often, what the students did not grasp, was that they should not be designing a supercharged do-hickey with an internal thing-a-ma-bob because they thought it would be a cool design project; they should be doing it because it's lighter, cheaper, easier to make, less risky, and has more performance than the turbocharged do-hickey with the thing-a-ma-bob mounted externally below it. It's probably been written in hundreds of books, but it's true and it's important so I'm going to write it again here: The hardest part of engineering is defining the problem. And you can't choose a solution until the problem is defined.

After graduation, I began working at a small company that design and manufactured very specialized training equipment for the aerospace industry. Within a couple of years, the company got a big contract for design of a new device. On this project, I was fortunate enough to work with some very bright engineers on design of a *new* system, from concept to final design. Although I had been developing VVASE for several years now, this experience weighted heavily in the addition of new features and some modifications to the interface.

Our senior mechanical engineer had been with the company for 20 years and had designed several many similar machines from the ground up. Many of the other engineers at this company had comparable years logged, and had also been involved with design of previous machines. So here, knowledge transfer was not an issue (although it certainly would have been an issue had one or two of these engineers decided to leave the company). The people responsible for the design of this machine were experts. They had done it before and they knew what pitfalls to look for, where to duck and where not to step.

The senior mechanical engineer was interested in improving the efficiency of the design process and wanted to let the design "ebb and flow" until after some time it would converge and mature into the final solution. His inspiration came from a book he had read about Toyota Motor Sales and how they use a parallel design process to move through each step of the design process. Using this kind of approach can be very helpful, and I think very valuable when you're trying to identify what solutions for each part of the system will result in the best overall system. Our senior mechanical engineer would say "if a sub-system is approaching 99% of a 'perfect system,' you should take a step back and look at the system as a whole because something else is probably suffering. The best system is the one where all of the sub-systems are in the 80–90% range and you have arrived at a well-balanced system." VVASE is designed to facilitate this approach to the design of an automobile.

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Introduction

This document is comprised of three parts. The first partis intended to be a reference for using the VVASE software. Here, one will find

The second partis written so that it can be read straight-through. Although it discusses how to use VVASE to design automobiles, it also discusses an approach to design that is independent of which software tools are at one's disposal, and to some extend independent of what is being designed.

The third part is an in-depth look at the equations behind VVASE. It discusses their derivations and the assumptions made in the process in more detail than the explanations that are provided in Part I.

Part I

User's Guide

Chapter 1

Introduction

1.1 Purpose of This Document

This part of the document is intended to serve as the user's manual for the VVASE software program. It includes instructions for installing the software, an introduction to the user interface and instructions for basic usage. The user's guide is meant as a reference and is not designed to be read like a novel.

1.2 What Is VVASE?

The *Virtual Vehicle Analysis and Simulation Environment* software is a set of tools to aid with the design and analysis of automobiles.

1.3 Installation

1.4 User Interface

Chapter 2

Creating the Car

2.1 What Do I Want to Accomplish?

2.2 Tires

2.2.1 Kinematics

Only diameter matters - width is for display purposes only.

2.2.2 Dynamics

There is no component that is more critical for determining a car's performance than tires (NEEDS REFERENCE!). This means that there is no component for critical for a vehicle dynamics simulation that is more critical than tires. Tire data is often very hard to find and expensive to create. Unfortunately, it is absolutely necessary to have high-quality tire data to produce high-quality simulation results.

VVASE provides several options for tire modeling:

Pacejka '96 — Also called the "Magic Formula" because of its ability to match a wide variety of tire force and moment curves by simply varying a few coefficients. Some optional extensions to this model are also provided to account for tire pressure variation, tire lag, etc.

Brush Model — This is a

Other one? — asdf

Determining the coefficients and parameters for the above models is considered to be somewhat of an art. VVASE provides some utilities to aid with determining these values, but in the end, it is likely that it will be necessary to do some "massaging" by hand.

2.3 Suspension

2.3.1 Kinematics

2.3.2 Dynamics

2.4 Mass Properties

2.5 Engine

2.6 Aerodynamics

Chapter 3

Analyzing the Car

3.1 Simulation as a Tool

3.2 Suspension Kinematics

3.2.1 Assumptions

3.2.2 Suspension Types

3.2.3 Outputs

3.3 Dynamics

3.3.1 Assumptions

3.3.2 Milliken Moment Method

3.3.3 Simulation

Like any simulation, there will be some error between the behavior of the simulated system and the behavior of the real-world system. It is up to the engineer to anticipate, understand and account for these errors.

Most engineering students and practising engineers are probably familiar with mechanics of materials and finite element analysis for determining stresses and strains in structures. Both methods are simulations. They can be validated by measuring the actual strain with a strain gage on the real structure. There are likely to be some errors in both approaches, but the sources of the errors are different, and that's what sets these approaches apart. Someone I once worked with put it nicely: "You've either got an exact solution to an approxomate problem or an approxomate solution to an exact problem."

Dynamic simulation follows the same rules (multi-body dynamics vs. Newton-Euler or Lagrangian formulation). In most real-world situations, the problem is too complicated to include all external effects (detailed aerodynamics, bearing friction - static and dynamic, etc.) unless you're using multi-body dynamics with a numerical solver, in which case the solution is only approxomate. The point is that somewhere, assumptions are being made. This is not necessarily a bad thing — in fact it is necessary! But it is important to know what assumptions are being made and what their influence will be.

An example is in the case of chassis torsional stiffness. A vehicle frame is not rigid, but accurately modeling the spring-like response of a frame is often something that is best accomplished with the use of finite element software. For any given frame, the neutral axis will change, or possibly even "bend" (so it's more of a "neutral curve" than an axis). It is reasonable to expect the loading along the length of the car to vary significantly as well, depending on where different masses are placed and how they are mounted to the frame. When simulating a car, there are a many options. Several options are presented below:

- Create a detailed model of the system, including frame geometry and material propeties (and if it's necessary to do this, it is probably also necessary to include a 6 DOF model of all of the suspension joints, etc.), thourough placement of masses throughout the system, and to use or create software that is capable of handling all of these inputs.
- Approxomate the frame as a series of torsion springs and masses.
- Approxomate the frame as one torsion spring connecting the front and rear suspensions.
- Assume the frame is rigid.

It is easy to say that the first option will have the least error, and that the last method will have the most error. Further investigation, however, can show that this is not necissarily true. The first method requires many inputs. These inputs may be unknown or may have some error associated with them. How accurately is the inertia of the motor known? What is the motor stiffness in each direction? Are there any welds that change the local stiffness of joints? Errors in these inputs may be amplified in the results of the simulation. If the model is being validated against track data, it is very difficult to find the source of any errors.

The last method will surely have some errors. There is little questions as to the source of the error, and the amount of error is apparent when comparing the simulation output to real-world data. This error is bounded and is not likely to create unexpected results in the simulation. The error is predictable.

There are many other books that describe the many benefits and drawbacks of complicated, detailed simulations as compared to simple models, so only a few key concepts are listed below:

Simple Models Complicated Models Good for trending, "big-picture" type simulations Good for detailed analysis Little room for mistakes Lots of room for mistakes MORE...

So basically, there's always going to be some error, and even if it's possible to reduce it or eliminate it, it may not be practical. So why go through the process of trying to understand the error? One reason is to try to understand how the error may or may not be bounded. Another, much more important reason is this: The amount of acceptable error is determined by the required accuracy of the solution. This may seem like an obvious statement, but often times it is overlooked or misunderstood.

The first step in solving a probelm is to define it. Here are some examples of problems that have been defined (although in practice, one sentence will rarely be adequate to define a problem):

- Design a suspension that minimizes scrub and provides a camber gain of 2 deg/deg
- Produce 350 power with a Honda B18C5 engine, naturally aspirated, while maintaining a budget of $3,000
- Specify an engine that produces 300 ft-lbf of torque between 2500 and 3000 RPM and costs less than $2,000
- Reduce the frame weight by 50 lbf, while keeping the stiffness above 3000 ft-lbf/deg
- Determine the influence of chassis stiffness on the variation in wheel loads while a car maneuvers through a salolom

Here are some examples of problems that have not been defined:

- Optimize the suspension
- Maximize the horsepower
- Pick an engine
- Reduce weight
- Pick a chassis stiffness goal

The key here is defining the criteria for your solution. Without criteria, how is it possible to know when the goal has been achieved? It is always a good idea to write down the criteria, even when working alone or with a small team. It is not difficult to get caught up on some detail of a project and get sidetracked. Writing down goals and defining the problem is very helpful for ensuring that the problem being solved is in fact the problem that needs to be solved.

After the problem is defined, the margin within which the solution should land must also be defined (one could argue that this is actually part of defining the problem...). Continuing with the chassis stiffness example, here are two possible problems:

- Determine a chassis stiffness goal for an autocross car within an order of magnitude
- Determine a chassis stiffness goal within 500 ft-lbf/deg for an SCCA club racer that will drive at Watkin's Glen, Mid-Ohio, and Road America

It is up to the engineer to work out the math and estimate the errors at each part of the process, but it might be reasonable to assume that a simple single spring model might provide good answers to the first problem, while this would be inadequate for the second problem. It is also reasonable to assume that a rigid-frame model would provide sufficient accuracy for either problem.

Although it is not included in either problem definition above, time is almost always a factor that must be considered. This could include the time it takes to create the model, as well as the time that it takes to run the simulation or interpret the results. Different problems can be expected to have different time requriements.

3.4 Sensitivity Analysis

3.5 Response Surface Regression??

3.6 Optimization

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The front matter has a number of sample entries that you should replace with your own.

Replace this text with the body of your book. Do not delete the `mainmatter` TeX field found above in a paragraph by itself or the numbering of different objects will be wrong.

The typesetting specification selected by this document uses the default class options. There are, however, a number of class options. The available options include setting the paper size and the point size of the font used in the body of the document etc. Details are given as comments right after the `documentclass` command.

Chapter 4

Troublshooting

4.1 Errors

Part II

VVASE for Vehicle Design

Chapter 5

Introduction

Chapter 6

The Vehicle as a System

I've heard from many sources that the frame should be the absolute last component to be designed. Its only purpose is to hold all of the other components in place and connect the four corners of the suspension to the rest of the car. While this idea has some merit, it also has some shortcomings. For example: I need to design a car to meet an acceleration requirement — how can a motor selection be made until after I know how much the frame will weight? Doesn't the weight of the frame influence the torque requirement of the drivetrain? What if I design my frame, then find out that I am unable to fit a large motor into the car? Am I forced to sacrifice performance and use a smaller motor? But wait — doesn't the motor itself have weight, and thus affect the size of the motor that I mush choose?

Obviously, this linear approach to designing a vehicle doesn't work.

Software design schemes

6.1 Design Goals

6.1.1 Mass and Inertia Goals

6.1.2 Suspension Kinematics

6.2 Design Process

6.2.1 Selecting Tires

Tire are arguably the single most important component on a car, in terms of performance. It then follows that tires should be selected very carefully and thorough consideration should be taken in analyzing different options. Unfortunately, the process of analyzing different tire options can be very difficult and cost prohibitive, especially for amateurs on a budget.

The process of getting tire data can be very expensive. The testing is expensive, and tires are a consumable in this process, which can also be expensive.

The more data required, the more tires needed, and the more test time required. How much data is required to make a comparison between two different tires? This is a good question — and one that won't be explicitly answered here. Hopefully the information here will serve as good guidance, however.

Formula SAE teams and possibly autocrossers or club racers should take a look at the FSAE Tire Test Consortium.[1] More information about the FSAE-TTC and how to process the data is freely available in SAE paper 2006-01-3606 by Kasprzak and Gentz.[2] The FSAE-TTC provides high-quality low-cost tire data for a wide selection of tires. Goodyear provides limited data for their FASE compounds free-of-charge on their web site, too. For designers working outside of this category — the least expensive option probably involves buying many tires

[1] The FSAE-TTC website is hosted at http://www.millikenresearch.com/fsaettc.html.
[2] Available at http://www.millikenresearch.com/TTC_SAE_paper.pdf.

Part III

Equations and Derivations

Chapter 7

Introduction

Appendix A

The First Appendix

Appendix B

The Second Appendix

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