MONASH MOTORSPORT

FINAL YEAR THESIS COLLECTION

Vehicle Simulation to Drive Formula SAE Design Decisions

Steven Webb - 2012

VEHICLE SIMULATION TO DRIVE FORMULA SAE DESIGN DECISIONS

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Summary

This report covers the creation of a simple program that approximates lap time and energy for Formula SAE cars. In 2010 it was decided that Monash Motorsport would do a “clean sheet” design, so the simulation was made in order to find the effect each aspect of the car has on the cars total performance. This report also shows how to correctly validate raw test data against the equations used to create the model in order to improve the accuracy and understanding of the model and to calculate suitable performance metrics for the car.

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1. INTRODUCTION

Formula SAE is a student design competition where university students design and build a formula style racecar. There are multiple competitions throughout America, Europe, Asia and Australia with over 400 teams worldwide. The Competitions set a strict set of rules that specify car and engine limitations, as well as point allocations and scoring formulas for each event.

Monash University has been competing since the first Australian based competition, in 2000, since then they have created 13 different cars and competed in 16 competitions. They have benefited from recent successes by achieving overall victory at the Australian competition in 2009 and 2010 and an overall 3rd place position at Formula student in the U.K. in 2010. The Monash team is now looking for their first international victory and a number 1 world ranking in order to make themselves the most respected team in the world.

In order to improve their car, a large number of significant design changes will happen throughout the 2011 season, however their resources are limited. In order to allocate resources effectively to gain the most advantage, Monash wants simulations to estimate the gains of each potential design change. Whilst most simulation software used by the team is for structural or flow analysis, they are yet to successfully use software packages to simulate overall vehicle performance.

Formula SAE cars are extremely lightweight, with competitive cars weighing between 130-250kg, this creates problems when using current simulation software designed to simulate much heavier cars. Formula SAE tracks are also much more confined and with more changes in direction than the majority of racetracks so many simulation packages will struggle to accurately simulate a car around a Formula SAE track due to inaccuracies in the transient characteristics (Phersson, 2009). Another problem with using commercial vehicle simulation software for analyzing FSAE cars is that Formula SAE is not a race, it is a series of competition challenges that award points for speed, fuel economy, cost, acceleration and handling.

If Monash have a vehicle simulation package that can accurately simulate the performance of their car at a Formula SAE competition, there would be incredible advantages as it would allow them to focus their time and money on areas which would benefit them most. It could also benefit them during each competition as it could potentially help them set up their competition strategy over their closest competitors.

1.1 Goals and Performance Metrics

Formula SAE is unique within motorsport as each competition is made of several different events, each with their own prizes and at the end of the competition there is an overall winner. Each event rewards slightly different performance aspects of the car so compromises are often made during competition in order to give the highest chance of winning.

In other forms of motorsport, in order to have the highest chance of winning you need to drive your car around the track as fast as possible, so if there is something that may make your car faster around the track, it will always be beneficial. In Formula SAE things that may improve your performance in one event may be detrimental to another, the classic example is endurance speed vs fuel economy.

The standard performance metric at competition is points, each team is awarded points at each event, and the team with the most points at the end of the competition wins the overall prize. However, due to the relative scoring equations (See appendix) there is the effect that a team may become less likely to win, even with more overall points.

For example, imagine if team A predicted they would have the fastest Endurance time (300 points) and their predicted fuel usage would give the team 75 points in Ecomomy, giving a combined score of 375. If a team member decides that by limiting engine performance they still win endurance (300 points) but by much less of a margin, and they would use less fuel, giving them 85 for economy for a total of 385 points. If there was another car, Team B, at that event that originally scored 270 points for endurance and 100 points for economy (370 combined), the slower endurance strategy of Team A could increase Team B's endurance score due to the closer margin. Team B's endurance could rise to 290, their fuel score would remain unchanged, giving a combined score of 390. So even though Team A's strategy gained them an extra 10 points (385 vs 375) it caused Team B's score to increase even more (390 vs 370) costing Team A the victory. This introduces the importance of relative point scoring over actual score. Team A originally had a relative score of 5, yet their new strategy caused their relative score to drop to negative 5.

The issue with relative scoring is of course, who the team should be scoring against. In the FSAE competition simulator there are 2 metrics used, LeadAverage and LeadMax. LeadAverage is the score of a car relative to the average score of all other competitors, whereas LeadMax is the score relative to the highest scoring competitor. LeadMax should be maximized in order to have the highest chance of victory, however the maximum scoring competitor in the simulation is often different to the highest scoring competitor at a competition. In order to maximize the chance of victory independent on which cars are competitive each year, Monash Motorsport has decided that LeadAverage will be the metric on which all concepts will be judged. When "Point sensitivity" is used in this document, it refers to how a change in performance will change LeadAverage. However, during competition when the main rivals are identified, LeadMax should also be considered when making strategic decisions.

1.2 Variations between different Formula events.

1.2.1 Scoring

The Society of Automotive Engineers in the USA (SAE) are responsible for creating the rules for the two American FSAE competitions. Competitions outside of the USA use these rules to the extent that an American car can still compete outside of the US; however, addendum are published by foreign event organizers that make small changes to some rules in order to better reflect the requirements of local industry. The most significant variations between major events are;

- Combining Combustion (petrol) and electric classes at Formula Student UK (FSUK)
- Calculating economy using CO^2 produced to compare petrol and electric cars at FSUK
- Efficiency event instead of Economy event at Formula Student Germany, rewarding cars which combine both speed and economy.
- Different maximum event scoring for Australia and Germany

The different maximum scores for each event between the competitions is shown below

Maximum Event Scores				
	FSAE-A	FSAE	FSUK	FSG
Skidpad	**75**	**50**	**50**	**75**
Acceleration	**50**	**75**	**75**	**75**
Autocross	**100**	**150**	**150**	**100**
Endurance	**300**	**300**	**300**	**325**
Economy/Efficiency	**125**	**100**	**100**	**100**

Table 1.1: different maximum event scores between competitions.

Comparing different event maximum scores can be misleading. At first glance somebody would think Skidpad in Australia is 1.5 times as important as Skidpad in America or the UK. However, in 2011 this was not the case. A quick analysis was done using 2011 results for each competition, observing what would happen to the score of the team coming 3rd in each event if their performance dropped by 1%. This is a very crude point sensitivity analysis but due to the nature of the scoring it is the best way to compare the importance of performance in different events. For this analysis to work however, you need to estimate the fastest times and lowest fuel consumption at each competition.

	FSAE-A	FSAE	FSUK	FSG
1% slower skidpad	**3.2**	**3**	**3**	**3.8**
1% slower Acceleration	**1.6**	**2.2**	**1.9**	**2**
1% slower autocross	**4.4**	**7**	**6.9**	**4.6**
1% slower endurance	**7.5**	**7.6**	**7.5**	**8.9***
1% more fuel/energy used	**1**	**1**	**0.7**	**0.9**

Table 1.2: Event point sensitivities between different competitions
*(*FSG Endurance speed sensitivity is made up of 8 points in endurance and 0.9 points in efficiency)*

Due to the wet skidpad in Germany and the much quicker fastest time in Australia (set by Monash) combined with the relative scoring formula means the scoring sensitivity of each event varies much less than the maximum scores do. The same effect occurred in fuel economy for Australia, with most teams using much less fuel than an equivalent team overseas (possibly encouraged by the greater point potential). As Vmin was reduced in the scoring formula, a 1% change in fuel usage in Australia has the same effect on points as a 1% change in fuel in an American competition, even with the event being worth different amounts. In the UK, the inclusion of electric vehicles means "Vmin" is extremely low, which severely reduces the point sensitivity for fuel usage. Endurance speed at FSG is worth significantly more than at other competitions, this is a combination of the greater overall points given (325 vs 300) as well as the importance of speed in the Efficiency event.

Overall, Autocross is the only event that has a significant change in overall point sensitivity between competitions, other than that the main changes in point sensitivities is down to the performance of other cars. The sensitivity/scoring formula for each event should be estimated for all planned competitions in order to gain a full understanding of what will have an effect on point scoring.

1.2.2 Track Layout

There are specific guidelines within the FSAE rulebook about the track layout in order to try and standardize the competition. Track marshals still have the ultimate say in track layout, quoting rule D7.2.4 "The organizers reserve the right to deviate from the standard specifications when they determine it is appropriate given the characteristics of a particular competition site." (FSAE, 2011). As competition sites vary from a Formula 1 circuit in Europe to a narrow driver training course in Australia, the track layouts themselves will vary. Comparing different tracks is often done by comparing average speed and top speed, average speed specified in the rules to be between 40 and 48km/h for autocross and between 48 and 57km/h for endurance.

Speed Comparison				
	2009 FSAE-A	2010 FSUK	2010 FSAE-A	2011 FSAE-A
Top speed	93.6	99.9	92.8	85.9
Average speed	49.6	56.5	53.1	48.3
Minimum Speed	27	32	24	20

Table 1.3 Speed comparisons of Monash's 4 most recent endurances.

As table 1.3 shows, all of Monash's recent endurances fall within the average speeds specified in the rules, however when you consider that Monash was the fastest car at FSAE-A in 2011, the track was indeed quite slow, with only Monash and UWA being above the 48km/hr minimum.

When comparing 2010 FSUK with 2010 FSAE-A, their average speeds are very similar, within 3km/h. However, in Australia both the maximum and minimum speeds are significantly lower than in the UK. Someone can guess that there are some tighter corners and shorter straights in Australia, but to get a more thorough idea of what the track consists of it is best to create an inverse corner radius histogram. Inverse corner radius, calculated as A/v^2 shows exactly how tight each corner is.

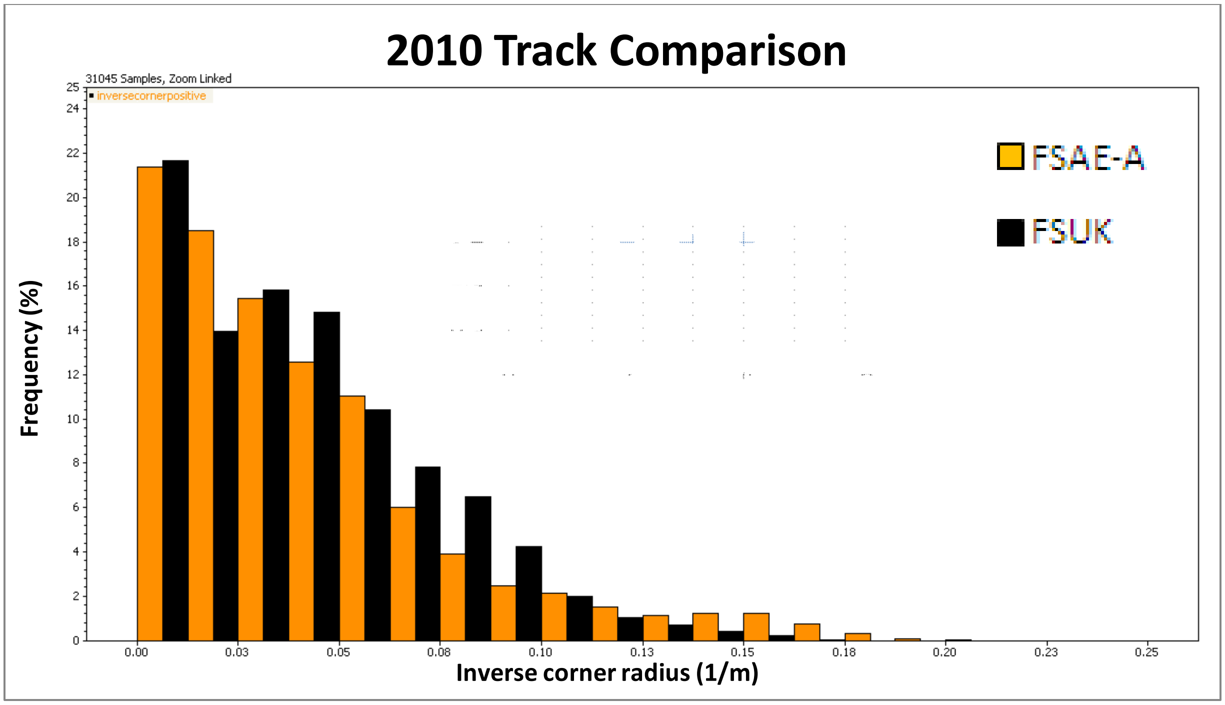


Figure 1.4: corner radius histogram of 2010 FSAE-A and FSUK endurances.

Showing the histograms on the same chart gives a direct back to back comparison of the corners used in the track. Figure 1.4 above shows how much more time is spent in a corner with a less than 8m radius (more than 0.125 ICR) in Australia compared to the UK, with the minimum radius being much less. The UK has more flowing corners (10-26m radius(.0325-.1 ICR)) whereas Australia has more very open corners (40-80m radius) likely to keep average speeds up or as a result of the course being laid out over a curved track.

Using Inverse radius histograms to compare tracks has the benefit of the corner radii not being dependent on the performance of the vehicle, as long as the vehicles travel a similar path. There is the possible error caused by cars of different widths (see 2.4) but the overall effect is minor in comparison to the effect of the track.

Due to the variations in track layouts between different competitions, teams must make sure that any design changes that may appear to be beneficial in some competitions is actually beneficial to all competitions the teams are planning to compete in.

1.3 Different vehicle concepts within Formula SAE

One of the great things about the Formula SAE competition is how much freedom there is in the rules to build significantly different cars. There are however similar styles of car that can be categorized as different concepts. 3 popular vehicle layouts common in FSAE are shown below, but there are abundant variations to each concept and many layouts not shown.

By far the most popular vehicle layout is the simple car powered by a 4 cylinder 600cc street bike engine. This concept has seen success with many different teams and is definitely the “standard” FSAE car.

Cornell university was arguably the most successful team in history with their 600cc 4 cylinder (Saabman, 2006)

The next most popular FSAE layout is the ultra-lightweight car. Usually powered by a single cylinder 450cc dirt bike engine these cars usually weight 50kg less than other cars. These cars sacrifice engine power for gains in cornering ability and fuel economy. The light weight concept has also won a significant portion of FSAE competitions by multiple teams.

RMIT has been extremely successful with the lightweight concept since 2003 (Bansal, 2007)

The other significant vehicle layout is the winged car. The winged car is gaining a lot of popularity in recent years especially with more lenient aerodynamic rules for 2011. These are typically based of a four cylinder layout but with slight differences to take advantage of the aerodynamic potential of wings.

University of Texas at Arlington is known for a long history of aerodynamics. (Bailey, 2003)

As can be seen with just these 3 examples, FSAE cars can vary significantly in their basic layout. With such diverse possibilities it is difficult to decide which direction gives the best chance of success. All teams are different and most cars are not at the same stages of development, so it is unwise to compare vehicles using previous event history alone. This is where the need of a basic vehicle simulation becomes clear. Teams looking into a different concept need to be able to see if the change is worth the investment of resources.

1.4 Currently available Simulation software

1.4.1 Commercial Motorsport Software

There are a number of commercial motorsport simulation packages available at the moment, the most popular of which are ChassisSim and Bosch LapSim. These are both full 6 degree of freedom 4 wheel simulations with nonlinear tire models. These both solve in a similar fashion, using onboard recorded data to create data for both the track and the car, varying the simulation parameters in order to make the simulation data match the real world data, creating a model that accurately duplicates a real life lap. After the model is completed, changes can be made to the car's parameters and the altered car is simulated through the same track. The simulation is run using time steps, calculating minimum speed for each corner apex, and the then calculating how the car will enter/exit the corner. Shown below is a screenshot of Bosch Lapsim midway through a simulation. The yellow line is the measured data used to create the baseline (speed and Lateral acceleration), and the red line (currently incomplete) is the calculated speed and acceleration for the modified car (in this case a significant increase in downforce) as shown, it is mid way through solving for between the 2nd and third corners, with all corners already solved (red dots)

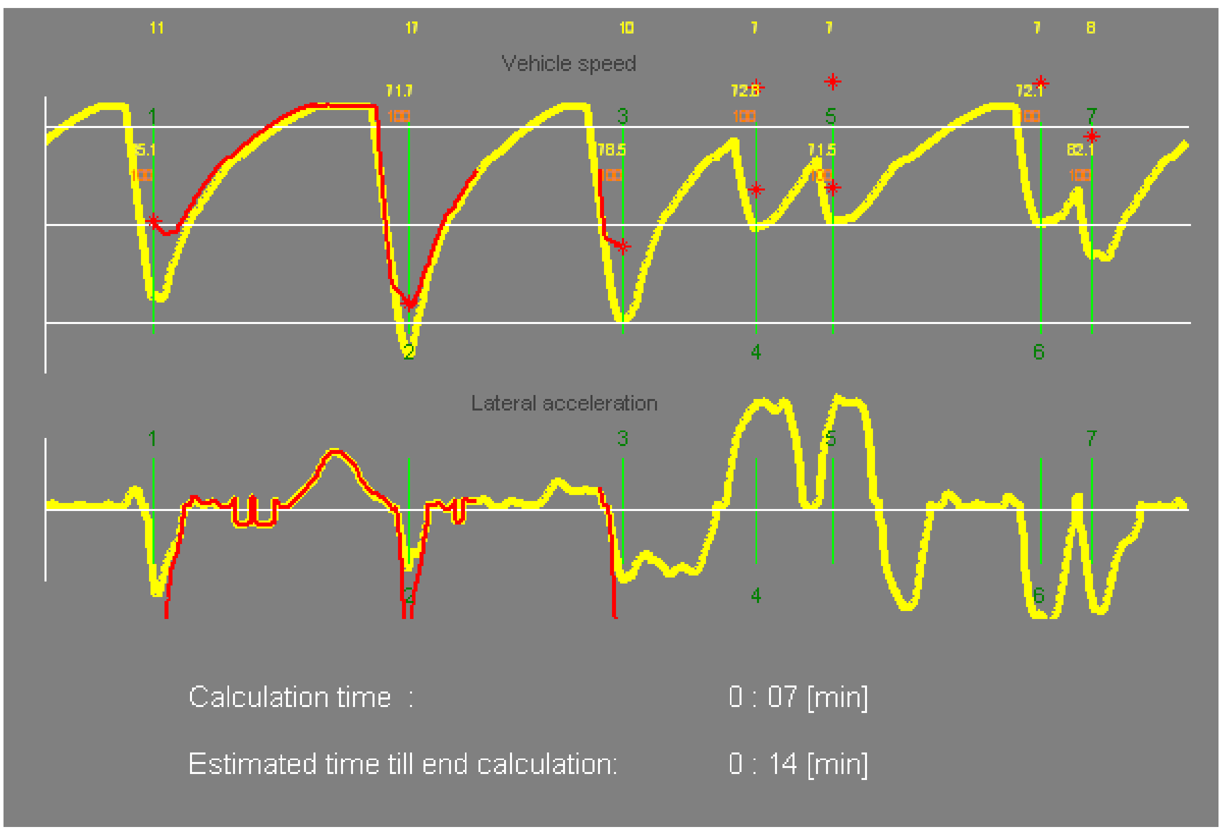


Figure 1.5: Screenshot of Bosch Lapsim showing time-step calculation style starting at corner apexes.

The calculations at each time step are fairly complex, solving for both lateral and longitudinal accelerations (and even Yaw in the case of ChassisSim). Due to the increased complexity for every timestep, calculation takes over a minute per run. Whist one minute per simulation is very quick and does not limit the intended use of the program if someone was to try and use large decision matrices (for example figure 3.2) requiring hundreds of simulations, the computing time could become significant, so there may be benefits to a faster solving program.

Another potential problem in using such an advanced simulation package is the number of independent parameters required for the model. While some parameters are easily identifiable or estimated (weight, power), some are difficult to quantify (cornering stiffness, non-linear properties of tires and aerodynamics) and it is often unclear how accurate these factors need to be in order to trust results. When making small tweaks to a verified model (the programs intended use) this is less of an issue as the parameter used to make the simulated model match real world data (even if they are wrong) are still likely to give accurate results if no parameters are drastically changed. For example, see the similarities between a load sensitive tire with high downforce and a non load sensitive tire with less downforce. If tire load sensitivity and downforce was approximated from onboard data the model could be skewed without knowing. It is also difficult/impossible to create or modify a track as every circuit model is originally made from on board data, however it would be possible to create fake on board data using excel or MATLAB.

As explained in 1.1, the goal of a Formula SAE team is not to be the fastest, but to score more points than any other team. This means that Commercial software misses the final step, simulating points. If a team was to use commercial simulation software it would need to export lap data from the software, calculate fuel usage and then compare with other previous simulations in order to get a point score. This would become very tedious if a team wanted to test a significant number of parameters.

Commercial software is extremely good at what it does, which is accurately predicting small changes to a car around a track which it has previously raced. Yet due to the uncertainty of track layout in FSAE, the magnitude in which vehicle parameters can vary, the number of possible simulations and the missing step to get to competition points it is worthwhile to develop a model specifically for the needs of a Formula SAE team starting from a clean sheet of paper. Later on in the project when the ideal concept has been narrowed down there is still a significant benefit in having a more accurate and more complex commercial simulation.

1.4.2 FSAEsim.com open source simulation

Mid-way through this project, in October 2011 another FSAE team member from a foreign team launched a free FSAE simulation online. It is a very simple java based program that lets people adjust parameters and see their effects. Although it sounds very similar to my own program it has many key differences and flaws. Some key differences of this online sim are.

- Using recorded torque curves of actual cars, rather than a constant power model.
- Appears to use a load sensitive tire model, but does not show how much.
- Gives a choice of 4 different tires, yet does not give information on them.
- Does not allow independent changes to Lateral and longitudinal coefficients other than “tire choice”
- Assumed constant 1.5g braking
- Does not appear to correct for “speed jumps” (see 2.10.1), track map would cause many speed jumps
- Uses Aerodynamic parameters of “downforce” and “downforce to drag ratio”
- Reducing downforce to drag ratio while keeping downforce constant (aka increasing drag) makes everything faster, even acceleration event.
- Scores are given, yet every simulation get full scores for every event
- There is no way to view the simulated data, other than the results at the end, so the user can't see where or how the changes in performance are caused.

Another difference is that it does not do everything Monash wants it to do. The creator has generously uploaded MATLAB code used to create the model so it is possible to use the MATLAB code to create a more useful tool, but that would likely be more time consuming than creating a new model from scratch with specific targets in mind.

2. Creating a New Simulation Tool

Because the was no currently available vehicle simulation that was able to quickly simulate the potential design changes for the 2011 Monash FSAE car I decided to create a basic model that would be able to simulate approximate changes in point scoring potential. In order to reduce the need for accuracy to real world data, it was decided to only compare simulated data against other simulated cars using the same modelling technique. This is because the team is mostly concerned with how changes in parameters will affect performance, with exact performance predictions less important.

2.1 Relevant Parameters and simulation Complexity

The complexity and accuracy needed from a simulation is defined by the parameters you wish to model, with some parameters needing very complex models in order to simulate a change. Fortunately the parameters that will have the biggest effects on a cars performance are quite simple to simulate. In other cases "effective" parameters can be used, which are estimated values that may be affected by thousands of different parameters on the car. For example the Lateral Grip coefficient is affected by many different variables on the car and is the main cause of complexity. All of that complexity can be avoided by using a "Effective Lateral Coefficient" instead, which can be measured empirically or simply estimated.

By using "effective" or averaged parameters in most cases simplifies the calculation process but requires the user to know how each parameter is affected by a change. For example to accurately know what would happen if track width was increased or more downforce was added, a separate pure cornering model/calculation should be created to see how it may affect the effective lateral coefficient. If someone using the sim does not understand the possible effects on every parameter it is likely that they could make incorrect decisions. For example if someone wanted to add more downforce to the car saying that "if we increase effective downforce by 10% we get an extra xx points" they may not have taken into account the possibility of effective lateral coefficient decreasing due to the increased load on the tires, which could reduce the possible gain. 2.1, 3 Show examples of different techniques to ensure any simulated gains would still be likely in the real world. Below is a list of Parameters used in the new model along with a brief description of how they are used and what may affect them.

Total Mass = Car + Driver Mass

Mass used in everywhere F=M*A and also in kinetic energy calculations. It is only affected by how much the car weighs.

CG Height, Wheelbase and Track width

CG height and wheelbase are used to calculate weight transfer to the driven wheels under longitudinal acceleration. For a car with 50/50 weight distribution use the number measure from the car. Unfortunately the sim only model cars with 50/50 weight distribution; however a similar effect to changing weight distribution could be achieved by decreasing the wheelbase. Track width does not affect the model, it is only included to estimate if a car will pass the tilt test.

Effective Vehicle Width

The effective vehicle width relates to how far a car needs to travel around cones (see 2.4). It is best measured empirically by driving through differently spaced slaloms (see 4.2). Effective vehicle width can be affected by Track width, wheelbase, overhangs, suspension settings, differential settings, lateral coefficient, weight distribution and driver skill.

Lateral and Longitudinal coefficient

The effective tire coefficients are simply how much lateral or longitudinal force a tire will exert on the car per unit of normal force on the tire. This is an overall/averaged number for the entire car at all speeds and loads, however as shown in figure 2.15 load/speed sensitive effects could be taken into account by changing the effective downforce levels.

Vehicle power * Power efficiency = Effective power.

The model uses Constant power during acceleration (Force = Power/Velocity). Vehicle Power is simply the maximum power predicted, where power efficiency is what percentage of maximum power is seen by the wheels on average during acceleration. The power efficiency/effective power can be affected by the width and shape or the torque curve, closeness of gear ratios, shifting RPMs and shifting time.

Thermal efficiency & Fuel energy

Thermal efficiency and fuel energy are used in the conversion of the estimated energy required to move the vehicle around the endurance track to the amount of fuel used. This could be calculated from empirical BSFC data averaged over an endurance (In order to average you would need an inverse BSFC channel, and then inverse again after averaging, to account for the times where BHP=0) or a values could be estimated that give correct numbers. The thermal efficiency should be adjusted on one of the cars so that VMin is similar to what it should be during the competition. As thermal efficiency is simply an average of BSFC, anything that changes BSFC will also change thermal efficiency.

Rolling drag

Rolling drag is the drag force constantly holding the car back. In reality it changes with vehicle speed (which can be overcome by effective aerodynamic drag), and also cornering g's (see figure 4.3). It can be affected by lateral coefficient, tire choice, wheel alignment, rubbing brake pads and tire pressure.

Effective Downforce Coefficients

The effective downforce is simply a measure of how much better a car can corner and brake as a function of velocity squared. For example if a 300kg car has 300kg of "effective" downforce, it can corner twice as hard as a car with no downforce, however in this case the actual downforce may be much higher. These are best calculated parallel with effective tire coefficient using increasing radius circles (See 4.2). The effective downforce can be affected by aerodynamic downforce, Aerodynamic balance, suspension setup and tire load sensitivity.

Effective Drag Coefficients

Similar to the effective downforce coefficients, the effective drag coefficient is the amount of drag on the car related to velocity squared. It can be affected by Aerodynamic drag, Aerodynamic downforce, lateral coefficient, tire choice, wheel alignment, rubbing brake pads and tire pressure.

2.2 Simulation Interface

The original plans for the simulation was to start in excel with a basic model, and then move to matlab as the model gained in complexity. However when the initial model was finished in excel it became evident that the widespread usability and the amount of different methods in which useful information could be extracted (see 3.2) was extremely valuable. Excel also makes it very clear what is happening at each point in the calculation, making troubleshooting errors much easier. The other gain to excel is the ease of modification, for example when simulating a drag reduction system the model needed to be modified. It was decided to simulate and compare 5 different cars at once, as this would allow us to compare LeadAverage against 4 different competitors, or else you could use 2 cars for direct comparison between variations of the same car, with the other 3 car there to ensure the events are scored accurately. The changes to each of the cars, and the final results are all shown on on the first page, “Car Parameters” (see appendix).

Because the final results do not show the full story, there is a scoring breakdown page (in appendix) as well as event breakdowns where it’s possibly to see exactly where a car’s points have come from. In the endurance and Autocross pages it is also possible to alter the number of cones a driver has hit in the event as well as how much fuel is spilled/wasted to see the effects of a finite fuel or lap time change above or below what the simulation predicts. It is also possible to go into the simulation page of each sector (See 2.3 below) and change aspects of the track, as well as viewing information such as speed, accelerations and energy use at each point in the track. Because the simulation is based in excel, it is very easy to view different aspects of the data, both for comparative and validation purposes. A good example of viewing the simulation data is the velocity vs track distance shown at the bottom of each sector.

2.3 *The Track layout*

Due to the variations in tracks (1.2.2) it was decided that the "track" which the car performance would be estimated would be made up of 4 different sections. Each section has a slightly different layout, with different average speeds and cornering radii. Depending on which competitions and tracks the team is expecting to compete on, it is possible to change the relative lengths of each sector. For example, an Australian track may be 25% sector 1 by length, but an American or European track may only be 5-10% sector 1 by length. This ensures any design decisions can be checked on how they perform on different style tracks. If for any reason any areas of the track require changing (due to new rules or a radically different track experienced at a competition) and of the corner radii, slalom spacing and straight lengths can be changed very simply as well.

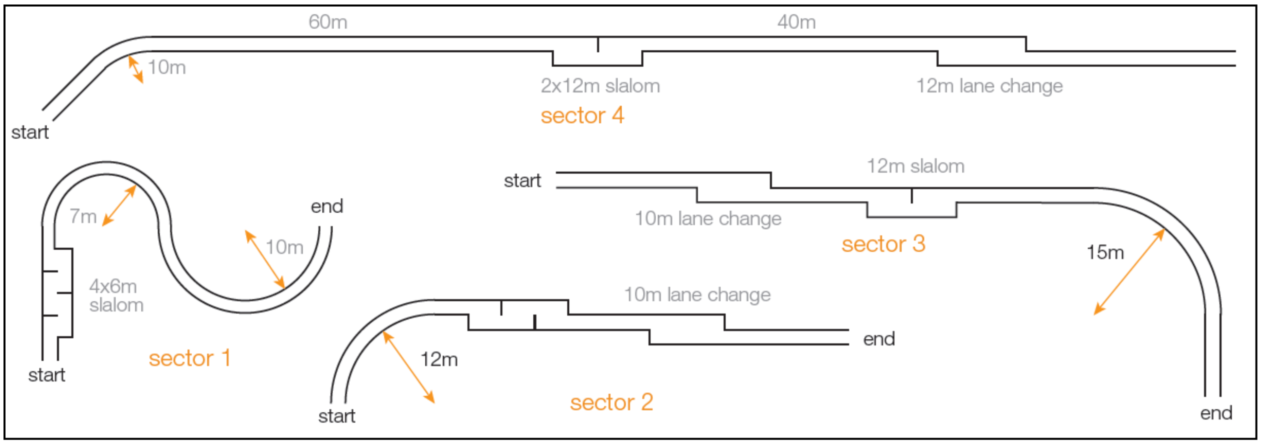


Figure 2.1: Drawings of each sector for the track used in the simulation.

	Sector 1	Sector 2	Sector 3	Sector 4	
Average speeds	37km/h	50km/h	63km/h	68km/h	
Australian competition	25%	28%	26%	21%	Average speed 51km/h
European competition	10%	25%	45%	20%	Average speed 56km/h
American competition	5%	30%	35%	30%	Average speed 58km/h

Figure 2.2: Average speeds of each sector, Sector percentage estimations for different competitions and resulting average speeds

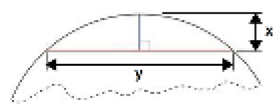
2.4 Corner radii in slaloms

Due to the quantity of slaloms and lane-changes in a typical FSAE track, it is agreed upon that there is a benefit to a narrow car due to a narrower car not needing to corner as tightly in slaloms. Monash's track width has been the same (1200mm front, 1150 rear) from 2006-2010. In 2005 Monash attempted to narrow the trackwidth (to 1100mm front, 1075mm rear) however due the car almost tipping over at competition the team decided that it was not worth the "risk" so track width was increased in 2006 and different track width were not experimented with until after the 2010 season.

In 2009, the University of Auckland surprised the opposition by designing their whole car to reduce CoG height enabling to run an extremely narrow track width of 1025mm front, 975mm rear. The gains were immediately obvious and helped Auckland achieve 5th place in Autocross. In order to investigate the potential benefits a narrow car, it was decided that the new model must simulate the effects of vehicle width has on the path taken by the vehicle through slaloms and lane-changes.

In order to keep the slaloms "variable" in the model it was decided to approximate the path taken by the car as a series of arcs linked together. This makes it possible to calculate corner radius versus slalom size and "effective width" (double the distance between a car's CG and the center of the cone) using equation 2.3 below.

$$r = \frac{y^2}{8x} + \frac{x}{2}.$$



Equation2.3: Equation used to calculate cornering radii through slaloms. X=Half effective car width, Y=slalom length

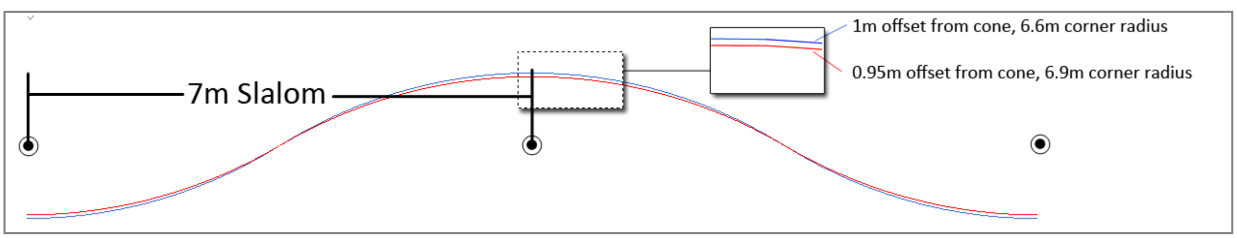


Figure 2.4: Path taken by vehicle using constant arc approximation.

After comparing radii through slaloms with on board data and looking at current FSAE cars, it is believed that the effective vehicle width of a Formula SAE car could range from 1.65-2.25 metres. The different slalom cornering radii estimated for each extreme of effective vehicle width is shown by figure 2.5 below

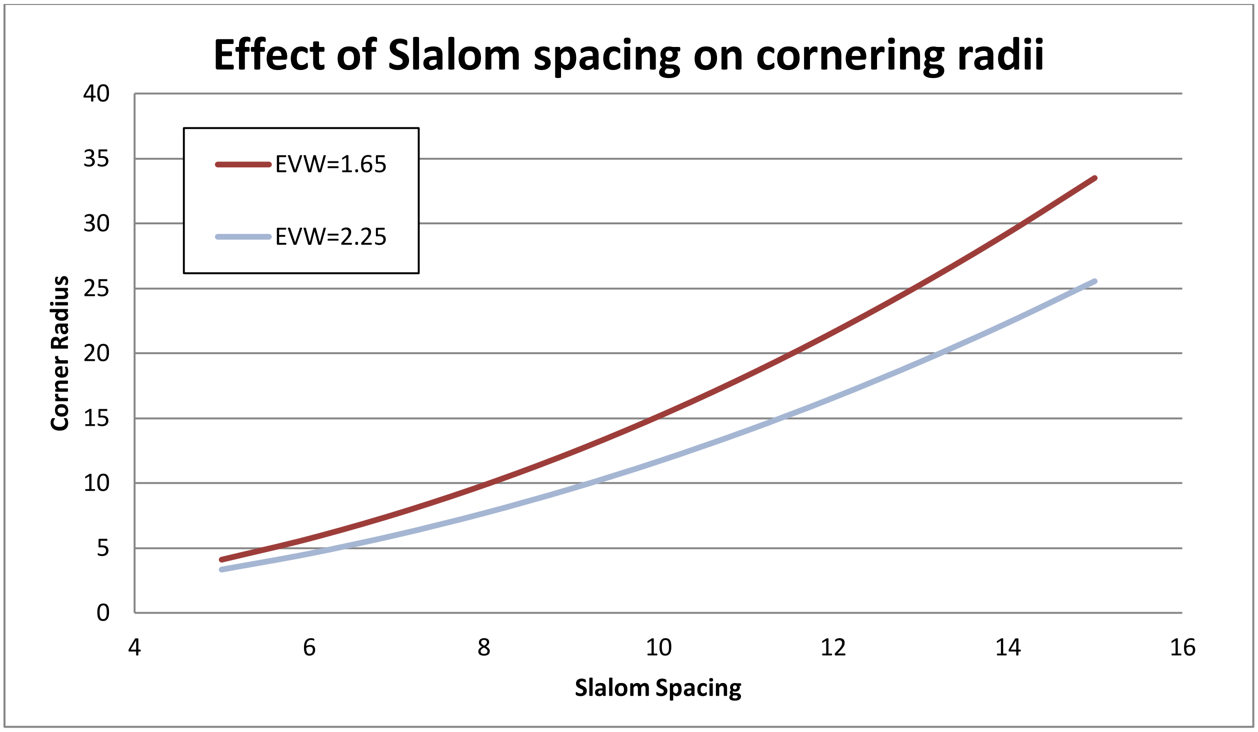


Figure 2.5: Corner Radius vs Slalom spacing for a wide and narrow car.

It is important to clarify that "Effective Vehicle Width" is simply a value used to approximate cornering radii in slaloms. Although it is strongly affected by car width, it can also change with a car's length, overhangs, suspension setup and driver skill. Shown below is a comparison of corner radius histograms from FSAE-A in 2009 of Monash's car and UWA's car, as well as UWA's car with a different driver. Monash's car had a 1200 mm track width, but it also had a spooled rear axle and large wings, UWA's car had a front track width of 1150, but also did not have wings and had a differential. Comparing the Monash and UWA corner histograms it can be seen that the UWA car does not take corners as tight as the Monash car, indicating the effective width of UWA was significantly less that Monash. The other interesting comparison is between the two UWA drivers themselves, with UWA Driver 1 spending much less time than UWA Driver 2 in tighter corner, with more time spent in more open corners. This shows that even with the exact same car around the exact same track, the driving line through slaloms (and therefore the estimated "Effective Vehicle Width") can change significantly.

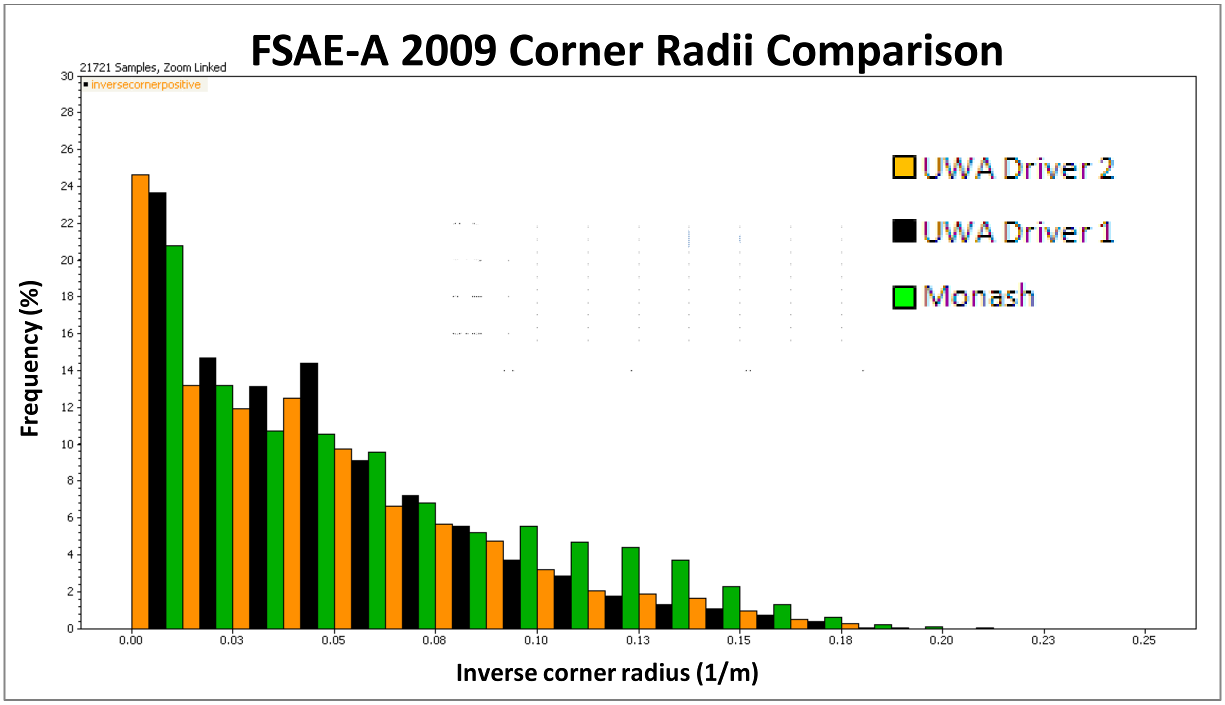


Figure 2.6: corner radius histogram showing the effect of car width and driver skill on corner radii, Data taken from 2009 FSAE-A Endurance.

2.5 Track Speed Vs Vehicle speed.

Due to the model's ability to change the path a vehicle takes around slalom and some hairpins, not every vehicle will be traveling the same distance. In order to make analysis of vehicles at each point on the track, each aspect of the circuit has both a "track speed" and a "vehicle speed". Track speed for slaloms is how fast your car would look if you were standing side on. For example if a car was driving through 10m slaloms, and was driving through 2 slaloms every second, the "track speed" would be 20m/s (72km/h) yet because of the car weaving , the actual vehicle speed would be slightly higher. On some hairpins, the model changes radius slight for narrower cars, allowing them to "cut corners", in this case, the distance the car travels is less than the circumference of the corner, so vehicle speed is actually slightly lower than track speed. Track speed is used to give times through the track, yet vehicle speeds are crucial in the calculation of the speed at the start/end of straights, as well as fuel calculations. Because of the difference between track speed and vehicle speed, the traces of Track speed Vs Distance at the bottom of each sector appear to have unexplained jumps in speed at hairpins and slaloms. On the straight sections, there is no difference between track speed and vehicle speed. Shown below (2.7) is a track speed trace, to show how track speed will suddenly drop slightly in slaloms (left) and pick up slightly in hairpins (right). It is important to realise that the vehicle speed does not jump in this way, it is simply an effect of the car needing to travel more distance in slaloms and less distance through hairpins than the "central" line.

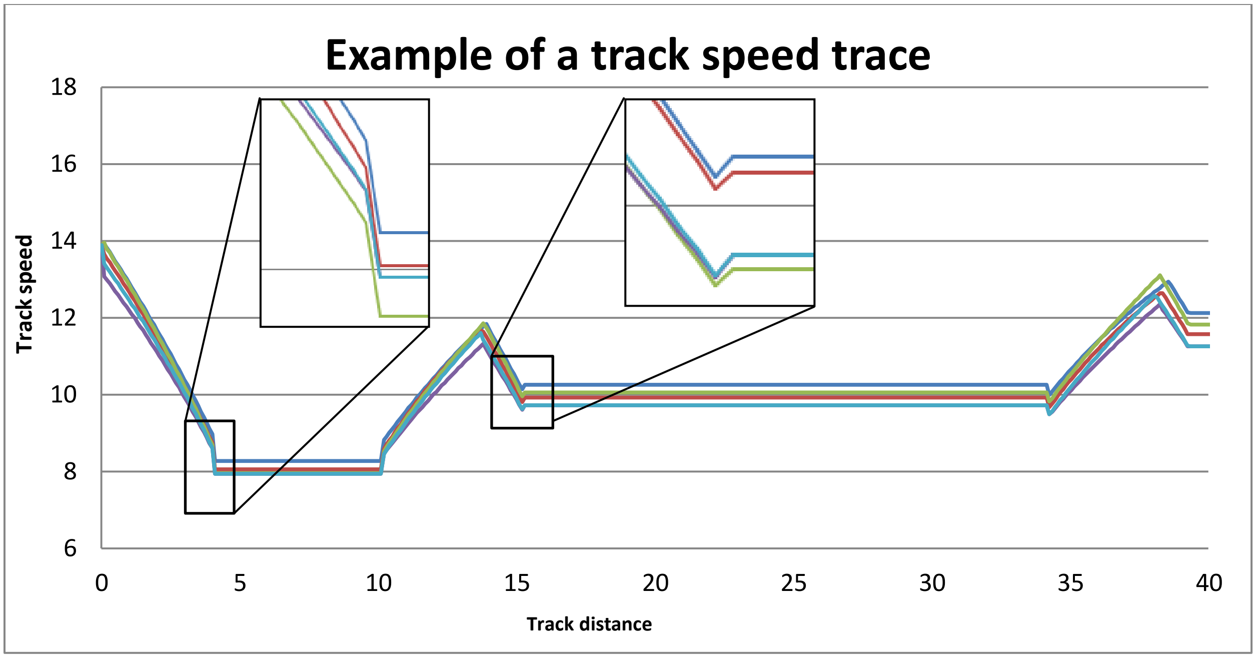


Figure 2.7: Track speed trace of a car going through a slalom (left) and a hairpin (right)

2.6 Simulating Cornering Speed

After the track is defined as corner radii and slalom sizes (and the slalom radii are calculated as in 2.4) then the next step is to calculate speed through each corner. The decision to approximate corners and slaloms as constant radius arcs and assuming lateral coefficient and downforce coefficients are constant makes the calculation of vehicle speed through corners a single equation.

The equation to solve for cornering velocity is

$$V = \sqrt{A_{Lat} * R}$$

Where V=cornering velocity, A_{lat} = lateral acceleration, R= Corner radius. R is already known, so A_{lat} needs to be solved. The cornering equation will then become

$$V = \sqrt{\frac{N * CF_{lat}}{M} * R}$$

Where N = Normal load on the tires, CF_{LAT} =Effective lateral coefficient and M=Mass. If we were to not consider downforce, then N=M*G which would make A_{LAT}=CF_{LAT}*G making the equation easy to solve in terms of known parameters. But with downforce the normal load will vary with speed, turning the above equation into

$$V = \sqrt{\frac{(M * g + \frac{1}{2} * \rho * ClA * V^2) * CF_{lat}}{M} * R}$$

With g=Gravitational Constant=9.81m/s^2, ρ= Density of Air = 1.225kg/m^3 and ClA=effective Aerodynamic Downforce Coefficient. When solving for V gives

$$V = \sqrt{\frac{CF_{lat} * g * M * R}{M - (R * \frac{1}{2} * \rho * ClA * CF_{lat})}}$$

Which is the equation used for every corner and slalom. Figure 2.8 shows Corner speed vs corner radius for 2 cars, one with no downforce, and one with a significant amount of downforce. For both cars M=275kg, C_{lat}=1.4

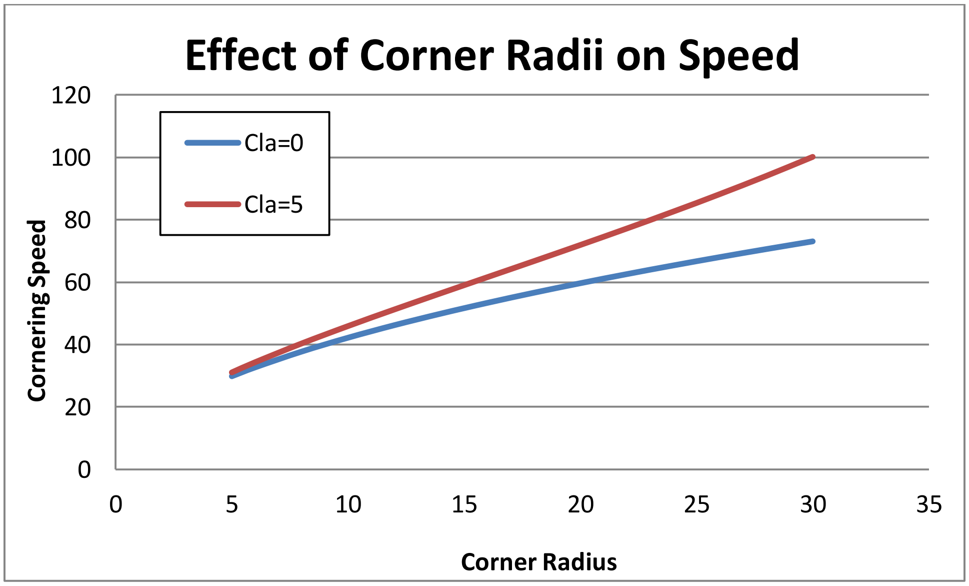


Figure 2.8: Corner Radius vs Speed for a car with and without downforce

2.7 Straight line performance

After the speed in each corner has been calculated, it was time to calculate everything in between, the straights. Similar to commercial software, the straight line acceleration will be continued from the corner exit speed of the previous corner, while simultaneously the braking accelerations will be calculated from the entry speed of the next corner. The "braking point" will be the point along the straight where the maximum speed caused due to acceleration becomes more than the speed which would cause the car to stop at the correct speed for the corner. Figure 2.9 show how velocity is calculated forwards from the previous corner exit speed, and backwards from the next corners braking speed.

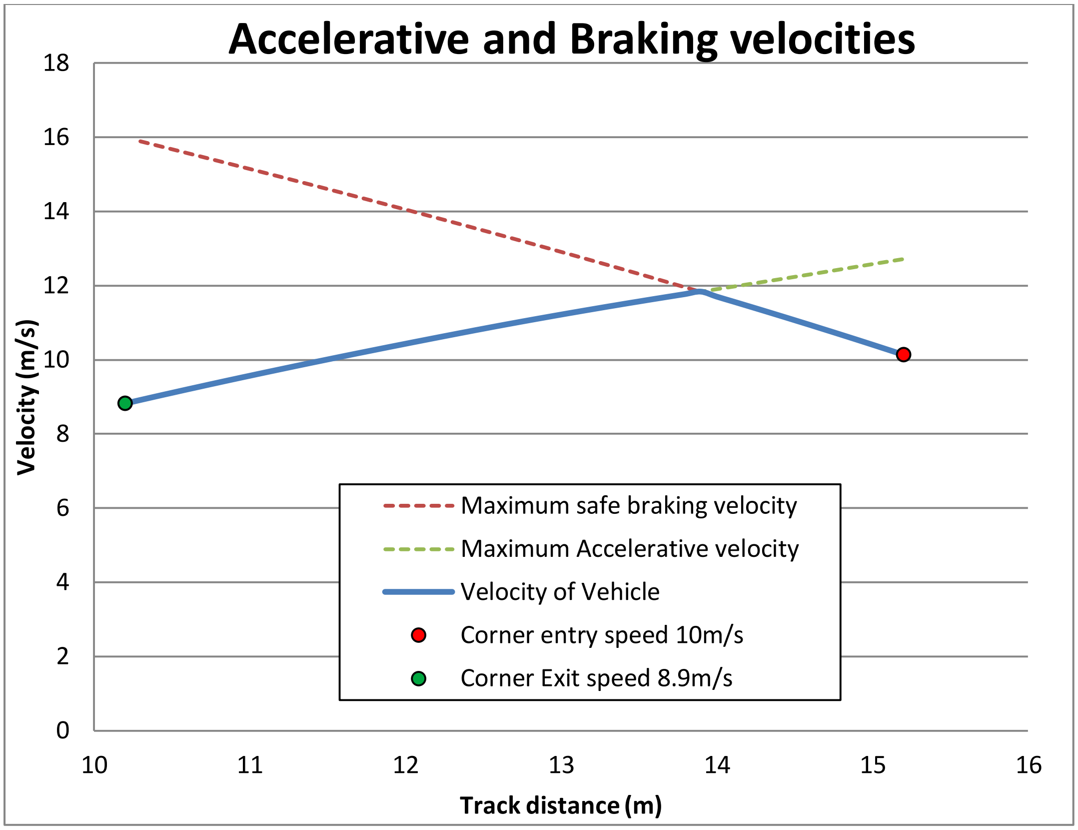


Figure 2.9: Straight line velocity showing the change from acceleration to braking.

In order to monitor each step along the straight, it was decided to calculate using distance steps of 0.1 meters. This would allow the user to monitor velocity, acceleration and energy usage along the straight, as well as allowing ease of customisation if someone wanted to add extra features to the straights (see 3.3). Braking and Acceleration velocities were calculated by using the Euler method after calculating the accelerations at each distance step (see below). The Euler method was deemed adequate due to the acceleration not being effected much by the velocity and the small step size already required in order to target the braking point accurately.

It is possible with certain car/track combinations that the previously calculated corner exit velocity is so high that the car cannot accelerate in time. This is discussed in detail in 2.10.1.

2.7.1 Calculating Maximum Acceleration

Acceleration in an FSAE car has two stages, Grip limited acceleration and power limited acceleration.

For calculating grip limited acceleration

$$A_{Grip} = \frac{F_{Net}}{M} = \frac{N_{Rear*}Cf_{Long} - Drag_{Total}}{M}$$

Where A_{grip}=Longitudinal Acceleration, N_{rear} is the normal load on the rear axle under acceleration, CF_{Long} Is the effective Longitudinal grip coefficient, M=Mass and $Drag_{total}$ is the sum of aerodynamic and rolling drag. The Normal load on the rear axle is a function of vehicle weight, Rear downforce, and weight transfer under acceleration. When fully expanded, the equation becomes

$$A = \frac{\left(M * g * RWD + \frac{1}{2} * \rho * CLA_{Rear} * V^2 + \frac{CoG * M * A}{WB}\right) * Cf_{Long} - (RD + \frac{1}{2} * \rho * CdA * V^2)}{M}$$

Where RWD=Rear weight distribution, CLA_{rear}= effective coefficient of downforce acting at the rear, V=Velocity, CoG= center of gravity height, WB = Wheelbase, RD=Rolling Drag, CdA = Effective aerodynamic drag coefficient. Solving for A becomes

$$A = \frac{-WB * (\left(M * g * RWD + \frac{1}{2} * \rho * CLA_{Rear} * V^2\right) * Cf_{Long} - \left(RD + \frac{1}{2} * \rho * CdA * V^2\right))}{M * (Cf_{Long} * CoG - WB)}$$

For power limited Acceleration the equation is much simpler.

$$A = \frac{\frac{P}{V} - (RD + \frac{1}{2} * \rho * CdA * V^2)}{M}$$

Where P= Effective vehicle power.

The Acceleration of the vehicle is simply the minimum of the Grip limited and power limited accelerations. The grip limited, Power limited and actual acceleration predicted for the 2011 Monash car are shown below.

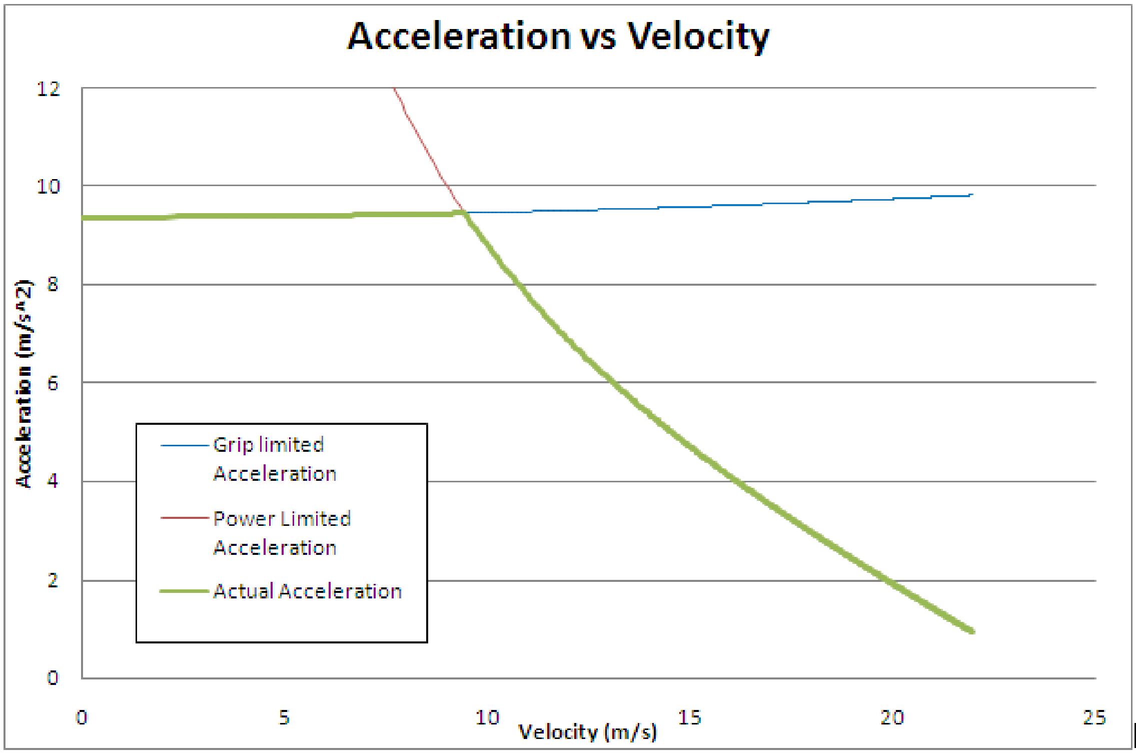


Figure 2.10: Grip and Power limited acceleration prediction for the M11

2.7.2 Braking

The calculation for braking acceleration is shown below

$$A = \frac{F_{Net}}{M} = \frac{N * Cf_{Long} + Drag_{Total}}{M}$$

Where A=Braking acceleration N=Normal Load on all tires, Cf_{long}=Longitudinal coefficient of the tires. When expanded, this is equal to

$$A = \frac{\left(M * g + \frac{1}{2} * \rho * CLA * V^2\right) * Cf_{Long} + (RD + \frac{1}{2} * \rho * CdA * V^2)}{M}$$

Where CLA= effective coefficient of downforce, V=Velocity, RD=Roling Drag, CdA = Effective aerodynamic drag coefficient.

2.8 Energy and Fuel economy

Fuel efficiency is becoming an increasingly important aspect of formula SAE competition (see 1.2). In order to compare fuel usage between different concepts, an estimation of energy required to propel the car around the track. Two different kinds of energy were calculated, Kinetic energy and drag energy. Kinetic energy is only calculated when accelerating on a straight using the following equation for each distance step.

$$E_{Kinetic} = \frac{1}{2} * M * (v2^2 - v1^2)$$

Where M=Mass, v2=Velocity at next distance step, v1=Velocity at current distance step. Drag energy is calculated for everywhere on the track other than the braking zones. The drag energy is calculated with the following equation.

$$E_{Drag} = \left(RD + \frac{1}{2} * \rho * CdA * V^2\right) * D$$

Where RD=Rolling Drag and CdA is the effective Aerodynamic drag coefficient and D=Distance step/Corner length. It is assumed that the car uses no energy/fuel in the braking zones, however in the real world even with fuel cuts there will still be some fuel injected in the braking zones.

After calculating the total energy used, the energy density of the fuel and overall engine efficiency is used to give a volume approximation. This sim does not take into account possible changes in efficiency caused by other factors, such as engine size, which may have a bigger effect on fuel use than the energy required.

2.9 Scoring and Outputs

After the laptimes and energies are calculated for each event, the individual even scores for each car are calculated and given on a scoring breakdown page (see appendix). The outputs are given on the main car parameters page (see appendix) in terms of Total Points, LeadAverage and LeadMax (see appendix). An extra output row and a simple macro was added which copies the current LeadAverage for each team into another cell to create a baseline, then when changes are made the amount of points gained/lost from the baseline are shown in a new row, DeltaLead. Whenever sensitivities are displayed, it is generally the effect each parameter has on DeltaLead.

2.10 Assumptions, Errors, and Areas for Improvement

2.10.1 Insufficient space to gain speed before a corner

Certain car/track combinations can create errors if a straight before a corner is too short or a car has poor acceleration and therefore cannot accelerate up to the previously calculated cornering speed of the upcoming corner. This is not rectified using the assumption that if a car cannot reach the previously calculated cornering speed, then the entire corner will be spent at whatever speed the car was capable of reaching at the end of the straight. As Monash cars were more likely than any others to not reach their cornering speed, it was decided that this was a safe and conservative assumption to make. Figure 2.11 shows a speed trace using the initial calculation vs the current conservative assumption.

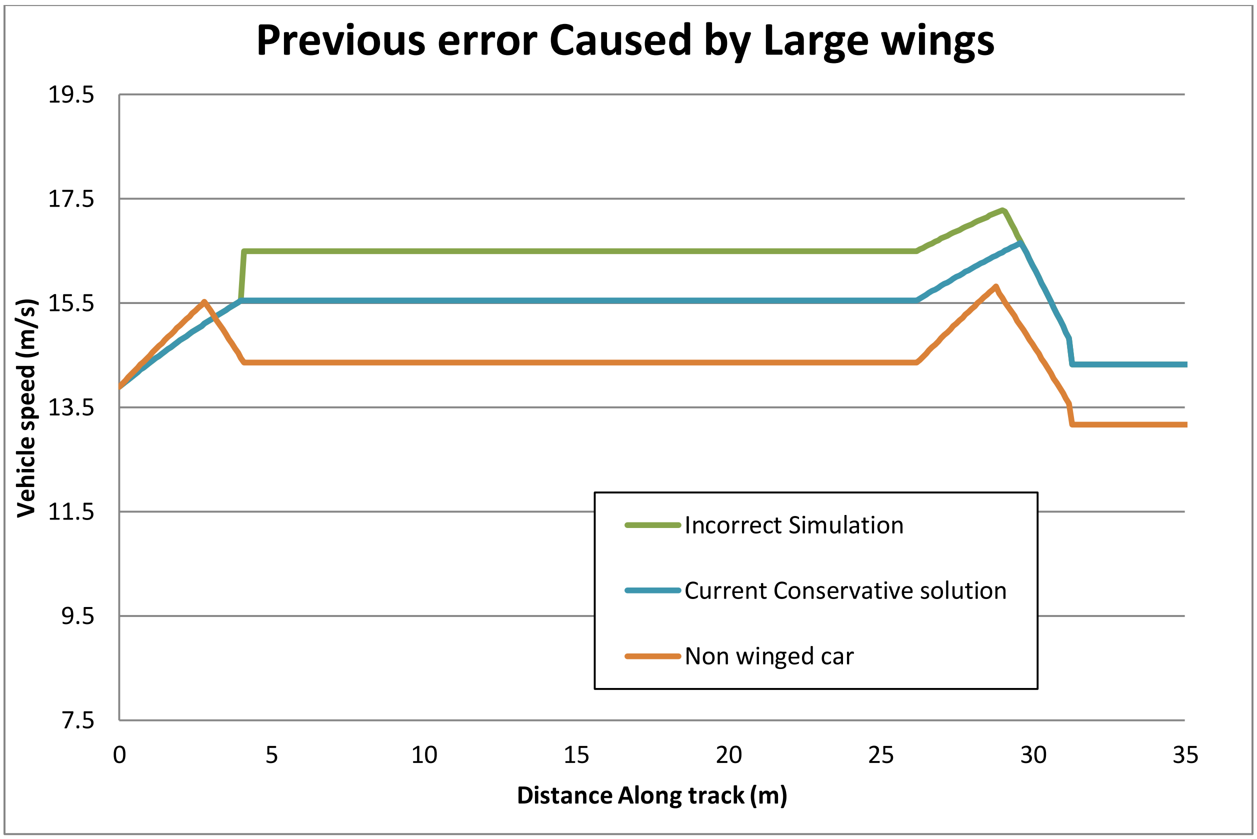


Figure 2.11: "speed jump" error shown against current conservative assumption.

This was first noticed when trying to create plots of Downforce Vs Points. Whenever a cornering speed could not be reached, the was a Jump in the data. Surprisingly, the majority of the points jump does not come from the falsified increase of speed, but in the fuel economy event as the speed jumps create extra kinetic energy that is not accounted for in the calculation of the straight. Each "Jump" in points on figure 2.12 was the error occurring at different corners.

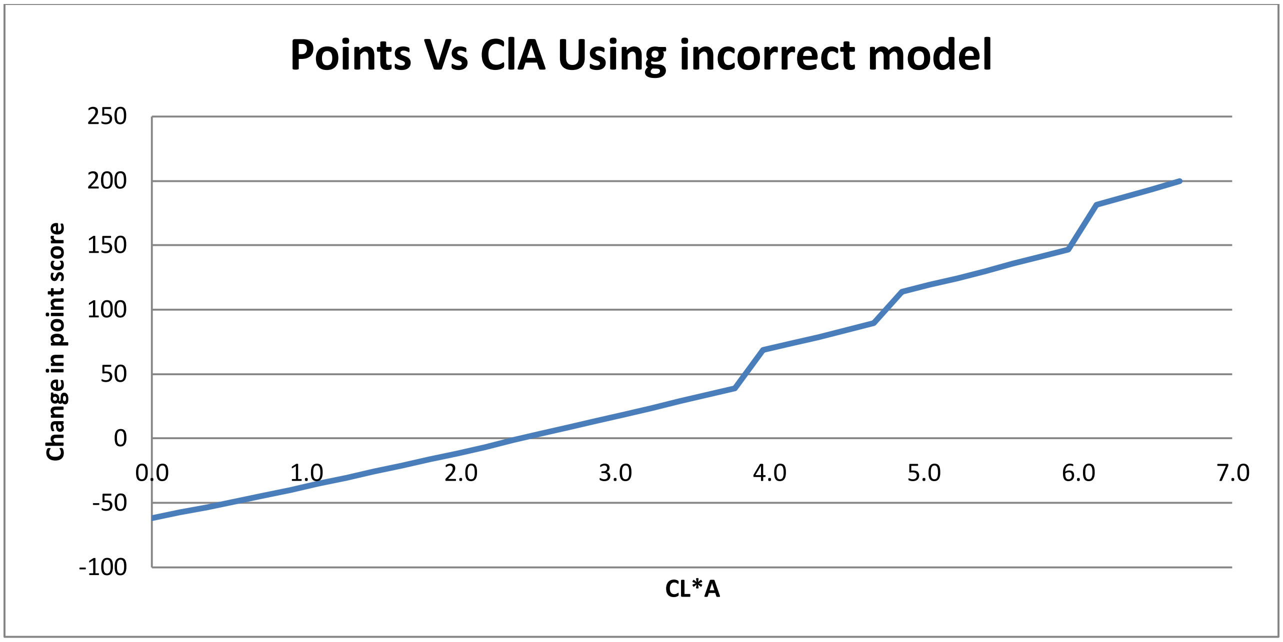


Figure 2.12: Points jumps shown due to incorrect model.

2.10.2 Possible errors due to the assumption of constant Grip Coefficient, and the effects of load sensitivity.

One of the biggest potential shortfalls of the model is the assumption of constant grip coefficients. This could create possible scenarios that give incorrect information to the user about the true sensitivity of some aspects of the car that affect the loading of the tires, e.g. weight, width, downforce.

Tire load sensitivity is very complex to calculate and measure, as it is very dependent on the testing procedure, with higher Mu surfaces creating curves very different to more realistic surfaces and load sensitivity changing dramatically with tire pressure (Trevorrow, 2006). Some data shows tire load sensitivity increasing with load (Smith, 1978) whereas some data shows load sensitivity decreasing with load (Mapson, 2011).

For the analysis in this section, the load sensitivity is assumed to be constant at 0.2/1000N. This is an overestimation of what we believe our current load sensitivity to be, so the following analysis will overestimate the importance of load sensitivity. The Grip coefficient will be approximated as

$$Cf_{LS} = 1.74 - 0.0002 * N$$

$$Cf_C = 1.6$$

Where Cf_{ls} is the load sensitive approximation for lateral coefficient and Cf_c is the constant coefficient approximation and N is the Individual wheel load in Newtons. Note that the following analysis is based around a base vehicle weight of 2800N, so $Cf_{ls} = Cf_c = 1.6$.

The first parameter that comes to mind when thinking about load sensitivity is the effect of overall vehicle mass on the lateral coefficient. However even with the relatively large variation in vehicle masses between FSAE cars, weight sensitivity has very little effect, with the calculated coefficient between the heaviest and lightest cars only varying 0.005 (~3%). So in order to get a significant increase in Cf due to weight reduction, there would need to a be a drastic change and weight savings of over 30kg for here to be a noticeable change.

Vehicle weight (kg)	130	140	150	160	170	180	190	200	210	220	230
Approximate Cf	1.640	1.635	1.630	1.625	1.620	1.615	1.611	1.606	1.601	1.596	1.591

Table 2.13: Approximate changes in Grip coefficient due to load sensitivity and vehicle Mass.

Another effect of tire load sensitivity is the reduction of effective coefficient due to the weight transfer during cornering. The % of a car's inside tire load transferred is related to the CoG height, track width and Lateral Acceleration. For Competitive FSAE cars the % weight transfer could range from approximately 70%(low, wide, no downforce) to 100% (narrow, higher, downforce). Therefore the Effective Cf change caused by weight transfer due to load sensitivity could vary by 0.07 (~5%). This shows that with this over estimated value for load sensitivity there is significant gain in reducing Cg height/Increasing track width; however the gain of a narrow car being able to better negotiate slaloms with a narrow car far outweighs the gain in Cf.

% of weight transferred	0	10	20	30	40	50	60	70	80	90	100
Approximate Cf	1.600	1.599	1.594	1.587	1.578	1.565	1.550	1.531	1.510	1.487	1.460

Table 2.14: Approximate changes in Grip coefficient due to load sensitivity and weight transfer.

The other significant effect load sensitivity has is the reduction of Cf when the wheel loading increases due to downforce. If the effect of load sensitivity is ignored altogether than the sim could over estimate the positive effects of downforce. This could create an error of over 0.1g at 75km/h in the case of the M11. Because the error is dependent on speed, the easiest way to rectify the problem is reducing the effective downforce. Shown below in figure 2.15 and 2.16, a reduced downforce coefficient with a constant grip coefficient can give very similar results to a load sensitive tire, with error being less than 0.02 up to 95km/h. This does need to be taken into consideration when deciding on wing size however as load sensitivity of the tires can reduce the effectiveness of the wings by up to 15%.

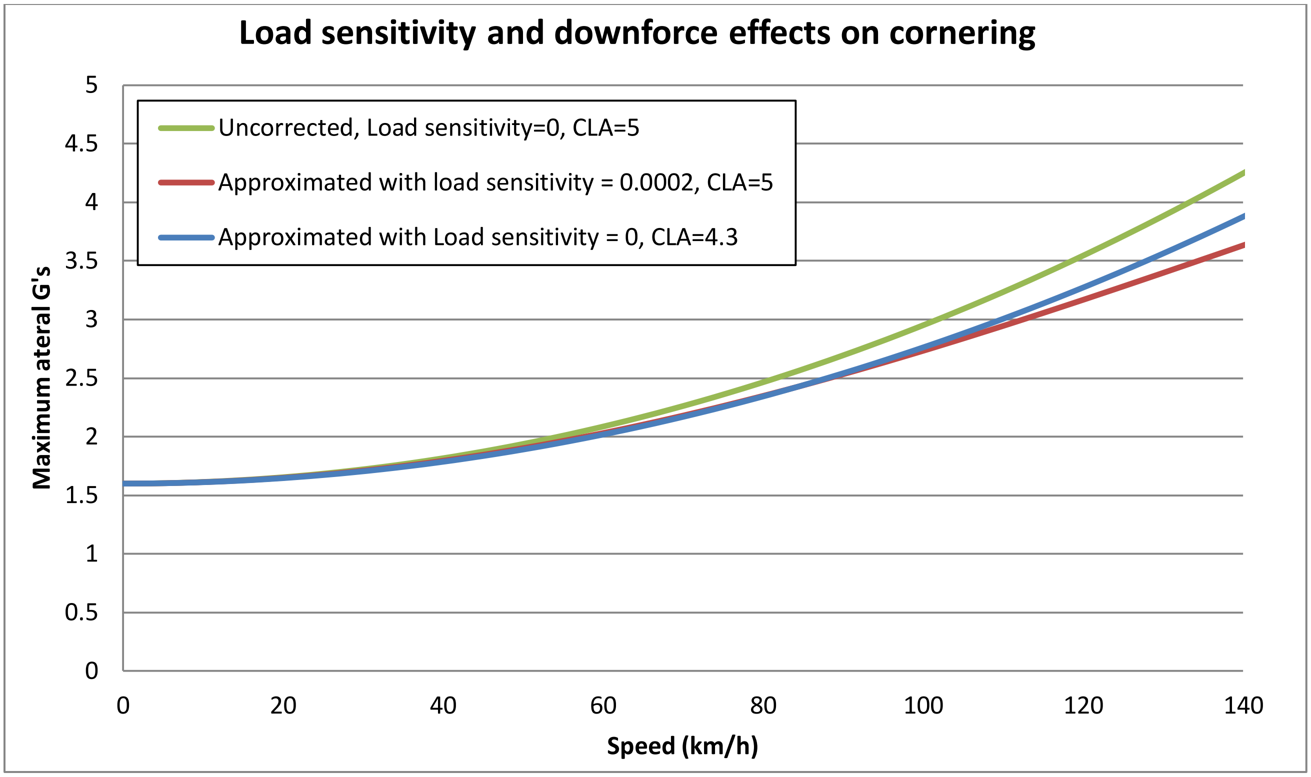


Table 2.15: Maximum Lateral Acceleration due to speed, ClA and load sensitivity.

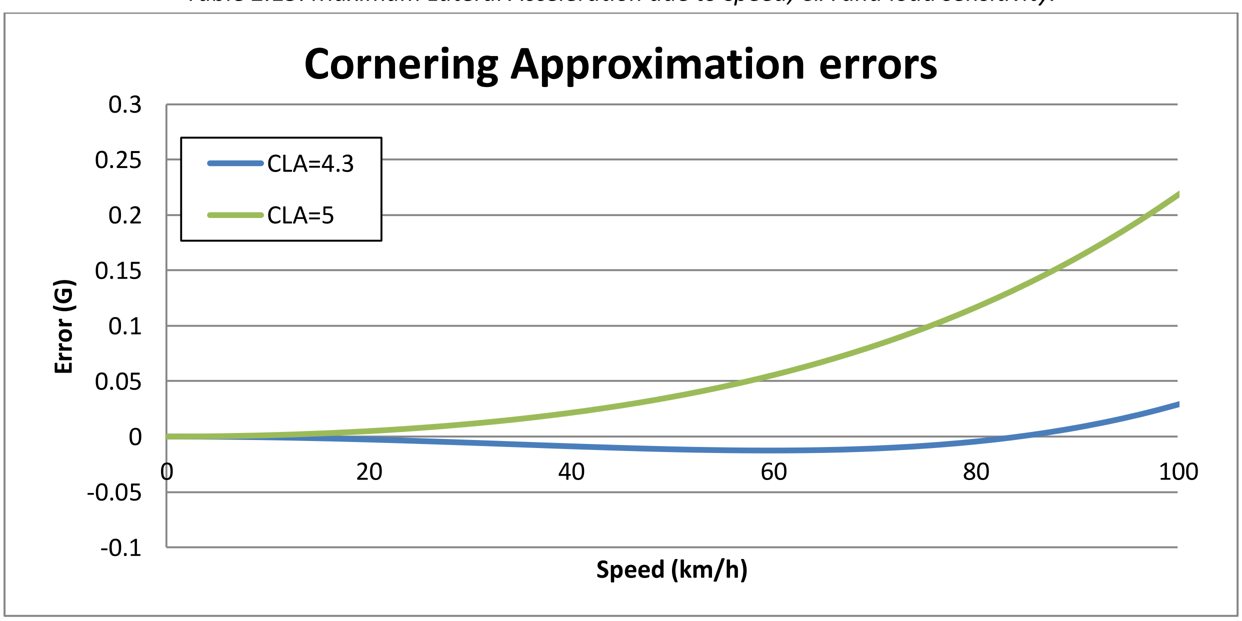


Table 2.16: Showing the reduction in cornering errors due to adjusting Aerodynamic Effectiveness

As a whole, in this overestimated example, load sensitivity can create a significant decrease in a car's coefficient of grip, with the possibility that some cars could have a 10% disadvantage compared to others. However when the effects of load transfer are considered and estimated when creating the vehicle parameters and assuming there are no unrealistic changes to parameters like weight and width, the overall error caused by load transfer would realistically be less than 1%.

2.10.3 Other recommendations

Errors and assumptions in longitudinal performance.

A FSAE car's performance does not heavily depend on its longitudinal performance, especially if it has as much grip/as little power as M11. Because of this there has not been much focus to improve on the initial calculations or add extra features. There is currently no way of changing the rear weight bias of the car in the model. Moving the weight rearwards in the model would increase grip limited acceleration, as it would in real life. This would give the intention that more rear weight is always better. However there could also be significant changes to the effective lateral coefficient and vehicle width which would not be accounted for, giving the possibility that someone using the model would specify a far more rearwards than optimal weight balance. Braking Performance in the model is defined by the same longitudinal coefficient as acceleration. However in testing the high speed braking performance of the car was much lower than in the model, and low speed braking performance was higher than expected from the model. In order to correctly simulate braking performances, Longitudinal tire performance should be separate for braking and acceleration, and it should be an option to specify a maximum braking acceleration (the limit of the braking system and driver).

Recommendations for simulation at Monash Motorsport.

Now that the major specifications (power,weight,width) have been decided using this model, Monash needs to start justifying the small decisions, gear ratios and shift points, wing angles for specific tracks, etc. In order to properly examine the effects of these smaller changes, there needs to be a more in depth simulation, either by expanding this current sim or by working in parallel with commercial software.

3. USING THE MODEL TO DRIVE DESIGN DECISIONS

3.1 Different Vehicle concepts

At the start of the conceptual cycle every significant concept was compared against each other to see what would happen if the “best” cars of each concept competed against each other in the initial sim. In this initial analysis effective widths, engine efficiencies and coefficients of friction were kept constant among every car, as their effect would be further analysed later. Table 3.1 shows a sample of the “extremes” of each concept, but there were other intermediate cars, twins with smaller aerodynamic packages, etc

	Weight (KG)	Power (KW)	Downforce (CL*A)	Drag (CD*A)	Simulated Skidpad time (points)	Simulated Accel. Time (points)	Simulated AutoX Time (points)	Simulated Endurance Time (points)	Simulated Economy Fuel (points)	Total simulated Points 2011 FSAE-a scoring	Total simulated Points Outdated (U.S.)scoring
Medium weight, large wings, single cylinder engine.	175	37	5.2	2.7	**4.68s (75)**	**4.33s (36.6)**	**44.9s (97.4)**	**1437s (295.6)**	**3.8L (72.7)**	**927.3**	939.5
Large wings, 4 cylinder, evolution of 2010	205	60	5.2	2.7	**4.723s (71.8)**	**4.00s (47.5)**	**44.7s (100)**	**1429s (300)**	**4.6L (40.7)**	**909.9**	936.5
2010 Monash car	215	60	4	1.9	**4.83s (64.8)**	**4.02s (46.9)**	**46.2s (84.4**	**1477s (273.6)**	**4.2L (56.0)**	**875.6**	891.9
Competitor, No wings, four cyl. Engine	190	60	0	0.7	**5.107s (48.1)**	**3.94s (50)**	**48.8s (59.8)**	**1561s (231.9)**	**3.2L (97.9)**	**837.7**	837.9
Competitor, No wings, single cyl. Engine	140	37	0	0.7	**5.107s (48.1)**	**4.12s (43.4)**	**49s (57.8)**	**1568s (228.5)**	**2.5L (125)**	**852.8**	843.1

Table 3.1: Initial concept comparison table, showing individual event performance.

The table above showed a slight (18 point) advantage to the single cylinder over the winged four cylinder car, with other concepts significantly behind. Due to the lighter car, and smaller engine package, Monash estimated that on every one of the parameters held constant (grip, width & efficiency), the single cylinder would have better performance than the 4 cylinder car, further increasing its potential lead.

After looking at resources and the timeline, the team decided to see the effects of what would happen if individual parameter targets were not met. This allowed the team to concentrate resources on increasing the performance of the parameters that gave the most advantage at competition for the resources required. These point sensitivities helped develop the exact specification for every part in order.

3.2 Parameter Point Sensitivities

Due to the use of excel as an interface, there is the opportunity to display the information in a variety of different ways. As explained in 1.1 the performance metric we wish to improve is the average lead. So the majority of information in this section is shown in terms of difference of LeadAverage compared to a baseline. Below are some examples of different ways to show the same data, in this case, the effects of power and weight. The most basic of which is a data table of a large range of calculated powers and weights.

0	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53	55	57	59	61	63	65
130	-38.7	-18.3	-0.1	16.0	30.2	41.6	51.8	58.2	61.9	65.1	68.0	70.8	73.2	75.4	77.3	79.2	80.7	82.2	83.3	84.6	85.5	86.2	86.8	87.2	87.5	87.8
135	-42.7	-22.6	-4.6	10.9	25.1	36.4	46.3	52.1	55.7	58.9	61.8	64.6	66.9	69.2	71.1	73.0	74.5	76.0	77.3	78.4	79.3	80.2	80.8	81.4	81.7	81.8
140	-46.5	-26.8	-9.2	6.0	20.2	31.4	40.9	46.0	49.7	53.0	55.7	58.6	60.8	63.2	65.2	66.9	68.4	70.0	71.2	72.2	73.4	74.3	74.8	75.5	75.9	76.0
145	-50.3	-30.8	-13.8	1.3	15.2	26.5	35.8	40.4	44.1	47.2	50.0	52.8	55.0	57.4	59.1	61.1	62.6	64.3	65.4	66.6	67.4	68.4	69.2	69.7	70.0	70.5
150	-53.8	-34.7	-18.3	-3.3	10.5	21.9	30.7	35.0	38.4	41.7	44.4	47.2	49.6	51.7	53.7	55.6	57.2	58.7	59.8	61.0	62.2	63.0	63.9	64.3	64.7	65.2
155	-57.3	-38.6	-22.5	-7.7	5.9	17.4	25.6	29.7	33.1	36.2	39.1	41.7	44.1	46.3	48.2	50.0	51.8	53.0	54.4	55.5	56.9	57.6	58.4	58.9	59.6	59.7
160	-60.8	-42.5	-26.5	-12.1	1.5	12.9	20.7	24.5	28.1	31.0	33.9	36.5	38.9	41.0	42.9	44.6	46.4	47.8	49.2	50.3	51.4	52.2	53.1	53.8	54.4	54.5
165	-64.2	-46.4	-30.6	-16.2	-2.9	8.4	15.9	19.6	23.0	26.1	28.9	31.3	33.9	35.7	37.9	39.6	41.3	42.8	44.1	45.2	46.1	47.1	48.1	48.5	49.2	49.6
170	-67.4	-50.1	-34.4	-20.2	-7.1	3.8	11.2	14.7	18.2	21.2	24.0	26.5	29.0	31.0	33.0	34.7	36.3	37.7	39.2	40.2	41.1	42.3	43.3	43.8	44.5	44.9
175	-70.6	-53.7	-38.2	-24.2	-11.1	-0.5	6.3	10.1	13.6	16.6	19.2	21.8	24.0	26.2	28.0	29.9	31.6	32.9	34.5	35.5	36.6	37.5	38.3	39.0	39.6	40.2
180	-73.9	-57.2	-41.9	-28.0	-15.1	-4.7	1.8	5.6	8.9	12.0	14.7	17.1	19.4	21.6	23.5	25.3	26.9	28.3	29.5	30.9	31.7	32.9	33.7	34.4	35.0	35.4
185	-77.1	-60.5	-45.4	-31.7	-18.9	-8.8	-2.6	1.1	4.4	7.5	10.2	12.7	15.0	17.0	19.0	20.7	22.4	23.9	25.0	26.2	27.2	28.2	29.1	29.5	30.5	30.8
190	-80.3	-63.8	-48.8	-35.3	-22.6	-12.7	-7.0	-3.2	0.0	3.3	5.9	8.4	10.5	12.6	14.4	16.2	17.7	19.2	20.6	21.7	22.8	23.9	24.6	25.1	26.1	26.5
195	-83.2	-67.0	-52.2	-38.9	-26.3	-16.5	-11.1	-7.4	-4.3	-1.1	1.7	4.2	6.3	8.4	10.2	11.9	13.4	15.0	16.1	17.5	18.4	19.3	20.3	21.1	21.7	22.3
200	-86.3	-70.1	-55.5	-42.2	-29.8	-20.3	-15.1	-11.3	-8.3	-5.2	-2.4	0.0	2.3	4.3	6.0	7.9	9.3	10.9	11.9	13.3	14.3	15.2	16.1	17.0	17.5	18.0
205	-89.1	-73.2	-58.8	-45.6	-33.3	-24.0	-18.9	-15.4	-12.3	-9.4	-6.7	-4.1	-1.7	0.1	2.0	3.7	5.1	6.6	7.9	9.0	10.2	11.0	11.9	12.7	13.4	13.9
210	-91.9	-76.2	-61.9	-48.9	-36.8	-27.6	-22.8	-19.3	-16.2	-13.3	-10.6	-8.1	-6.0	-3.8	-2.0	-0.3	1.2	2.6	3.9	5.0	6.2	6.8	7.9	8.6	9.5	9.8
215	-94.7	-79.1	-65.1	-52.1	-40.1	-31.0	-26.5	-23.0	-20.0	-17.1	-14.5	-12.0	-9.8	-7.8	-5.9	-4.2	-2.8	-1.2	-0.1	1.1	2.1	2.8	3.7	4.7	5.2	5.9
220	-97.4	-82.0	-68.1	-55.2	-43.4	-34.5	-30.0	-26.6	-23.7	-20.9	-18.3	-16.0	-13.6	-11.6	-9.7	-7.9	-6.5	-5.2	-3.9	-2.7	-1.8	-0.9	-0.1	0.9	1.4	1.8
225	-100.0	-84.7	-70.9	-58.2	-46.5	-37.8	-33.3	-30.1	-27.2	-24.5	-22.0	-19.6	-17.4	-15.5	-13.6	-11.9	-10.2	-8.9	-7.6	-6.6	-5.5	-4.7	-3.8	-2.9	-2.4	-1.8
230	-102.5	-87.5	-73.8	-61.2	-49.5	-40.9	-36.7	-33.6	-30.5	-27.8	-25.5	-23.1	-21.1	-19.2	-17.2	-15.5	-13.8	-12.7	-11.4	-10.3	-9.4	-8.4	-7.4	-6.7	-6.0	-5.5
235	-105.0	-90.1	-76.6	-64.1	-52.6	-44.0	-40.0	-36.9	-33.9	-31.4	-29.0	-26.7	-24.7	-22.8	-20.9	-19.3	-17.5	-16.3	-14.9	-13.9	-12.9	-11.7	-11.0	-10.4	-9.9	-9.1
240	-107.4	-92.7	-79.2	-66.9	-55.5	-47.0	-43.1	-40.1	-37.2	-34.6	-32.3	-30.1	-28.0	-26.1	-24.4	-22.8	-21.3	-19.9	-18.6	-17.3	-16.5	-15.1	-14.5	-14.0	-13.1	-12.4
245	-109.7	-95.2	-81.9	-69.6	-58.4	-50.1	-46.2	-43.2	-40.5	-37.8	-35.5	-33.4	-31.4	-29.6	-27.8	-26.2	-24.6	-23.2	-22.0	-20.7	-19.8	-18.6	-18.1	-17.5	-16.5	-16.1
250	-112.0	-97.7	-84.4	-72.3	-61.2	-52.9	-49.1	-46.3	-43.5	-40.9	-38.7	-36.5	-34.6	-32.7	-31.1	-29.6	-28.0	-26.7	-25.4	-24.2	-23.3	-22.3	-21.3	-20.9	-19.8	-19.3

Table 3.2: Power & Mass point deltas.

The amount of information shown in the data tables can be confusing and often hard to interpret, yet by making extra plots the sensitivities can be shown in clearer ways. In order to see the effect of weight on points, as well as the difference between a single cylinder and 4 cylinder car, then 2 columns of data extracted from the data table can give clearer results, as seen below.

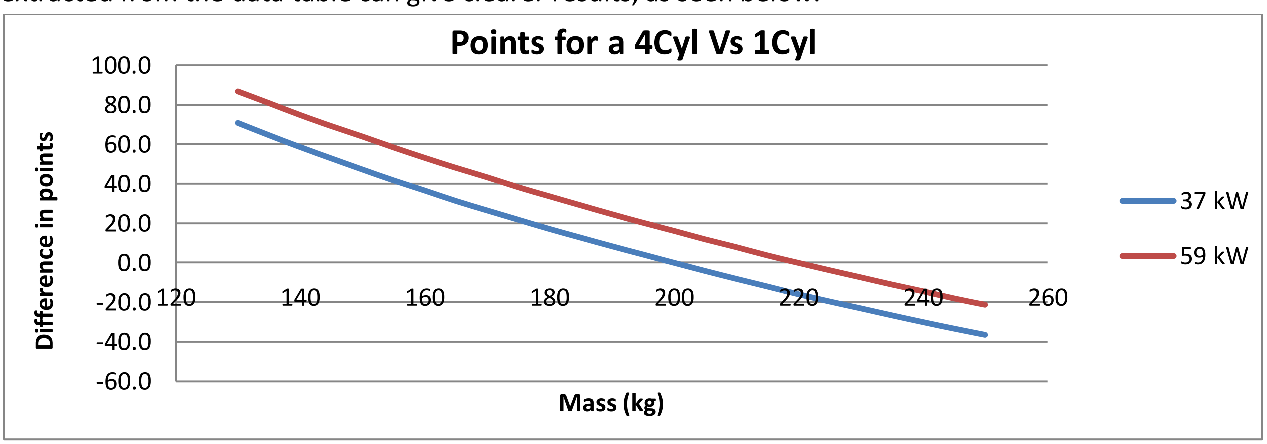


Figure 3.3: Power & Mass point deltas.

The above graph makes it clearer to see that a 37kw car will score approximately 17 points less than an otherwise equal 59kW car. However if the 37kW car was 20kg lighter than the 59kW car, then they will be very evenly matched. Interestingly, the point sensitivity does not seem to change noticeably between the 2 power levels, indicating that the gains and losses for a single cylinder are independent of the original vehicles weight.

Another useful way to display the information is the relative sensitivity of each parameter. Figure 3.4 shows a bar graph of the relative importance of each parameter, by varying each parameter by 10%, and observing it's effect on DeltaLead.

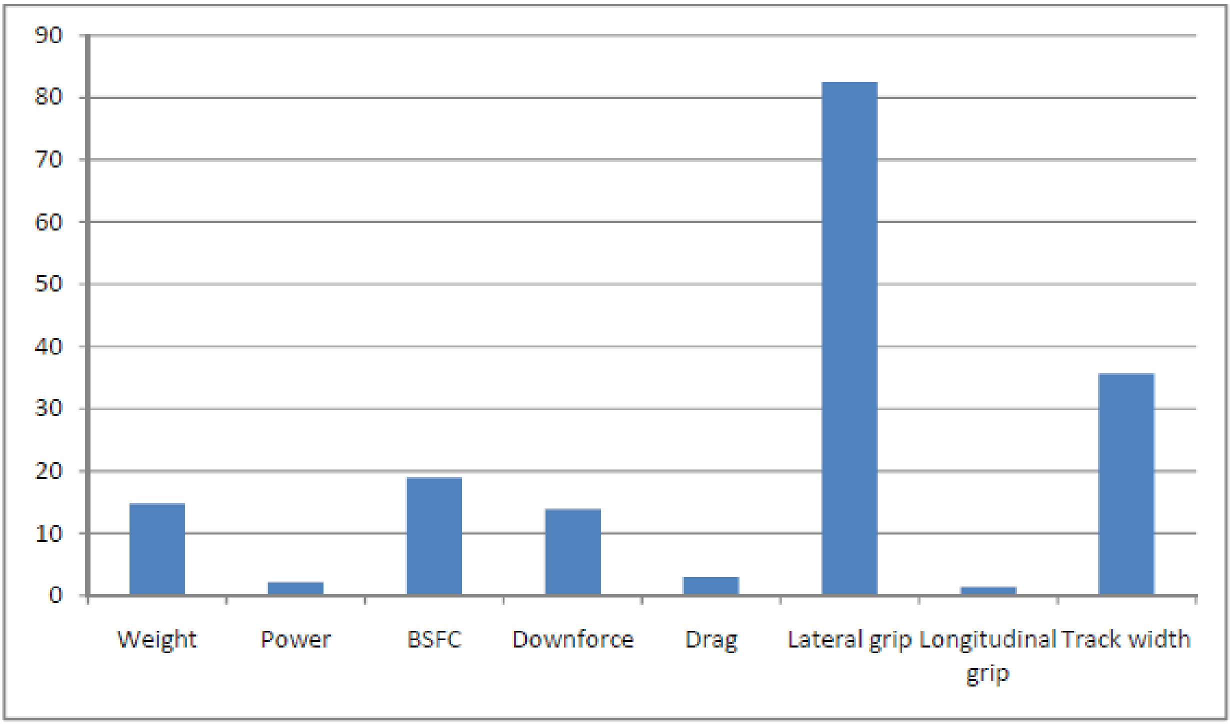


Figure 3.4: Relative point sensitivity for a 10% change in each parameter. (Mapson, 2012)

3.3 Validating the advantage of specific parts and subsystems

The model can be used for proving whether a project or part is a worthwhile investment of funds.

In the majority of cases, the advantage of a part can be defined by existing parameters. For example the pneumatic gear shifter in 2009 was an object of significant debate. The advantage of the shifter was decreased shifting time, allowing effective power to be much closer to maximum power. If this model existed then, the slight increase in power, and efficiency could have been entered into the simulation to see the slight points advantage (approximately 2 points).

A system currently up for debate is a Drag Reduction System (DRS). This required adding additional information into the calculation of straight line speed. (2.7) shows how the acceleration at a given time is the minimum of the grip limited and power limited acceleration. To calculate when was the lowest safe speed to open the flaps for DRS, the complete Acceleration/Velocity curves needed to be calculated for regular and DRS modes. Then the maximum curve can be found. The maximum acceleration for a car with will be grip limited acceleration at the beginning, until the tires overcome the engine power, the flaps can be opened to reduce drag, but for a brief moment the acceleration will be grip limited again due to the lower level of downforce, finally the car will follow the power limited curves for activated DRS.

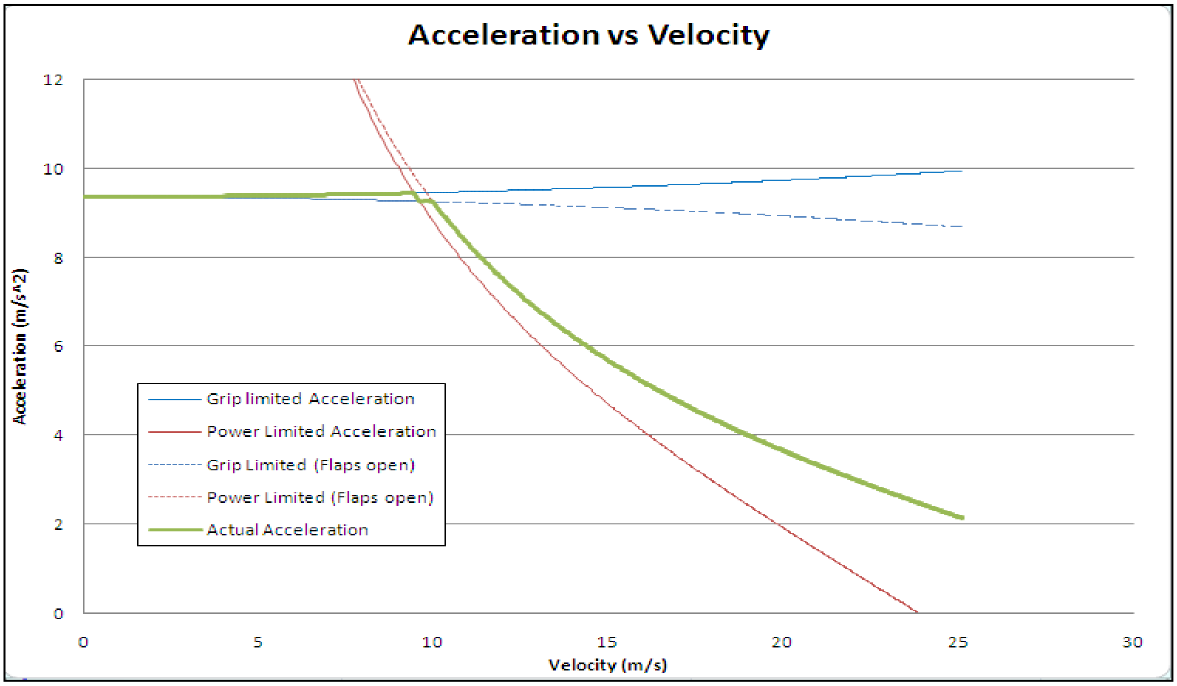


Figure 3.5: Different stages of DRS acceleration

On the medium speed track used in the sim, DRS showed to be a small advantage (9 points over the competition). However as the team was heading to Europe, with much faster tracks, It was decided to do some more specific calculations. Using straight lengths, corner exit and corner entry speeds from data measured at FSUK 2010 a mock up sim of only the replica straights was made (Webb, 2012). The speed and fuel difference on the calculated straights was considered using FSUK 2010 lap times and number of laps in an endurance. Due to one significantly long straight (85 metres, much longer than the rules recommend) the points gain of DRS is much higher (18 points) but a reliable system could not be made in time.

4. Comparisons of the model and real world data

Due to the significant amount of testing undertaken by Monash Motorsport, as well as the extensive data measured on track, it is possible to see how well the predicted performances compare with the measured data. This allows the team to confirm some of the parameters used in the simulation, as well as see any shortfall between their predicted and actual performance. By using the Simulation to approximate performance parameters, it is also possible to extract information about the car from the data. Monash is also attempting a Data Swap with other top Australian teams which, using the sim, will allow them to compare cars on a parameter basis.

4.1 *Longitudinal performance and power*

4.1.1 *Acceleration Vs Velocity.*

Due to the narrow speed range of driving on the track, the only useful data in which to compare longitudinal accelerations is from the acceleration event. Shown below in figure 4.1 is a comparison between the Acceleration/velocity curve and date taken from the logging hardware at competition during Monash's fastest acceleration run. There is a significant deficit in the 35-50km/h range, this is due to the gear ratio used being slightly too high, reducing the effective power in this speed range. This shows where there will be a benefit in modeling engine torque curves and gear ratios.

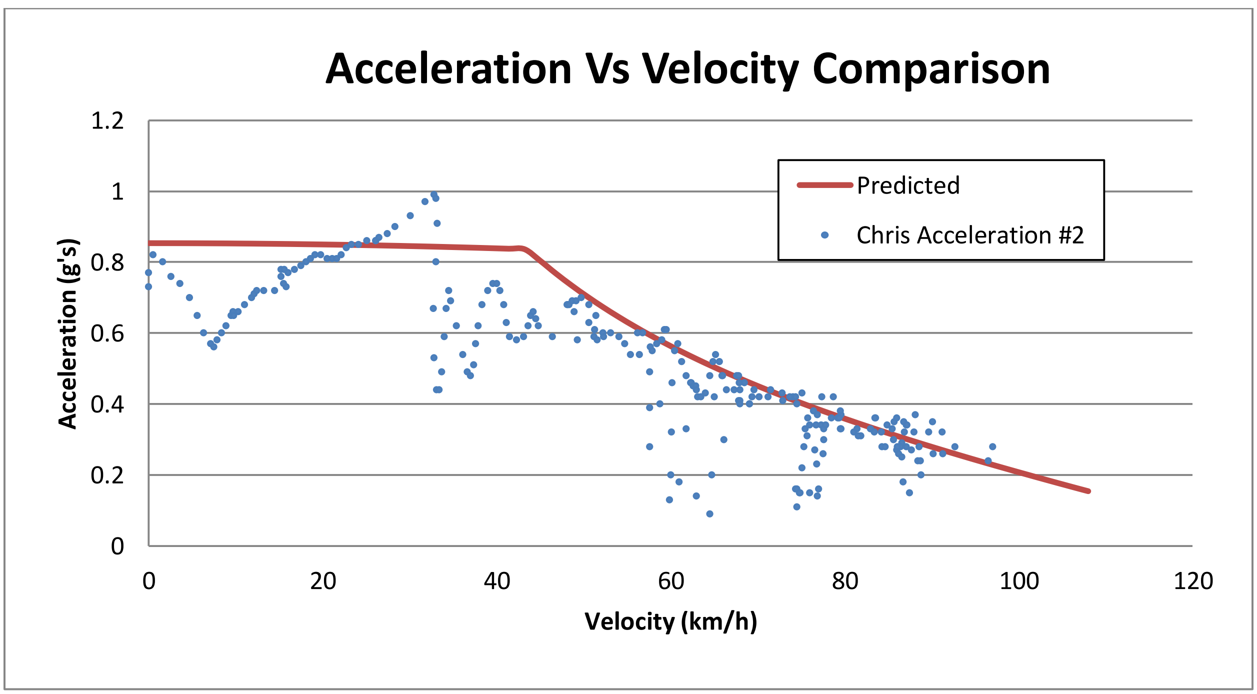


Figure 4.1: Measured Vs predicted longitudinal performance.
Estimated parameters, Cf_{long}=1.2, ClA=1, CdA=1, Power =37kw, M=210kg

4.1.2 Power, energy and Drag.

Monash was able to use a rolling road dyno on the lead up the FSAE-A competition. This allows the team to approximate the power output of the engine at each point in time based off throttle percentage and RPM. This helps validate the simulation as "Simulation power" can be estimated using the effective parameters of the model, CdA, Rolling drag, Mass and on board data for Longitudinal Acceleration and Speed. Comparison in I2 between the engine output power and the Simulation estimate power help fine tune and find errors in the model. The simulation Power was always slightly lower than the Engine Estimations (Figure 4.2) so the error was plotted against channels which may have an effect on power usage (figure 4.3). It was found that the error increase with lateral acceleration, this would be caused by the increased drag on the tires under hard cornering. In order to rectify this error in I2 the rolling drag was changed from a constant 100N to a function 200N + $250*G_{Lat}^2$. Before using the model to redesign a new vehicle it is recommended to understand and implement the effects of cornering drag on fuel usage.

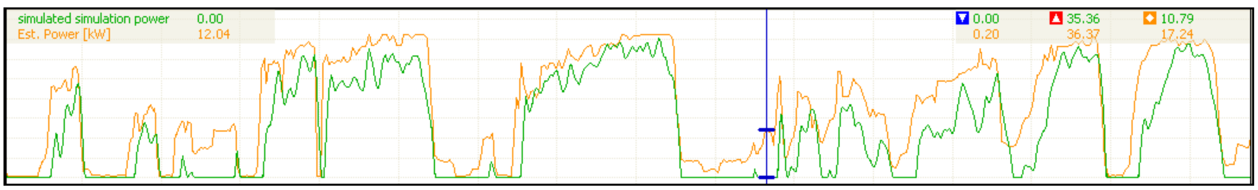


Figure 4.2: Engine power estimated from dyno data (yellow) Vs
Initial Power estimates using CdA, Rolling drag, Velocity and Acceleration (Green)

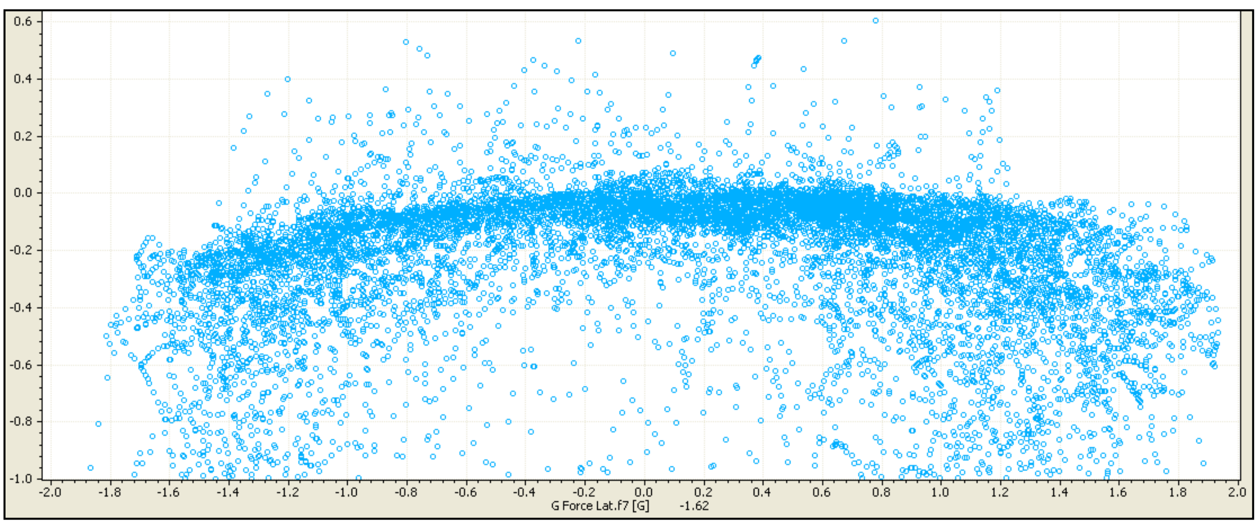


Figure 4.3: Error in initial power estimation (kW) Vs Lateral Acceleration (g)

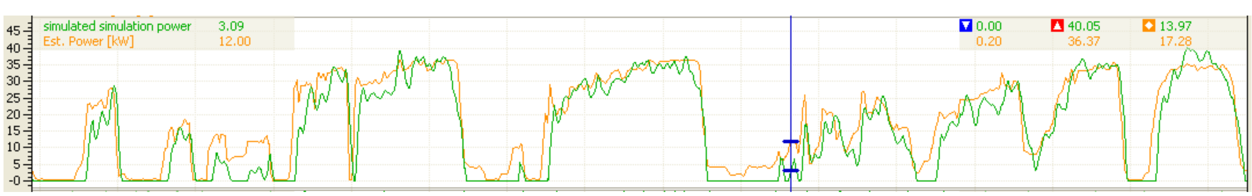


Figure 4.4: Engine power estimated from dyno data (yellow) Vs
Adjusted Power estimates using CdA, Rolling drag, Velocity and Acceleration (Green)

4.2 Lateral Performance and slaloms

In order to compare M11's lateral Performance to M10, The team conducted a thorough test day at the Australian Automotive Research Center. The cars were driven in circles of 5, 8, 12 and 20 meter radii, and also through slaloms of 6,8,10 and 12m spacing. The speeds, accelerations and corner radii were all logged on the onboard data acquisition system.

Using the data from the constant radii, effective CF_{LAT} and CLA's were calculated. The simulated data could be easily made to match the raw data.

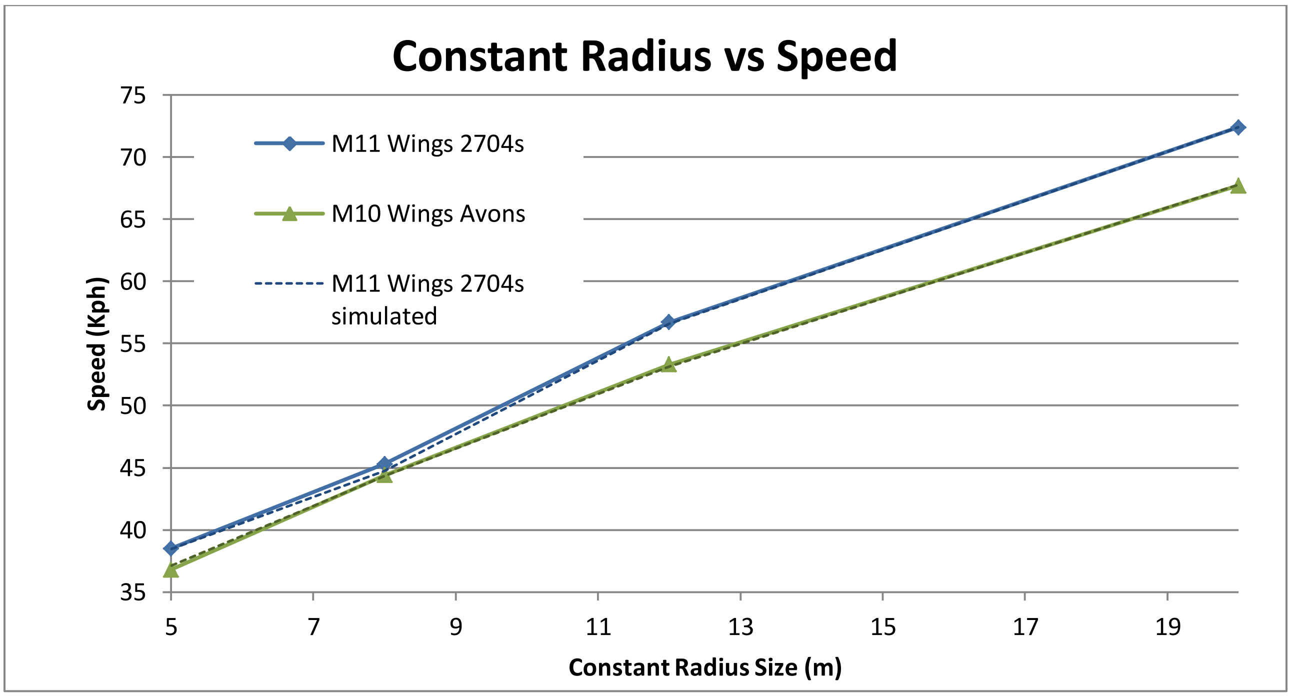


Figure 4.5: Constant radii Vs speed, predicted and actual

For the Slaloms, the measure corner radii were compared with the corner radii calculated using the vehicle width calculations. The Measured Lateral g's in the slalom was slightly higher than expected for the longer slaloms and lower than expected for the tight slaloms compared to what the corner radii and previously measured coefficients suggests. The different corner radii than expected and the difference to expected g's, as a higher g's shown (possibly caused by the offset of the G sensor from the cars cg) cause the "radius" to be tighter than simulated, however because the g's are higher than simulated the resulting speed in the slalom is very close (within 3km) to the speed estimated through slaloms using vehicle width, CLA and $CF_{lat.}$

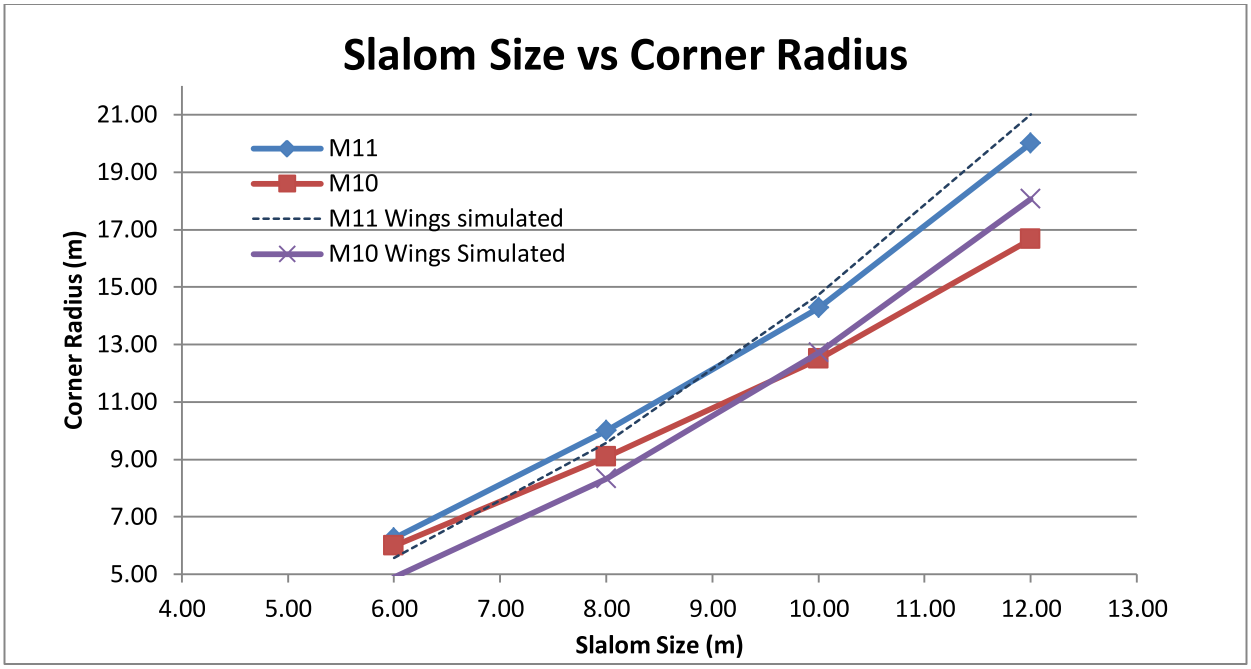


Figure 4.6: Corner Radii Vs slalom length, Measured and predicted

The lateral performance at competition is initially analysed using a Speed Vs Lateral G's plot, with the theoretical performance curve plotted over the top. Even though the initial assumption is that this would be the easiest curve to fit, the layout of the track means the car was not pushed to its limits at high speed.

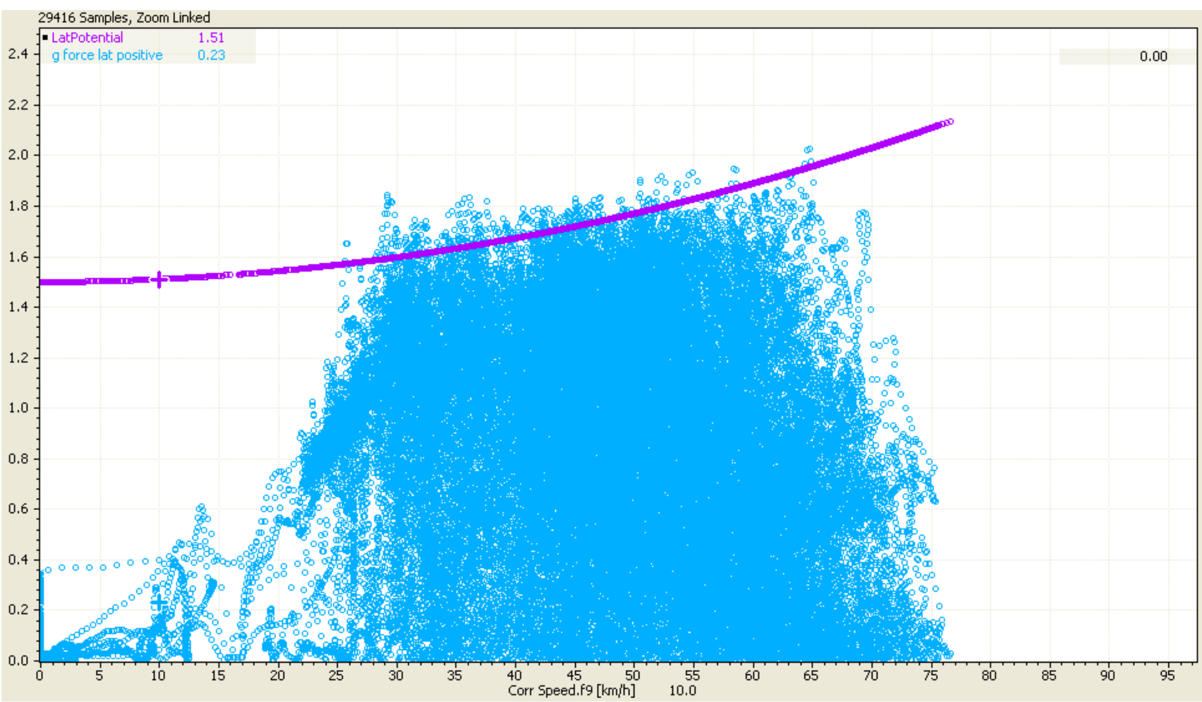


Figure 4.7: an attempt to fit a curve to a Speed vs G plot

In order to properly match up the coefficients and fit the curve, it is best to try and match the maximum speed of each corner radius rather than pure g's as the speed trace has less erratic data points at the limit (even though one is used to calculate the other..). The Inverse radius vs Speed plot is shown below with a curve showing Cf_{LAT}=1.5, CLA=4.5.

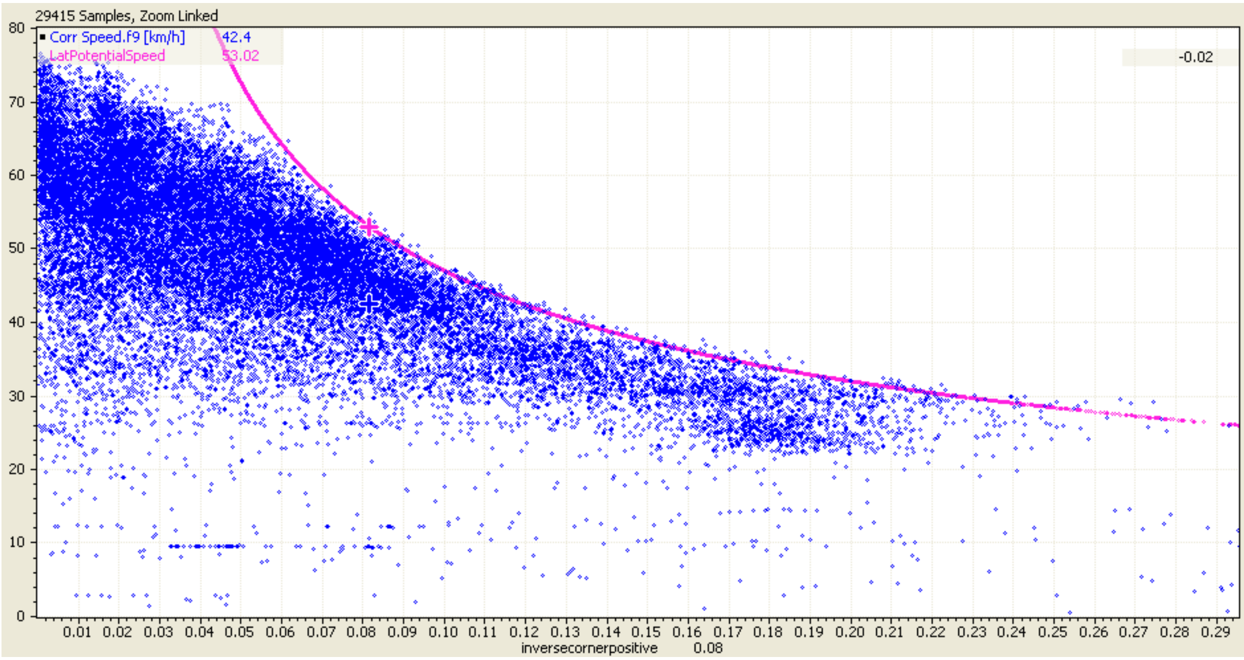


Figure 4.8: Fitting a curve to the Inverse corner radius Vs Speed plot

The raw data follows the simulated curve relatively closely until the Inverse corner radius becomes less than 0.065 (corner radius greater than 15m). The scatter plot suggests a serious error in the model if the car can not get to the correct cornering speed for any corners wider than 15m, as the cornering histogram estimated that 60% of the time the car is in a corner with a radius greater than 15m. Thankfully, this "error" appears because during turn in/exit , and particularly the transition between left and right slaloms the Instantaneous radius will be much larger than the apex which controls the speed. For example the moment when swapping between left and right slaloms, V=Slalom cornering speed, yet the radius shown is far greater than the tightest radius of the corner. The difference between calculated speed and actual speed in this case is the fact that the sim oversimplifies corners as a constant radius, so even though the Sim is at the grip limit for longer, the speeds through corners are the same.

See the data traces (4.9) below of the car traveling through slaloms at competition in 2011. Note how the car follows a near constant speed (as it would in the model). However due to the corner radius increasing and reaching infinity for the change between left and right slaloms (which does not happen in the model) then the predicted maximum possible speed through the "corner" also increases to infinity.

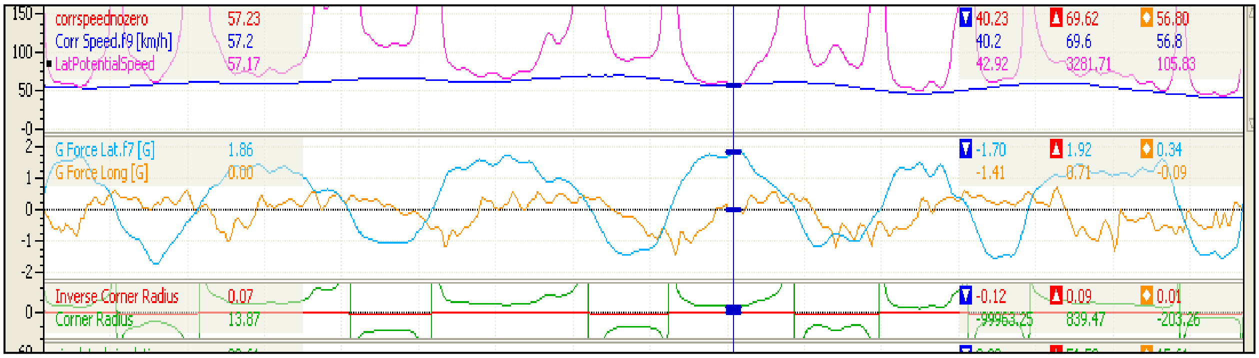


Figure 4.9: Speeds, maximum potential speed and corner radius

Overall the lateral performance of M11 when compared to the model shows a very strong correlation, allowing Monash to trust their sim and believe their very impressive cornering parameters extracted from the data of Cf_{LAT}=1.5, ClA= 4.5.

As a comparison, using the same method on the data from the 2010 Formula SAE competition, the suitable cornering coefficients to fit the curve are Cf_{lat}=1.35, ClA=3.2. This makes it very clear that, in terms of lateral performance, Monash have improved very significantly over their previous car. Shown below is a plot of inverse corner radius vs speed, with the approximation for 2010(red) and the approximation for 2011 (pink). This shows that the 2011 car can go over 10% faster through corners.

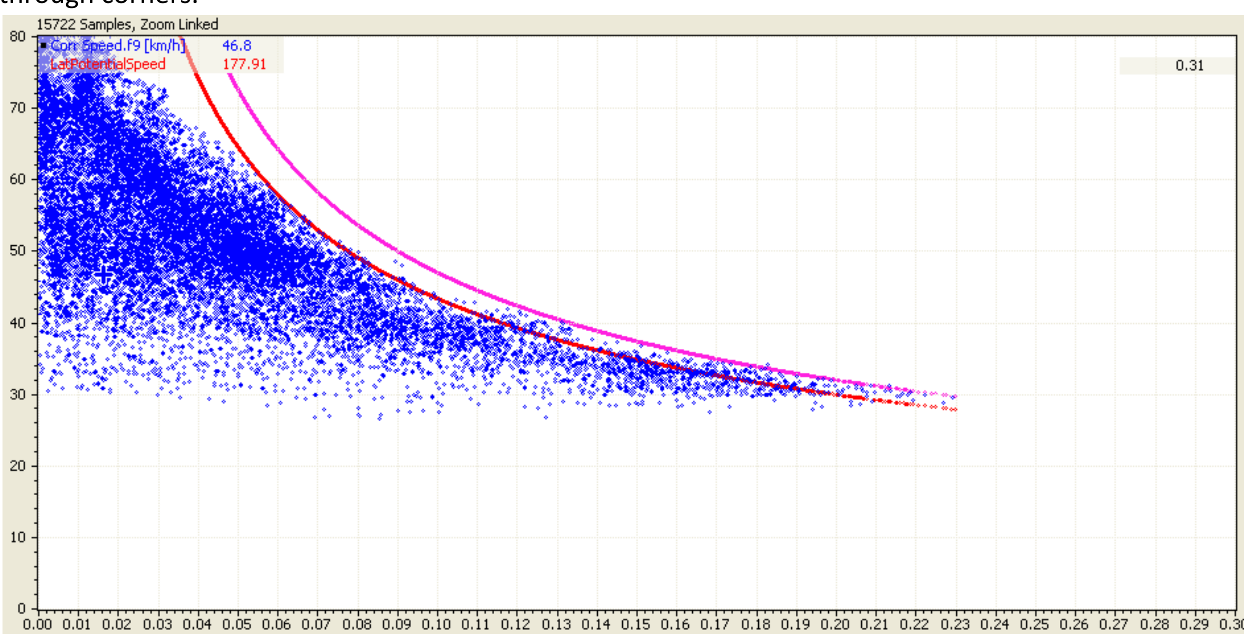


Figure 4.10: Fitting a curve to the Inverse corner radius Vs Speed plot of 2010 (red) and comparing it to the 2011 curve (pink)

5. Conclusions

This new method of justification through simulation has already proved successful in Monash Motorsport's 2011 season. It allowed them to make a big step forward to build a truly unique car, already armed with the knowledge of what to expect in terms of performance. Conservative assumption was made along the way and the new car has exceeded expectations.

6. Acknowledgements

Special thanks to Scott Wordley, the entire 2011 Monash Motorsport team, especially the management team, for giving me a year of their life to create one of the most impressive vehicles ever in an even more impressive time frame, Monash Motorsport Alumni for teaching me what I know and creating the framework of the team, and the greater FSAE community for making it all worthwhile.

7. References

Bailey, S. (2003, July 30). *2003 Formula SAE Competition - Racing*. Retrieved May 22, 2012, from Rod and Track: http://www.roadandtrack.com/racing/motorsports/2003-formula-sae-competition

Bansal, G. (2007, November 30). *RMIT FSAE 2008*. Retrieved May 22, 2012, from Fickr: http://www.flickr.com/photos/29498210@N04/3640144549/in/photostream/

FSAE. (2011). *FSAE Rules and important documents 2012*. Retrieved May 22, 2012, from SAE: http://students.sae.org/competitions/formulaseries/rules/

Mapson, A. (2011). *Design, manufacture and testing for a Formula SAE Car.* Monash University.

Saabman, C. (2006, june 12). *Cumberland Motor Club - Formula SAE*. Retrieved May 22, 2012, from Cumberland Motor Club: http://skism.org/cmc/viewtopic.php?f=1&t=257

Smith, C. (1978). *Tune to win.* Aero Publishers.

Trevorrow, N. (2006). *A Theoretical model and Experimental investigation of racing slick tyre performance and behaviour.* Monash University.

Webb, S. (2012). *DRS Vaidation Report.* Monash Motorsport.

Appendices

Below are screenshots of every significant step in the model.

Car Parameters, this is where the majority of car inputs and outputs are controlled

Car Parameters

Description	M11	M10/ECU		uwa	single		
Car mass	195	205	225	190	140	kg	
Driver mass	80	80	80	80	80	kg	
Toal car mass	275	285	305	270	220	kg	
cg height	0.33	0.33	0.33	0.3	0.28	m	cg of car with driver
Wheelbase	1.53	1.53	1.55	1.53	1.53	m	
Average track width	1.175	1.175	1.2	1.1	1.1	m	Average of front and rear track widths
Limiting cornering width	1.9	2	2	1.9	1.9	m	distance between cg and cone *2
Lateral coefficient	1.4	1.4	1.3	1.4	1.4		Coefficient of friction of the tyres
Longitudinal coefficient(accel)	1.3	1.3	1.2	1.32	1.2		Coefficient of friction of the tyres
Pass tilt?	PASS	PASS	PASS	PASS	PASS		
Track errors	GOOD	GOOD	GOOD	GOOD	GOOD		
Vehicle Power	36	62	62	62	36	kw	
	48.27678691	83.14335524	83.14335524	83.14335524	48.2767869	hp	
Power efficiency	75	75	75	75	75	%	used in conversion to average power/torque
Average power	27	46.5	46.5	46.5	27	kw	
Thermal efficiency	17	17	17	17	17	%	
Fuel energy	33000	33000	33000	33000	33000	kj/L	
Rolling drag	100	100	100	100	100	N	
Frontal Area	1	1	1	1	1	m^2	
Autocross Downforce Coeff	5	5	4	0	0		
Autocross Drag Coeff	2.95	2.959183673	1.9	0.67	0.67		
Endurance Downforce Coeff	5	5	4	0	0		endurance and autocross use the same config for car 1
Endurance Drag Coeff	2.95	2.959183673	1.9	0.67	0.67		
DRS downforce	5	5	4	0	0		drs only in car 1
DRS drag	2.95	2.959183673	1.9	0.67	0.67		
drs sector 1 (tight)	NO						
drs secttor 2 (medium)	NO						
drs sector 3 (fast)	YES						
drs sector 4 (fast w straights)	YES						
DRS Accel	NO						
ACC Downforce Coeff	0	0	0.8	0	0		Wings adjusted for acceleration event
ACC Drag Coeff	1	1	1.05	0.67	0.67		Wings adjusted for acceleration event
SP Downforce coeff	5	5	4	0	0		Wings adjusted for skidpad event
endurance speed limiter	2000					km/h	
Max Speed Autocross	97.60185172	116.8703877	135.4702478	191.7506558	159.970706	km/h	autocross setup
Max Speed Accelertion	139.9798088	167.7883457	165.0816087	191.7506558	159.970706	km/h	Acceleration setup
TOTAL SCORE	**938.3714374**	**931.6513**	**842.27812**	**857.94519**	**867.5263**	**points**	
				-80.4262491	-64.125008		
Downforce at 60 km/h (autocr	86.80555556	86.80555556	69.44444444	0	0	kg	
drag at 60km/h (autocross)	51.21527778	51.37471655	32.98611111	11.63194444	11.6319444	kg	
Ref Speed	80	80	80	80	80	km/h	change to any speed to find downforce
df autocross	154.3209877	154.3209877	123.4567901	0	0	kg	
Lead average	63.52121296	55.12103854	-56.5954316	-37.0115984	-25.035221	Points	How much this car is ahead of the average competitor
Lead max						Points	how much this car is ahead/behind of the highest scoring competitor
Baseline Lead Average	47.97652639	47.82464394	-26.9908758	-32.0044045	-36.80589	Points	**CTRL-SHIFT-P to reset these vaues for a new baseline**
DELTALEAD	**15.54468656**	**7.2963946**	**-29.60456**	**-5.007194**	**11.77067**	**Points**	How many points gained/lost from the baseline
Scoring	AUS 2010	AUS 2011	AUS 2010				

Track parameters, this is where the user can change the makeup of the track, as described in 2.2

Track parameters								
	average speed		calculated length		Desired sector length		avg time	
Sector 1 (tight)	10.16812552	m/s	91.93849	m	0	m	0	s
	36.60525187	km/h						
	average speed		calculated length		Desired sector length		avg time	
Sector 2 (medium)	13.61887622	m/s	82.44956	m	200	m	14.6855	s
	49.02795438	km/h						
	average speed		calculated length		Desired sector length		avg time	
Sector 3 (fast corners)	17.2375364	m/s	116.1619	m	190	m	11.02246	s
	62.05513105	km/h						
	average speed		calculated length		Desired sector length		avg time	
Sector 4 (straights)	18.83429665	m/s	151.836	m	150	m	7.964194	s
	67.80346792	km/h						
	average speed				Track length		avg time	
TOTAL	16.03699166	m/s			540	m	33.67215	s
	57.73316999	km/h						
endurance length	22	km			40	laps	21.6	km
Fuel Vmax					5.616	litres		

Overall Score. This is simply where the scores for each event are displayed and totalled

OVERALL SCORE						
	M11	M10/ECU	0	uwa	single	
Static event scores	350	350	350	350	350	points
Skidpad	75	56.56370522	73.30410885	52.74275358	52.74275358	points
Acceleration	32.87543613	32.93620879	46.60431523	50	38.27758214	points
Autocross points	100	71.3056881	87.85624837	64.52358642	59.37936679	points
Endurance points	300	251.3371319	279.4053335	239.835322	231.1112068	points
Fuel points	77.6360941	93.18838999	45.03630032	83.80407554	125	points
TOTAL SCORE	935.5115302	855.331124	882.2063063	840.9057375	856.5109094	points

Calculation of a straight section of the track

	Monash M11							
	Velocity	Acceleration(grip limited)	Acceleration(power Limited)	Braking velocity	Braking acceleration	Acceleration energy	Drag Energy	
0	13.88889	9.510115634	6.482234461	15.3631438	14.89244049	187.9847994	21.81520062	1
0.1	13.93548	9.511257166	6.456460395	17.12888485	15.3286694	187.2373515	21.89460799	1
0.2	13.98174	9.51239416	6.431016977	17.03929627	15.30539464	186.4994923	21.97369963	1
0.3	14.02766	9.513526673	6.405896475	16.94937126	15.28215523	185.7709978	22.05247959	1
0.4	14.07325	9.514654762	6.381091414	16.85910425	15.2589511	185.051651	22.13095182	1
0.5	14.11852	9.515778482	6.356594568	16.76848948	15.2357822	184.3412425	22.20912019	1
0.6	14.16347	9.516897889	6.332398943	16.6775211	15.21264848	183.6395694	22.28698847	1
0.7	14.20811	9.518013035	6.308497777	16.58619305	15.18954989	182.9464355	22.36456036	1
0.8	14.25244	9.519123972	6.28488452	16.49449916	15.16648637	182.2616511	22.44183946	1
0.9	14.29647	9.520230751	6.261552834	16.40243308	15.14345787	181.5850322	22.51882929	1
1	14.3402	9.521333421	6.238496577	16.3099883	15.12046434	180.9164007	22.59553331	1
1.1	14.38364	9.52243203	6.215709801	16.21715811	15.09750572	180.2555842	22.6719549	1
1.2	14.42679	9.523526627	6.19318674	16.12393564	15.07458196	179.6024155	22.74809734	1
1.3	14.46965	9.524617258	6.170921805	16.03031385	15.051693	178.9567323	22.82396388	1
1.4	14.51224	9.525703967	6.148909576	15.93628546	15.0288388	178.3183777	22.89955767	1
1.5	14.55455	9.5267868	6.127144796	15.84184303	15.00601931	177.6871991	22.97488181	1
1.6	14.59658	9.527865801	6.105622365	15.74697887	14.98323446	177.0630486	23.04993934	1
1.7	14.63835	9.528941011	6.084337332	15.65168511	14.9604842	176.4457826	23.12473321	1
1.8	14.67986	9.530012473	6.063284892	15.55595362	14.93776849	175.8352619	23.19926634	1
1.9	14.7211	9.531080228	6.042460378	15.45977605	14.91508727	175.231351	23.27354158	1
2	14.76209	9.532144315	6.021859258	15.3631438	14.89244049	174.6339185	23.34756172	1
2.1	14.80283	9.533204774	6.001477129	15.26604801	14.8698281	174.0428367	23.4213295	1
2.2	14.84332	9.534261644	5.981309711	15.16847955	14.84725004	173.4579816	23.4948476	1
2.3	14.88356	9.535314963	5.961352846	15.07042901	14.82470626	172.8792325	23.56811864	1
2.4	14.92356	9.536364767	5.941602489	14.9718867	14.80219672	172.3064722	23.64114521	1
2.5	14.96332	9.537411093	5.922054707	14.8728426	14.77972135	0	0	0
2.6	14.87284	9.535034207	5.96665842	14.7732864	14.7572801	0	0	0
2.7	14.77329	9.532435425	6.016249397	14.67320743	14.73487293	0	0	0
2.8	14.67321	9.529840589	6.066651566	14.5725947	14.71249979	0	0	0
2.9	14.57259	9.527249694	6.117891562	14.47143684	14.69016061	0	0	0
3	14.47144	9.524662732	6.169997248	14.3697221	14.66785536	0	0	0
3.1	14.36972	9.522079698	6.222997789	14.26743833	14.64558397	0	0	0
3.2	14.26744	9.519500587	6.276923729	14.16457296	14.6233464	0	0	0
3.3	14.16457	9.516925391	6.331807081	14.06111299	14.60114259	0	0	0
3.4	14.06111	9.514354105	6.387681414	13.95704496	14.5789725	0	0	0
3.5	13.95704	9.511786724	6.444581956	13.85235492	14.55683607	0	0	0
3.6	13.85235	9.509223241	6.502545698	13.74702842	14.53473325	0	0	0
3.7	13.74703	9.50666365	6.561611511	13.64105045	14.51266399	0	0	0
3.8	13.64105	9.504107946	6.62182027	13.53440548	14.49062824	0	0	0
3.9	13.53441	9.501556122	6.683214989	13.42707737	14.46862595	0	0	0
4	13.42708	9.499008173	6.745840968	13.31904934	14.44665707	0	0	0
	Average S	14.33738616	m/s					
		51.61459016	km/h					
	Time	0.278990881	s					
	Energy	5.063473567	kj					

Calculation of a corner/slalom on the track

	Part 2-Slaloms					
	slalom size	9	m			
	1/2 slalom size	4.5				
	Number of cones	4	cones			
	Number of slalom	3	slaloms			
	part length	27	m			
				M11		
	Corner Radius		m	11.13289474	m	Corner Radius
	corner length		m	9.265068281	m	corner length
	part length		m	27.79520484	m	part length
	Vehicle speed		m/s	13.57647943	m/s	Cornering speed potential
				13.57647943		cornering speed Conservative
	Vehicle Speed		km/h	48.87532595	km/h	
				1.689429812	g	
28.149556	"average" speed		m/s	13.18806415	m/s	"average" speed
55.149556				13.18806415		
				47.47703095	km/h	
	Time			2.047305782	s	Time
	Energy		kj	9.99687669	kj	Energy

Skidpad Calculations

Skidpad calcs						
Track Diameter	17.5	17.5	17.5	17.5	17.5	m
Track Distance	54.97787144	54.97787144	54.97787144	54.97787144	54.97787144	m
	M11	Monash M11	Edith cowan	uwa	single	
Speed no aero	10.962	10.962	10.962	10.962	10.962	
Speed	11.780	11.107	11.720	10.962	10.962	m/s
time no aero	5.015	5.015	5.015	5.015	5.015	
Time	4.667	4.950	4.691	5.015	5.015	s
SCORE	75.0	56.6	73.3	52.7	52.7	points
km/h	42.40745256	39.98501136	42.19042965	39.4643586	39.4643586	
Lat G's	1.617	1.437	1.600	1.400	1.400	
Speed	42.40745256	39.98501136	42.19042965	39.4643586	39.4643586	

Endurance and economy calculation.

Endurance						
	M11	monash 11	Edith cowan	uwa	single	
Sector 1 time	0	0	0	0	0	s
Sector 1 energy	0	0	0	0	0	kj
Sector 2 time	13.93864714	14.74978277	14.42981969	15.17098536	15.21720486	s
Sector 2 energy	140.034532	113.9672375	171.6370603	116.2885551	92.34445774	kj
Sector 3 time	10.37204189	11.15973542	10.69788329	11.43033346	11.53505109	s
Sector 3 energy	157.7959311	131.5599866	203.7504131	144.2356546	107.9526613	kj
Sector 4 time	7.706117828	8.165743814	7.715793033	7.999744074	8.25857656	s
Sector 4 energy	157.410563	143.1258384	219.4312649	168.308283	119.7442597	kj
lap time	32.01680686	34.07526201	32.84349602	34.60106289	35.01083	s
Lap energy	455.241026	388.6530625	594.8187383	428.8324928	320.0414	kj
average speed	16.86614166	15.8472736	16.44161144	15.60645699	15.4238	
% power limited	17.02266651	16.64174259	13.38970484	2.473654982	8.415703	
Vmax	87.48936797	86.59296074	93.84182412	98.54860518	90.68765	KM/h
Endurance cones	0	0	0	0	0	cones
Total endurance time	1280.672274	1363.01048	1313.739841	1384.042516	1400.433	seconds
	21.3445379	22.71684134	21.89566401	23.06737526	23.34056	minutes
Endurance points	300	251.3371319	279.7237161	239.835322	231.1112	points
Total energy	18209.64104	15546.1225	23792.74953	17153.29971	12801.66	kj
fuel burnt	3.245925319	2.77114483	4.241131824	3.057629182	2.281935	L
fuel spilled	0	0	0	0	0	L
Total endurance Fuel	3.245925319	2.77114483	4.241131824	3.057629182	1.8	L
Fuel points	77.6360941	93.18838999	45.03630032	83.80407554	125	points