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FACULTY OF MECHANICAL ENGINEERING
INSTITUTE OF AUTOMOTIVE ENGINEERING

VÝVOJ ZAVĚŠENÍ KOL VOZU FORMULE STUDENT

SUSPENSION DEVELOPMENT OF FORMULA STUDENT VEHICLE

DIPLOMOVÁ PRÁCE
MASTER'S THESIS

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

Vývoj zavěšení kol vozu Formule Student

v anglickém jazyce:

Suspension Development of Formula Student Vehicle

Stručná charakteristika problematiky úkolu:

Navrhněte změny původního zavěšení vozidla D3 pro vozidlo D4. Vozidlo D4 podrobte analýze, vyhodnoťte jeho vlastnosti a navrhněte změny zavěšení pro nové vozidlo D5. Navržené změny zdůvodněte.

Cíle diplomové práce:

Cílem je návrh zavěšení vozu D4 a D5 úpravou zavěšení z vozidla D3. Za tímto účelem:
- pro vozidlo D4 proveďte konstrukční úpravy zavěšení vozu D3
- sestavte plán testů pro ověření funkce nového zavěšení vozu D4
- proveďte analýzu vlastností vozu D4
- navrhněte konstrukční změny zavěšení pro vozidlo D5

Seznam odborné literatury:

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Vedoucí diplomové práce: doc. Ing. Petr Porteš, Ph.D.

Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2014/2015.

V Brně, dne 19.11.2014

L.S.

prof. Ing. Václav Píštěk, DrSc. Ředitel ústavu	doc. Ing. Jaroslav Katolický, Ph.D. Děkan fakulty

ABSTRAKT

Tato diplomová práce je věnována vývoji a analýze zavěšení Formule Student. V úvodu je představena mezinárodní soutěž Formula Student, její disciplíny a historie týmu TU Brno Racing a UH Racing. V teoretické části je detailní popis charakteristik pneumatiky, kinematický návrh zavěšení a aerodynamiky s ohledem na závodní vozy. V části věnované konstrukčnímu návrh je popis vývoje ramen zavěšení, vahadel a zadního stabilizátoru. Návrh kinematických charakteristik vozu Dragon 5 je detailně popsán a porovnán s předešlou variantou. Mimo vývoje kinematiky Dragon 5 je popsán vývoj vozu UH 18. Závěrečná kapitola detailně analyzuje zaznamenaná data z testování vozu Dragon 4.

KLÍČOVÁ SLOVA

Formula Student, Zavěšení, Konstrukční návrh, Kinematický návrh, Analýza závodního automobile.

ABSTRACT

This diploma thesis observe suspension development of Formula Student vehicle. Introduction part presents Formula Student competition with disciplines and history of TU Brno Racing and UH Racing. In theoretical part there are tyre characteristics, suspension development and aerodynamics of racing car described. Design part of thesis introduces wishbone, rockers and rear-anti roll bar development. Development of kinematic characteristics of Dragon 5 and UH 18 are explained and compare to Dragon 4. Last chapter provides detailed analysis of Dragon 4 data from its test season.

KEYWORDS

Formula Student, Suspension, Engineering design, Kinematics, Race car data analysis

BIBLIOGRAFICKÁ CITACE

ŠTIPÁK, P. *Suspension Development of Formula Student Vehicle*. Brno: Vysoké učení technické v Brně, Fakulta strojního inženýrství, 2015. 147 s. Vedoucí diplomové práce doc. Ing. Petr Porteš, Dr..

ČESTNÉ PROHLÁŠENÍ

Prohlašuji, že tato práce je mým původním dílem, zpracoval jsem ji samostatně pod vedením doc. Ing. Petra Porteše, Dr. a s použitím literatury uvedené v seznamu.

V Brně dne 12. května 2015 ……..……..…………………………………………..

Patrik Štipák

PODĚKOVÁNÍ

V první řadě bych rád poděkoval svým rodičům za ohromnou podporu v životě a možnost studovat na vysoké škole. Dále Haně Zhánělové, která za mnou pevně stojí a je mou oporou celé studium na vysoké škole a díky ní nacházím rovnováhu mezi pracovním a osobním životem. Tým TU Brno Racing mi umožnil zažít neuvěřitelné okamžiky. Radost, znalosti a velká přátelství získaná během mezinárodních závodů Formule Student jsou chvíle, na které nikdy nezapomenu. Obrovské díky patří všem lidem, kteří tomuto projektu naplno pomáhají, především lidem přímo z průmyslu. Díky soutěži Formula Student jsem našel odvahu a motivaci ke studiu v zahraničí, kde jsem mohl rozšířit své znalosti a získat další sebevědomí do budoucího pracovního nasazení. V neposlední řadě bych rád poděkoval doc. Ing. Petru Portešovi, PhD. za vedení diplomové práce a udělení cenných rad.

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INTRODUCTION

The Formula Student project is one of the greatest opportunities for students at technical universities how to gain experience during their studies. It is an excellent way how to gain skills which are fundamental for their future employment. Modern companies need fully prepared engineers and that means not only the student is well technical educated. The team work, communication skills, ability to make a phone call and arrange a meeting with external business company, responsibility or technical documents preparation, these are only a few examples why the Formula Student produce the best next-generation engineers.

Race car engineering is a very complex term in motorsport world. There are a lot of race engineers in motorsport teams. For a single car there could be a lot of suspension engineers, engine engineers, electronics engineer, race engineers etc. All together have the only aim. To improve the car and the driver so that the final time is faster again. During the motorsport history the position of race engineers have been changing. The modern technology offers a lot of ways how to read the car‘s and the driver's behaviour. Therefore the data acquisition nowadays is the most important feature of racing car. Even in the Formula Student project there are different solutions of telemetry involved. Besides the data acquisition on which is this diploma thesis based there is an enormous amount of new innovative technologies used in Formula Student. Hence the Ross Brown once declared:

"There are only two innovative form of motorsport left. Formula 1 and Formula Student."

Formula Student is very motivated environment with the main target to educate student. Purpose of this Diploma thesis is to show the journey of learning process about suspension theory, suspension design development with modern using of the Finite Element Method, design of vehicle kinematics and using of Data Acquisition analysis to evaluate the performance of designed car.

Data logging is the great solution how to improve the car setup really quickly. In Formula Student it is also very important way how to learn drivers to drive the car properly. Data are also used for developing the next year car as well as such a knowledge are often taken into the road cars.

This diploma thesis will involve the race car engineering position from suspension point of view. While the aerodynamics have a great influence on the car behaviour there will be described not only suspension theory but even the basic aerodynamics principles.

Suspension has been studying during two years of Formula Student project at the Brno University of Technology and one year at the University of Hertfordshire thanks to the Erasmus project. It is easy to characterise the project as one circle shown in Figure 1. In fact there are two circles. The static disciplines preparation is very important part according to competitions. It naturally prepares students to writing their Master Projects or Diploma Thesis.

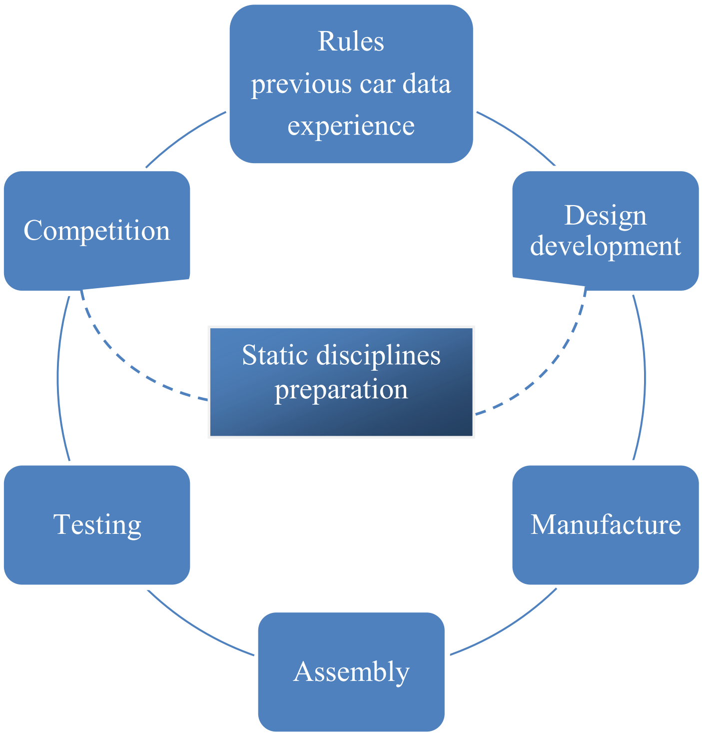


Figure 1 project circle

In this document there will be described life of the suspension during seasons 2013, 2014 and the preparation for 2015 season. The document will follow the smaller circle without the manufacturing and assembly part. For sure these are very important parts of Formula Student Project, however, this thoughts could be written in another book. The communication skills with the real world of industry, putting students hands on the real manufactured components which have been designed just a few weeks ago, these are another incredible moments in Formula Student.

Nevertheless, firstly, there will be Formula Student competition defined in detail. The main ideas meant in Formula Student rules will be offer. Secondly, the designing part of suspension will be interpret from the theory, CAD, FEM and kinematics design point of view. Last section of this diploma thesis will based on the Data Acquisition. The system and data analysis software will be shown as it helped with the data evaluating during the testing season of the car. The fourth generation of TU Brno Racing car achieved more than 500 test km before very first competition in Germany.

The conclusion will suggest some improvements which can be involved in next years by following student because as Smith (1996, p. 1-3) claims:

"There are actually two ways to learn anything – from our own mistakes or from someone else's."

1 FORMULA STUDENT COMPETITION

Formula Student Series competitions are covered with the technical regulation "Formula SAE Rules". Nowadays there are more than 550 universities all around the world involved in this competition. The purpose of the Formula Student competition is to demonstrate the design, fabrication and testing of a formula style vehicle for the non-professional, weekend, competition market. (SAE, 2015) To compare teams all around the world there is world ranking list available on-line.

Figure 1. 1 USA and Europe competition logos (eBaracus, 2014)

1.1 PROJECT TARGETS

The Formula Student competition was established in 1981 in the United States of America as Formula SAE with the aim to prepared students from technical universities for their future job positions in industry. The issue was that technical students did not have any experience with the real world of engineering environment. In that years industry leaders discussed with universities this kind or problem. Formula Student Competition seemed to be a suitable solution as the opportunity of the real race car developing, manufacturing, testing and racing was a huge motivation for students to attend. Pat Clarke – the mentor of Formula Student Germany competition - in one of his speech said that the aim of this project is primarily educative so that it could be any kind of engineering process but building some kind of refrigerator would not be attractive at all. On the other hand be part of the real motorsport world is attractive indeed. It took almost twenty years to bring the Formula SAE into Europe.

In 1996 the Formula Student project has been introduced to Europe. While using the same rules as the FSAE the aims are still the same. As the engineering world has changed radically with the computer technology involving, the education at universities followed. However the students' possibilities at technical universities remains the same from the manufacturing point of view. The idea of students are made up just for the technical drawing or the 3D CAD model nowadays.

Moreover, the engineering is not just to design some kind of part. If the designing process is done it takes a long time to have the real manufactured part assembled on the rest of final product. Here the Formula Student brings its invaluable benefit. Students are convinced to manage this whole process. The necessity of arranging a meeting with the real company, explain what he or she wants to produce it is a great experience for students' future. Although there is another inherent part of the project.

To be able to manufacture the car team have to determine the budget. It is crucial. Preparation of business plan is something very important in the real world of industry. Generally, the technical students are not prepared for such a kind of discipline. The way how to ask and persuade a company to be involved with the team, provide the team with money, products or manufacturing capability is one of the most valuable skill student can gain out of the project.

1.2 DISCIPLINES

All the required skills mentioned above are reflected in disciplines at the particular Formula Student Competition. That means not only the real racing is the part of competition. At the very beginning the car needs to be scrutinised at the technical inspection. To meet the educating element the competition is divided into dynamic and static part. The static disciplines are very important. There are 325 points available out of 1000 overall points.

The third of overall points reflecting how the team is prepared to present the car. In fact not only the car, team is expected to present its own company for producing the racing car. The deep engineering knowledge have to be presented in Design Presentation, the manufacture process is assessed in Cost Presentation and the ability to persuade the real industry is shown in Business Presentation.

The rest of 675 points are available in dynamic part of the event. There are four events where students presents how fast their car and driver are. While the human factor (the driver) is the part of the final achieved points the number of tested kilometres before competition absolutely important. The testing part of the season is presented in the Data Analysis part of this diploma thesis. The disciplines simply provide the team how to test the car. Skid pad event for suspension setup, Acceleration event where the car presents its power/weight ratio, Autocross and Endurance are the last to disciplines where the reliability and vehicle handling are demonstrated.

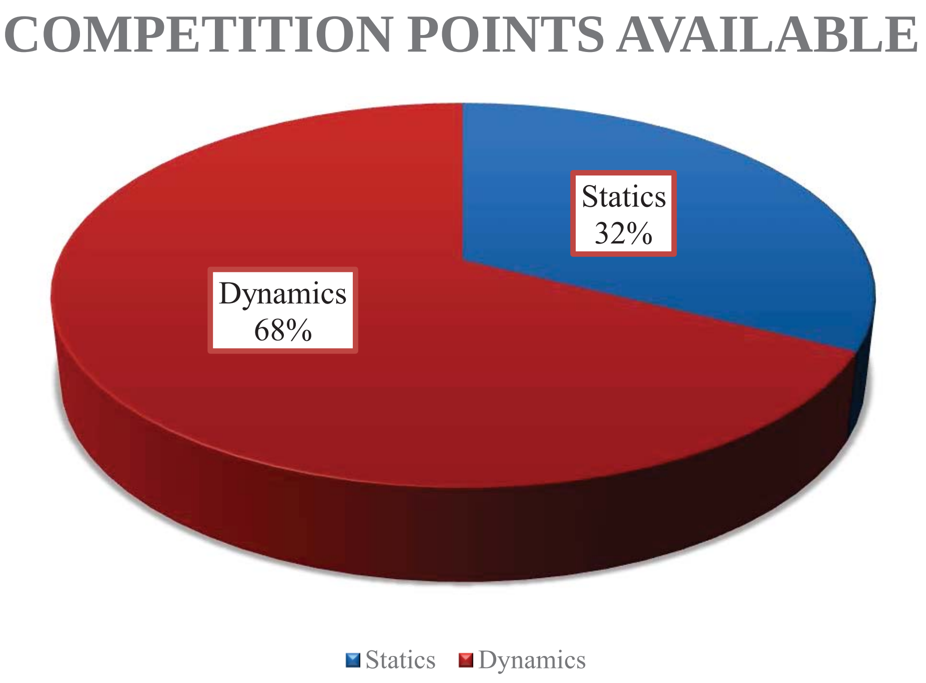


Figure 1. 2 Available points at Formula Student competition

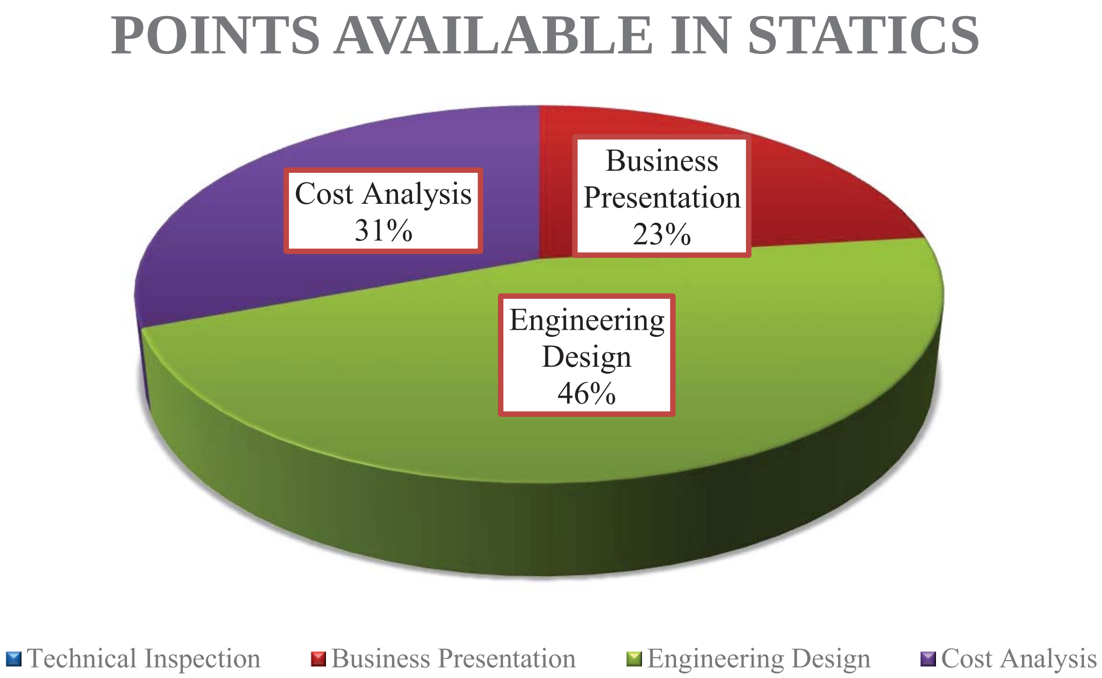


Figure 1. 3 Shows the percentage distribution of points in Static Disciplines. Note that the Technical Inspection is not part of the point's distribution. To pass the Technical Inspection is rewarded with the time saved for preparation. It can be preparation for the Static Events same as for Dynamics Events in Test Area

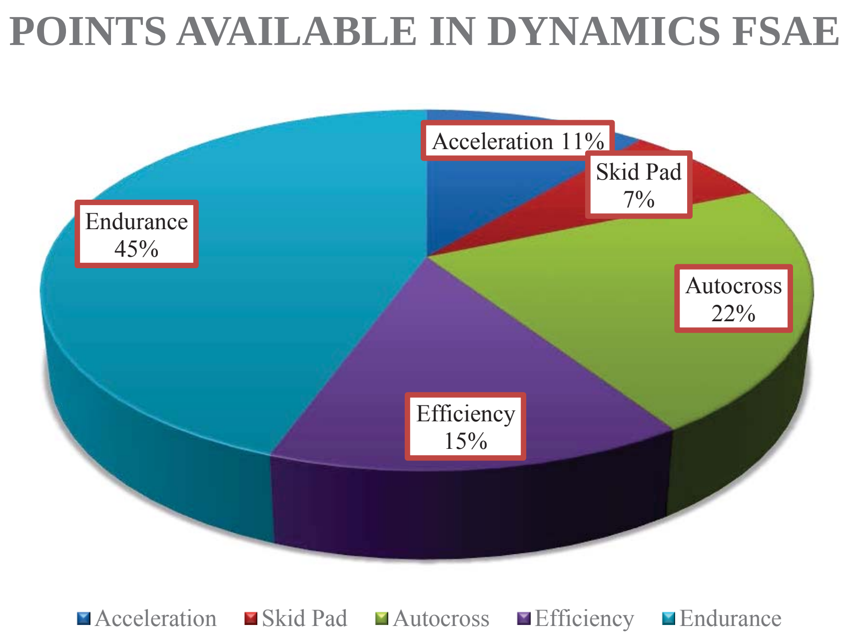


Figure 1. 4 Points distribution in Dynamics Events according to FSAE rules (SAE, 2015)

POINTS AVAILABLE IN DYNAMICS FSG

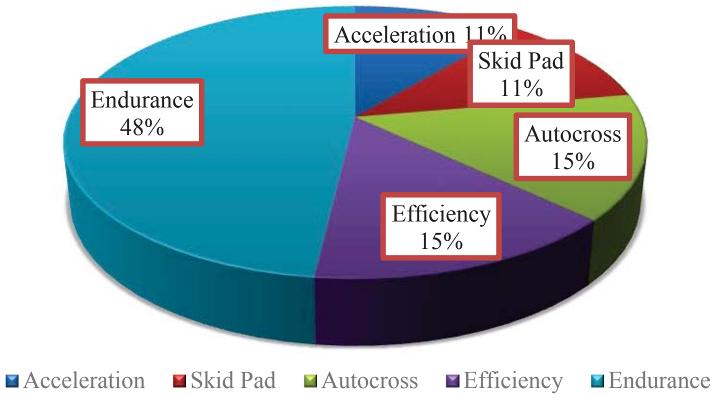


Figure 1. 5 There is difference at FSG competition in point's distribution. Skid Pad is more important against the Autocross (FSG, 2015)

1.2.1 Technical Inspection

Based on the general rules (SAE, 2015) or specific rules released by particular competition for example Formula Student Germany (FSG, 2015) the teams must to pass the Technical Inspection. There are four procedures which must be passed. At beginning the car is scrutinised by inspectors. If the car is eligible to continue the inspection there is the tilt test (Figure 7) where is the lateral acceleration of 1.6 G simulated. No liquids leaking have to be observed. After the car is weighted there is a noise test. According the new rules for 2015 season the restriction is the noise must not be above 100 dBC at engine idle and 110 dBC at all other speeds. Last part of Technical Inspection is brake test. The car have to block all four wheels at the same time and have to stay in the straight way. If the car gain all of the technical stickers (Figure 8) the team is eligible to attend the dynamic area for testing and dynamics events.

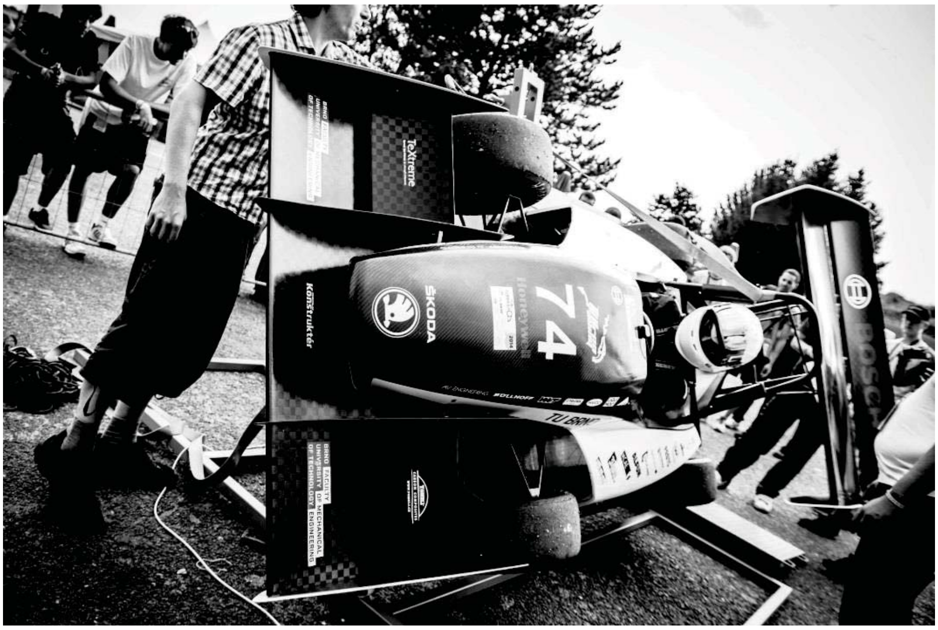


Figure 1. 6 Dragon 4 Tilt Test at Formula Student Czech Republic 2014

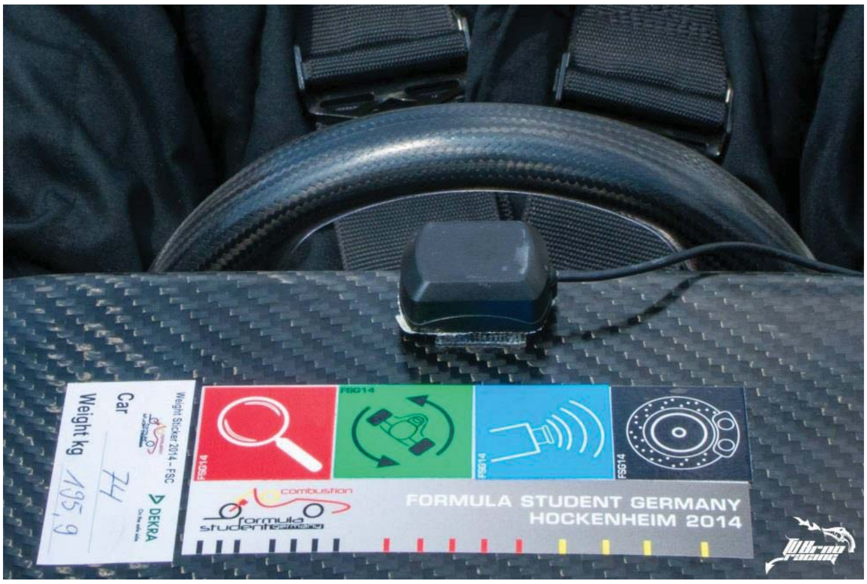


Figure 1. 7 Technical inspection stickers at Formula Student Germany

1.2.2 DESIGN PRESENTATION

Figure 5 demonstrates how important the Design Presentation is. The ability of students to present their work is crucial here. Students have chance to discuss with judges their design intend, the development challenges, manufacturing and the testing part of season. Judges are generally experienced people from industry. Thanks to that students have the best assessment what they can give.

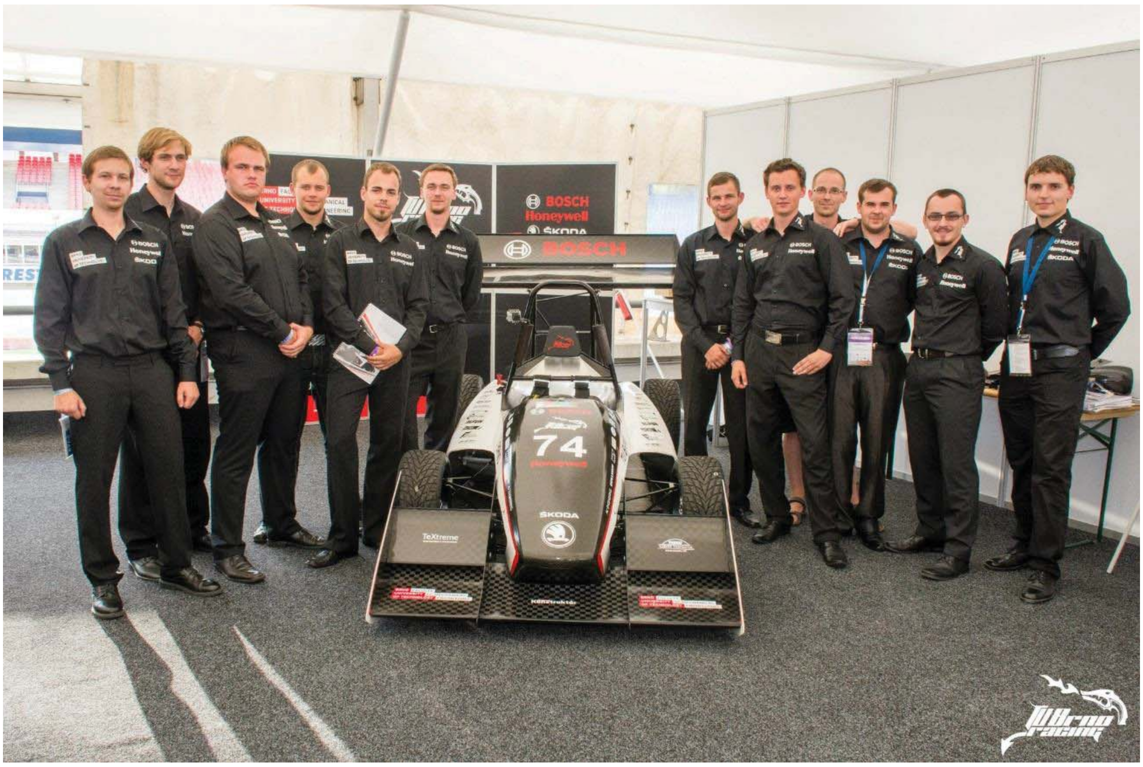


Figure 1. 8 Design Presentation members at Formula Student Germany 2014

1.2.3 Cost Presentation

In cost presentation every component of the car have to be included in the document for competition. During the presentation is required to present a few parts of the car. The part have to be searched nimbly in the documents and students have to show and vindicate that they have paid attention to every single detail of the manufacturing process. Judges nowadays asses the manufacturing approach. It is desired to look at the production of the car as a batch production of 1000 pieces.

1.2.4 Business Presentation

The aim of Business Event is to prepare students for the real industry. Therefore it is required to come with interesting idea of business plan and prepare a presentation for judges. The judges are typically employees in this specific area in industry. The target is to persuade judges as a virtual investor to involve into your company.

1.2.5 Skid Pad

Skid pad event is the first dynamic discipline at a competition. It is the first discipline which is generally run by the Formula Student teams even at the testing. Skid Pad is the best way where to start with setting up the racing car properly. According to rules competition the Skid Pad event looks like the number eight (Figure 10). The final time is the arithmetical average of second laps of each oval. The final time proves how well the suspension of particular car is set up.

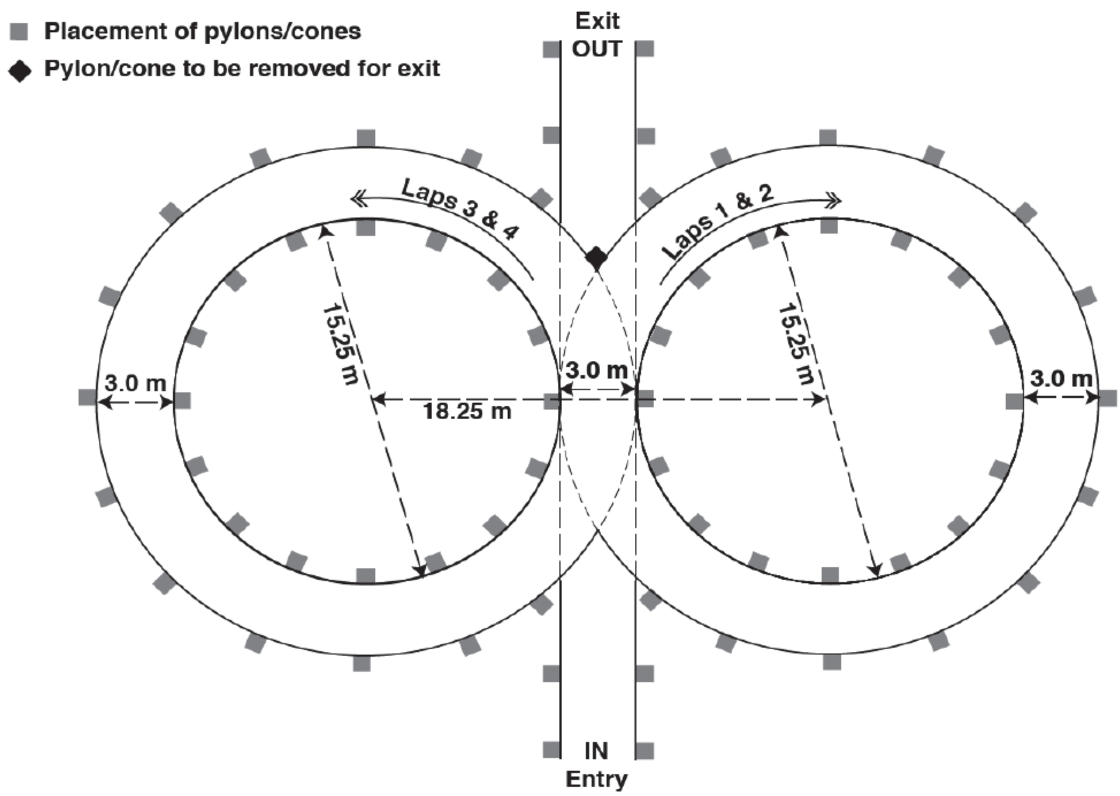


Figure 1. 9 Skid Pad layout (SAE, 2015)

At the Formula Student Germany official rules stand that the Skid Pad Events is run under the wet conditions. This should help to prevent non-equal conditions for every team and its attempt.

Figure 1. 10 wet pad at Formula Student Germany

1.2.6 ACCELERATION

In the acceleration event are points gained by the fastest car on the 75 meters distance. Even here a unique set-up can help (see Figure 12). Although mainly it is about the Newton's law

$$F = m * a \tag{1}$$

Where the *m* – mass of the car is particularly crucial as there is no weight limit in Formula Student competition. While once having the exact amount of traction power *F* of our engine, only how to improve the final time (or the *a* – acceleration in other words) is to reduce the weight of the car. That is the reason to pick up the lightest person within the team to take part in this event.

1.2.7 AUTOCROSS

The ½ mile long run on a tight course between cones is the event which evaluate the performance features of the whole car and driver. The performance characteristics shown on the track such as acceleration, braking and cornering are highly dependent on the driver. Not only here the amount of testing kilometres are demonstrated.

1.2.8 ENDURANCE

The portion of number of testing kilometres are shown mainly here in this final discipline. The 22 kilometres long run is the real pointer which proves how the team had been working during the winter season. The car's durability and reliability are evaluated here. If the car pass under the checker flag, celebrations can begin.

Last but not least important is the Fuel Efficiency. The car with least consumed amount of fuel wins. Another reason to have single cylinder engine.

Figure 1. 11 Acceleration event. Different car setup is clearly visible. Wing's flaps are in the "low drag" setup. Ride height is set up according to load transfer. Tyres have different pressure to affect the contact patch and resistance of the car.

Figure 1. 13 Autocross Event at the Formula Student Germany. Setup is changed from the acceleration to autocross. As the driver has only 2 laps to establish the time, car has to be set up according to this conditions. Biggest challenge is to heat the tyres.

Figure 1. 12 CTU CarTech car while Endurance at FSG. The reliability is crucial.

2 FORMULA STUDENT PROJECT

This part will be dedicated to the two teams the author has been member during his studies. The home university in Brno has been participating in Formula Student competition since 2010. University of Hertfordshire has the Formula Student team established in 1997 on the very beginning of the European born of this competition.

2.1 TU BRNO RACING HISTORY

First ideas about the Formula Student project came to the Brno University of Technology around the year 2000. There were first bachelor and diploma thesis dedicated to the project. It took another 10 years to establish the team TU Brno Racing. According to traditional myth of home town Brno, the first car was named Dragon. This tradition has been adhered to at every monopost. That means the every next generation of TU Brno Racing car is named Dragon 1, 2, 3…

2.1.1 DRAGON CARS SPECIFICATION

The main features of every car is the single cylinder engine, tubular space chassis out of steel tubes and unequal length double wishbone suspension layout. More details are provided in Table 1.

Table 2. 1 Dragon Cars Specifications

<table>
<tr><th></th><th>Dragon 1</th><th>Dragon 2</th><th>Dragon 3</th><th>Dragon 4</th><th>Dragon 5</th></tr>
<tr><td>Engine</td><td colspan="4">Water cooled single cylinder Husaberg FE 570</td><td>turbocharged Husqvarna FE 501</td></tr>
<tr><td>Maximum Power</td><td colspan="4">42kW at 8800 rpm</td><td>60 kW at 7000 rpm</td></tr>
<tr><td>Fuel</td><td>E85</td><td colspan="3">petrol</td><td>E85</td></tr>
<tr><td>Gearbox</td><td colspan="3">6-speed, paddles under steering wheel, electromagnetic actuated</td><td colspan="2">5 - speed, pneumatic actuated</td></tr>
<tr><td>Chassis</td><td colspan="5">space tubular, steel tubes</td></tr>
<tr><td>Suspension</td><td colspan="5">unequal length non-parallel double wishbone, on-board dampers</td></tr>
<tr><td></td><td colspan="4">pull-rod front, push-rod rear</td><td>pull rod front & rear</td></tr>
<tr><td>Brakes</td><td>Willwood</td><td colspan="4">ISR 4 piston front, ISR 2 piston rear, custom discs</td></tr>
<tr><td>Tyres</td><td colspan="3">Dry Hoosier 20.5 x 6.0-13 R25B
WET Hoosier 21.0 x 6.5-13</td><td colspan="2">Dry Hoosier 20.5 x 7.0-13 R25B
WET Hoosier 21.0 x 6.5-13</td></tr>
<tr><td>Wheels</td><td colspan="2">13” inches Kaiser – 4 bolts (Aluminium)</td><td>13” custom (Aluminium)</td><td colspan="2">13” OZ Racing Centre Lock (Magnesium)</td></tr>
</table>

Figure 2. 1 Dragon 1 after its first season. Only Formula Student UK competition was attended with this car.

Figure 2. 2 Dragon 2 took part at 3 competitions in the 2012 season. Formula Student UK, Formula Student Hungary and Formula Student Italy.

Figure 2. 3 Dragon 3 at the Formula Student Germany competition

2.2 Dragon 4 Targets

At the beginning of 4th TU Brno Racing season all team sat together and stated the main goals for that season. There were three major areas team aimed for. Weight, Reliability and portion of test kilometres before events. Everything affects everything in motorsport. With the weight reduction the car is faster, with more test kilometres the driver is faster and car has to prove its reliability a long time before the pinnacle of the season – Formula Student Germany. To finish means to be successful.

There are many more aspects the team would benefit with a huge portion of testing days. The Formula Student should be the educative environment at the very first place. When the car is built and ready to testing at least two months before first competition, team member can start to learn how to set up the car, how run the real motorsport team. Hence this diploma thesis can exists as it is based on the Setup Book prepared for exactly for competitions' static discipline – Design Presentation. Last but not least goal for the season 2014 was the number 700. This is the amount of points TU Brno Racing went to achieve at every competition.

To sum up the targets for season 2014 let start with the weight. The target weight was below 200 kilograms. The weight is crucial in motorsport and the Dragon 3 with its 226 kilograms was just fat. The goal for testing kilometres portion was above the 500. That meant to build the car before the end of May 2014. With this two assumptions the reliability should be tuned during this part of season. And of course to prepare as well as possible to all the disciplines and learn as much as possible for the future car or job after the university graduation.

Figure 2. 5 Dragon 4 before season 2014. First test day 31st of May. The missing livery shows how much composites were used to save the weight. Dragon 4 is the first winged car. Even with the wings it is 15% lighter than Dragon 3 without wings.

Figure 2. 4 Dragon 4 render. Team have improved in every way during the years. The marketing is one of the most important part of motorsport.

2.3 DRAGON 4 RESULTS

The goals which are stated for the season should motivate all team to work hard. It is necessary to think about the whole project from the psychological point of view. Always you need to believe in success! With that belief comes motivation and after that success comes as well. TU Brno Racing Team believed to finish in the top 10 at competitions. Nevertheless the target points of seven hundred should take place in top 10 overall.

First huge success is the date of the first test day. 31st of May. That meant there were two months saved only for testing, servicing and learning! Another huge success is the final weight of the car. 195.6 kilograms at the Formula Student Germany. Before the Formula Student Germany the Dragon 4 run over 500 kilometres. The details about the testing are subject of this diploma thesis and will be described in Chapter 6.

2.3.1 FORMULA STUDENT GERMANY

This competition is absolute pinnacle of Formula Student Competition in Europe. There are more than one hundred teams from all over the world. The organisation is excellent and the hosting circuit is the famous Formula 1 Hockenheimring. To be part of this race weekend is huge experience for every member of the student team!

Table 2. 2 Formula Student Germany 2014 Results

	points	out of	place
Dynamic disciplines			
Skid pad	48.8	75	**7.**
Acceleration	33.98	75	44.
Autocross	34.88	100	25.
Endurance	0	325	32.
Fuel Economy	50.91	100	21.
Static disciplines			
Design Presentation	115	150	**11.**
Cost Presentation	75	100	16.
Business Presentation	50.29	75	34.
Overall	408.86	1000	31.

It was a huge disappointment not to finish this competition. Hypothetically there would be around 280 points in the finish of Endurance which were waiting for the team. Unfortunately at the beginning of the second driver's stint the crankshaft position sensor failed at it was the end of the competition. To show the world how the Dragon 4 and the whole team was competitive, notice the 7th place in Skid Pad and the 11th place in Design Presentation.

2.3.2 FORMULA STUDENT CZECH REPUBLIC

Home competition of Formula Student is not part of the official Formula Student calendar. That means it is not counted to the world ranking. It is a good to test the car again and again. This year it was a challenge to repair the engine just in 3 days which are between the Germany and Czech Republic event. Unfortunately the engine stopped again at this competition.

Table 2. 3 Formula Student Czech Republic 2014 Results

	points	out of	place
Dynamic disciplines			
Skid pad	61.71	75	5.
Acceleration	45.53	75	12.
Autocross	66.34	100	7.
Endurance	0	325	19.
Fuel Economy	38.83	100	9.
Static disciplines			
Design Presentation	140	150	5.
Cost Presentation	68.69	100	4.
Business Presentation	57.29	75	9.
Sum	478.39	1000	13.

2.3.3 FORMULA STUDENT HUNGARY

This competition was the last chance to prove that Dragon 4 is great car. Formula Student Hungary is the only event with the concrete surface. That always bring the fast times during greater tyre grip. Finally the team TU Brno Racing reached almost the top as finished 7th overall. This is a huge step forward as we eventually finish the Endurance and prove how good car the Dragon 4 is.

Table 2. 4 Formula Student Hungary 2014 Results

	points	out of	place
Dynamic disciplines			
Skid pad	44.1	75	**6.**
Acceleration	32.8	75	16.
Autocross	108.2	100	11.
Endurance	222.6	325	**5.**
Fuel Economy	53.7	100	14.
Static disciplines			
Design Presentation	130	150	11.
Cost Presentation	50.3	100	25.
Business Presentation	57.1	75	26.
Sum	**698.8**	1000	**7.**

2.3.4 DRAGON 4 SEASON REVIEW

According to the targets which are set at the beginning of each season it is always very useful to review them. The season 2014 was a huge step forward in the TU Brno Racing team. The team have learnt a lot and improved the historical world ranking list. The target of points was 700. The Table 4 shows that Formula Student Hungary achievement is the 698.8 points. Target weight was below the 200 kilograms. At the Formula Student Germany competition the Dragon 4 is 195.6 kilograms weight. Before the FSG competition there were more than 500 kilometres logged with the car.

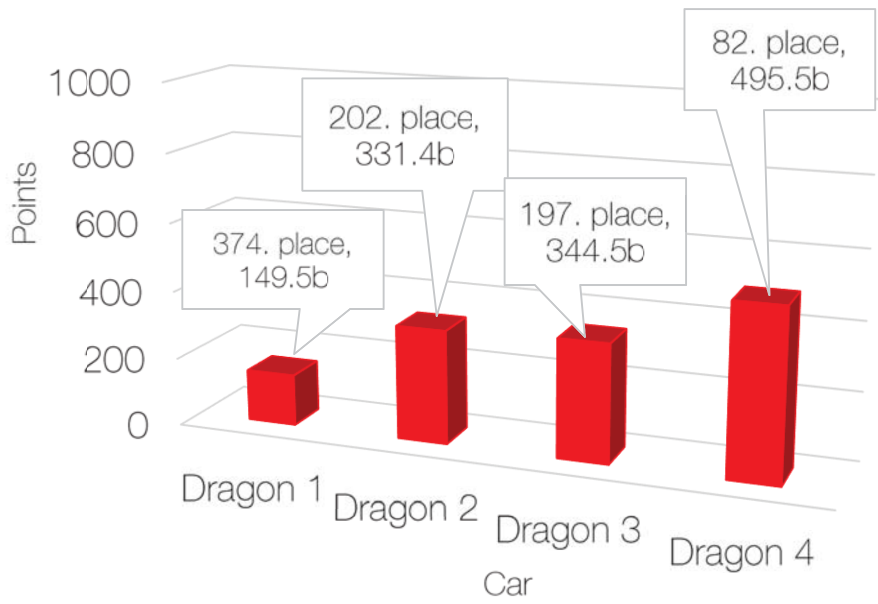


Figure 2. 6 World Ranking of TU Brno Racing during the history

2.4 DRAGON 5 DESIGN TARGETS

Thanks to the huge portion of kilometres which Dragon 4 has done, the team was available to collect and study a lot of data. That helped to identify the issues of that car and to make decisions about the new one. Even the weight was a success for the Dragon 4 still the 196 kilograms are more than it is expected at the single cylinder cars. Pat Clarke - mentor of Formula Student Germany Competition during his Design Review said that the edge of the space tubular chassis with single cylinder is 180 kg.

TU Brno Racing take this as a challenge and even with the turbo charger the aim is to be under the 180 kilograms. The way how to manage this weight was to change the whole concept of the car. For the first time in TU Brno Racing history, kinematics of the car are changed. This leads to safe the weight at the rear of the car as the differential will be the last part of the car. The kinematic change will be described in the chapter 5.

2.4.1 ENGINE AND POWERTRAIN

The engine is changed for the first time in the TU Brno Racing history. The single cylinder remains but the volume is reduced from 570 to 500 cc. As the aim is to turbo charge the engine, it will be a huge challenge to design, develop, test and run it during one year.

2.4.2 CHASSIS

The space tubular chassis weighted 35 kilograms at the Dragon 4. The change of the engine and suspension kinematics saved a lot. In CAD the Dragon 5 chassis is 3 kilograms lighter compare to Dragon 4 car.

2.4.3 SUSPENSION

The aerodynamics at Dragon 4 helped the car to achieve 2.7 G of lateral acceleration during the Formula Student Hungary Endurance. The issue was the jacking force. Dragon 4 struggled on the concrete surface with lifting of the both inner wheels during cornering. On the tarmac the issue was much smaller but still there where problem with the rear inner wheel which lifted during the corner.

The aim for Dragon 5 is to reduce the jacking force, change the position of the toe-rod at the rear suspension to allow to reduce weight of the chassis.

2.5 UH Racing

The University of Hertfordshire has the Formula Student Team since the very beginning of the European history of this competition. The team is said to be the most successful UK Formula Student Team. The truth is there are a lot of awards the team received during its long history. On the other hand the Oxford Brookes and the TU Bath FS teams state the same fact they are the most successful UK team of the history. Let do a research and decide yourself.

For the 2015 season the 18th car is being built. The concept of the car is based on the last year great changes. After many years with the four – cylinder engine Yamaha R6 team had decided to switch to single cylinder unit. It is the KTM 450 SXF. As the team has quite low budget compare to the opponents from UK or Germany chassis are made out of steel tubes. So that the only noteworthy difference in the TU Brno Racing and UH Racing concepts before the turbo era in Brno were the 10 inches wheels.

Figure 2. 7 University of Hertfordshire Formula Student Team has a long and successful history (UH, 2014)

The difference in the wheel size is very interesting as it can be compared in this diploma thesis in the chapter 5 where the kinematics of these cars are described. The author has been volunteering in the UH Racing as he is Erasmus student and has no Final Year Project or Master Project based on the new UH 18 car. On the other hand the influence as adviser could be visible. Interestingly the front suspension was similar to each other on previous cars and for the next season the rear suspension will be similar as well.

2.5.1 UH 18 Targets

The 2014 season was not successful except the Fuel Economy reward at the Formula Student UK. The biggest issue of the UH 17 was the small number of testing kilometres before the competition. The car was built literally the last night before the competition. As the team has change the engine for this season it was a disaster to run it and learn its behaviour at the competition. Nevertheless the drivers had no experience with that car.

The driver training is really crucial. The main goal of UH 18 is to be built at the end of March. This should lead to have the reliable car with perfect setup and perfect drivers. The other goals come with the first goal. Test a lot of kilometres, prepare the whole team for the static disciplines and win the FSUK and FSG. Simple.

Figure 2. 9 UH 15 at the Formula Student Germany - 6th overall fantastic place.

Figure 2. 8 UH 16 was the first winged car. Last UH Racing car with the four cylinder engine

Figure 2. 10 UH 17 in the workshop at university. Last year of such a big aero package in Formula Student due to the rule change

3 THEORY

The motorsport discipline is always depended on the forces which are moving the vehicle further on the ground. While the combustion engine changes energy of heat into the turning force onto a flywheel, the gearbox further transforms this energy to the driven wheels. That moment is crucial as it all depend on the force which the tyre is able to convert onto the ground. To increase forces in the contact patch of the tyre is the aim engineers in motorsport world search for.

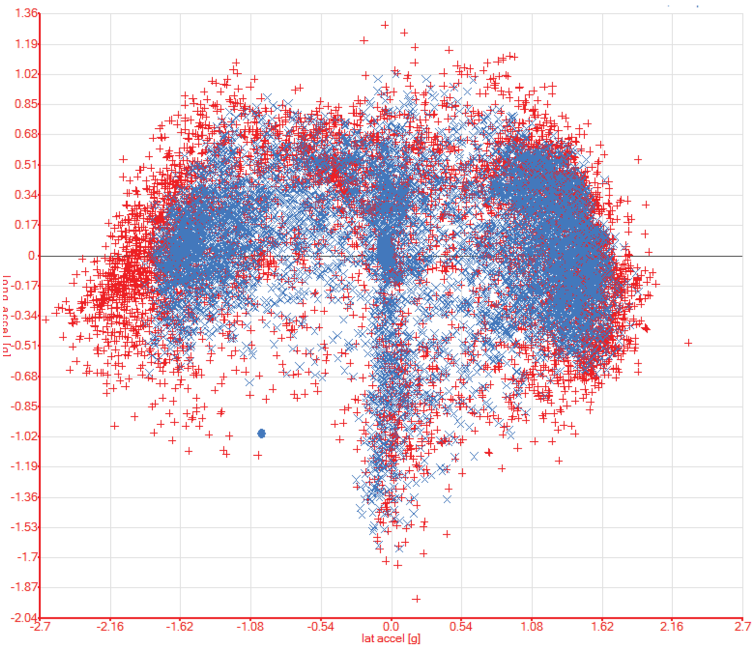
To be able to influence, control and increase forces in this area where the tyre is in the contact with surface beneath, it is beneficial to understand the tyre theory. This knowledge helps to understand how to treat with this black rubber. Awareness of tyre characteristics lead into the suspension design. To design the suspension kinematics with the property of tyre is critical as it enables the tyre to be on its best capability to transform as high forces as it is designed for. Furthermore with the knowledge how the tyre behaves, engineers are able to set up the car according to the particular track in particular conditions.

The tyre characteristics can change the design of a racing car from the scratch. Unfortunately, this is not a typical case of majority of racing teams. The typical way is to make use of the historical data of previous cars in such a case the data acquisition can really help. With tyre characteristics the design on kinematics can be controlled with success. The upright geometry based on the self-aligning torque, pneumatic trail and maximum lateral force can be design preciously indeed as this all influence steering geometry a lot. The sensitivity of tyre behaviour based on different normal loads and the camber effect can influence position of roll centres or the whole kinematic control of camber change.

Not only camber but the pressure and temperature of tyre influence the balance of the car. The car balance is the most important aspect what typical racing driver will be work or fight with. To increase forces in contact patch of tyre the aerodynamics can be utilize on racing car. The penalty of higher drag can improve the cornering ability of a car and also the pressure (downforce) can be transformed on the rear of front axle in a ratio which can control the car balance within higher velocity.

Figure 3. 1

The difference in G-circle is clearly visible. This is data from the same circuit. Formula Student Hungary 2013 & 2014. Blue data is Dragon 3, red is Dragon 4. The biggest difference brought the aerodynamics. But there is also influence of the weight reduction visible in acceleration.



3.1 Tyres

The only interaction of any car with the road is done by tyre. The position of the wheel travel respectively to surface on the one hand and to the body movement of vehicle on the other influences the safety and performance of the particular car. It does not matter if it is a road car or a racing car. The predictability and so the safety is truly important.

Tyre is made out of a rubber which characteristics are non-linear. The only exact way how to determine tyre characteristic before it is used at a testing track or in the race is to test its behaviour on a tyre test rig. Based on the particular test rig features it is possible to collect a huge amount of data. According to Calspan Tire Research (Calspan, 2013), the tyre test rig can measure tyres in loads up to 5 500 N within the speed in excess of 200 MPH. Furthermore the test rig can be set up to measure braking/accelerating or cornering behaviour influences by many controlled factors. For example slip angle, inclination angle, slip ratio, with exact inflation pressure, etc. Calspan Tyre Test Rig is shown in figure 3.3.

In this chapter the tyre characteristics will be described, also some real data which were measured on UH Tyre Test Rig (RC tyre 1:10th scale) will be shown. The scale test rig is shown in figure 3.2. The tyre construction is not the aim of this chapter as there are preciously described in different publications. The typical Formula Student tyre is Hoosier 20.5/7.0-13 with R25B compound. This tyre is cross-ply construction.

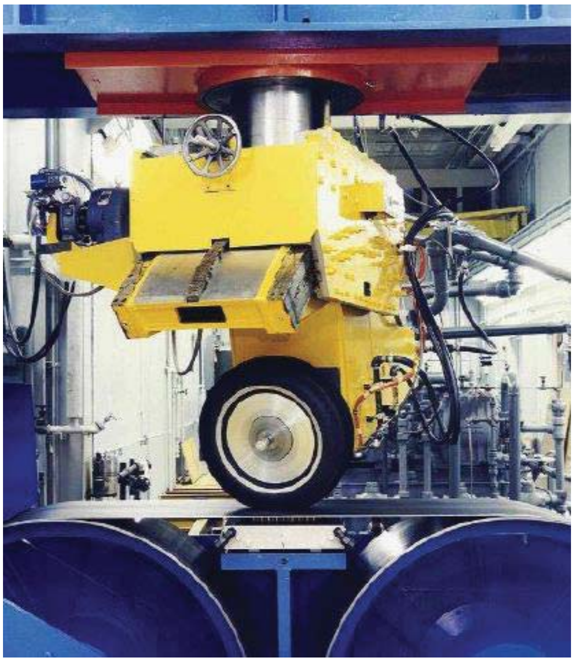


Figure 3. 3 Calspan Tire Research Facility, TIRF (Calspan, 2013)

Figure 3. 2 Tyre Test Rig of University of Hertfordshire. Scale 1:10th for measuring RC car tyres

3.1.1 PRINT IS THE GRIP OF TYRE

As it was described previously, the contact patch of tyre is very important. Everything what the car is going to do depends on that. In Figure 3.4 there are described the physical properties of tyre while cornering.

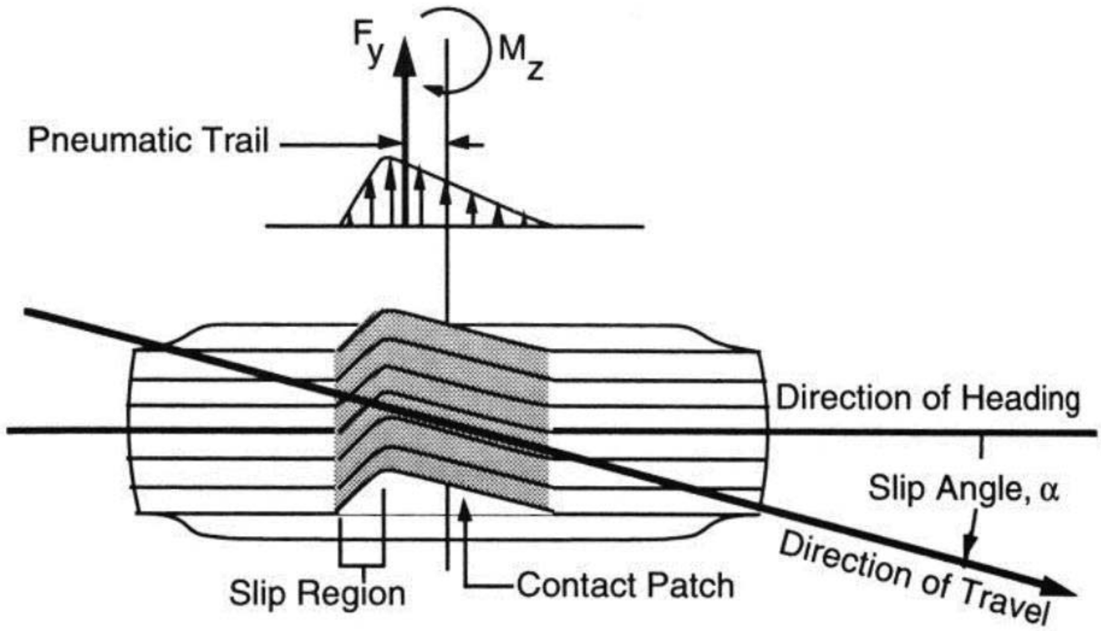


Figure 3. 4 Rolling tyre deformation under lateral force (Gillespie, 1992)

3.1.2 LATERAL AND LONGITUDINAL CAPABILITY OF TYRE

The deformation of contact patch while cornering produce distortion of tyre what results in producing slip angle. This deformation is very important. It brings heat into the tyre, it is depended on the amount of lateral force the tyre is capable to transform and also it influence the tyre wear. The lateral force is the resultant force of slip angle. The lateral force vs. slip angle can be divided into three main parts. Linear, transitional and frictional as it is in figure 3.5.

The tractive and braking force is described with slip ratio. This is difference between the angular velocity of the driven or braked wheel (Ω) and the angular velocity of the free-rolling wheel (Ω_0) (Milliken & Milliken, 1995). The slip ratio is one of the crucial parameter in data acquisition as it can analyse the function of traction control. The system can be driven to use the most of tractive force because same as the lateral force, the longitudinal force reaches its maximum with some amount of slip. The mathematical channel uses the same equation (2). It compares the speed of the driven wheel (Ω) to speed of the free rolling speed (Ω_0).

$$SR = \frac{\Omega - \Omega_0}{\Omega_0} = \frac{\Omega}{\Omega_0} - 1 \qquad (2)$$

While the SR = 0 the speed of driven wheel equals the speed of rolling wheels. With SR > 1 the tyre is losing grip (start to spin). Typical values of longitudinal force magnitude is between 5 – 15 % of slip ratio (Segers, 2014).

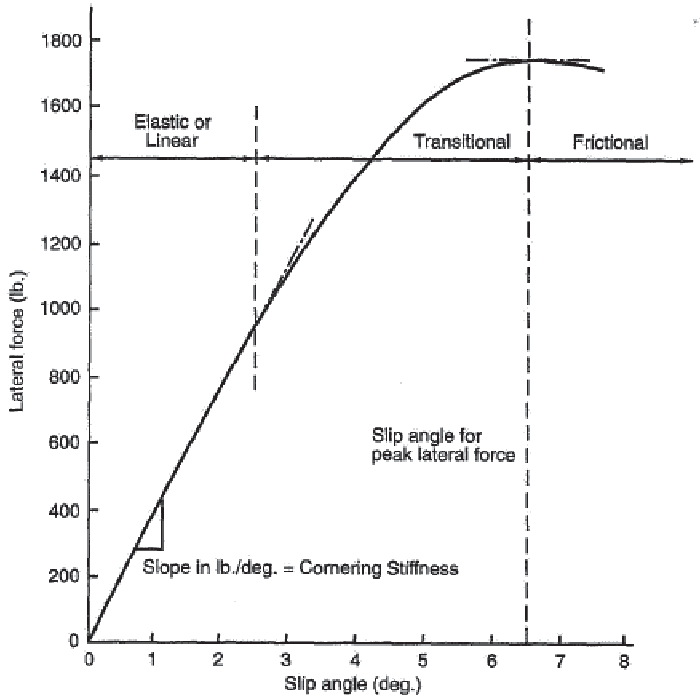


Figure 3. 6 Lateral force vs. slip angle for a racing tyre (Milliken & Milliken, 1995)

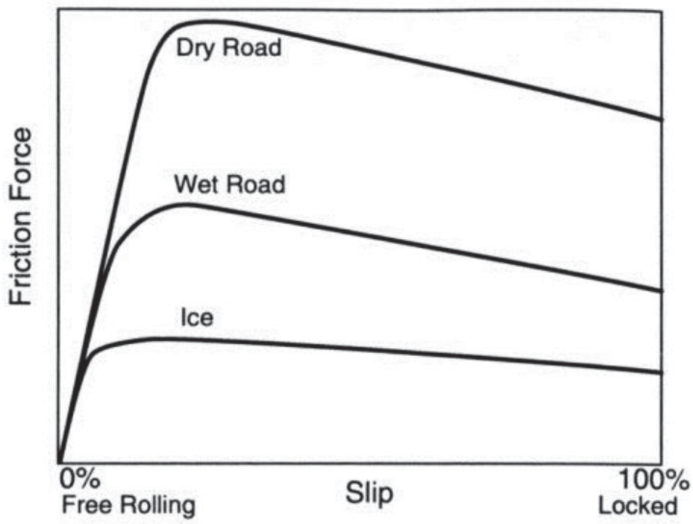


Figure 3. 5 Longitudinal force vs. Slip Ratio for different surface. Typical value of magnitude of friction force for racing tyre is between 5 - 15 % of SR. (Gillespie, 1992)

Despite of slip angle, two other factors influence lateral force of tyre. The normal load and the camber. Vertical load depends on mass distribution and on the transient behaviour of vehicle – the weigh transfer during accelerating, braking and cornering. Camber angle is driven by suspension and steering kinematics.

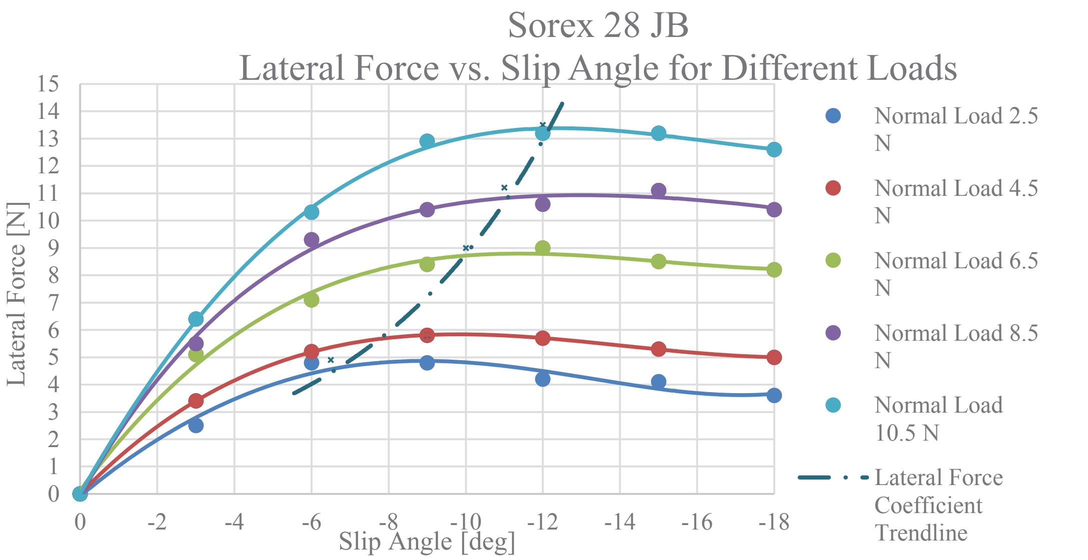


Figure 3.8 Sorex 28JB Lateral Force vs. Slip Angle for different loads. Lateral force coefficient trend line (lateral force magnitude). RC tyre data were measured on UH Tyre Test Rig.

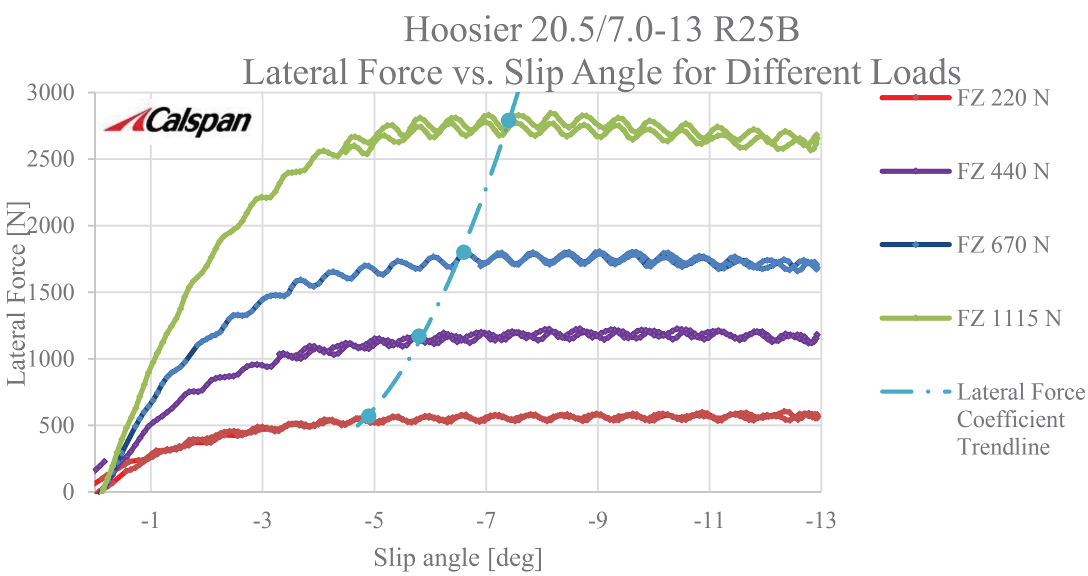


Figure 3.7 Hoosier 20.5/7.0-13 R25B Lateral Force vs. Slip Angle for Different Loads & Lateral force coefficient trend line (lateral force magnitude). (Calspan, 2013)

3.1.3 LATERAL FORCE COEFFICIENT & CORNERING STIFFNESS

Based on data shown in figure 3.7 and 3.8 two characteristics can be calculated. The lateral force coefficient and the cornering stiffness of the tyre – table 3.1. The cornering stiffness can be described as a slope of the curve at zero slip angle. It describes the responsiveness of tyre in steady state conditions. Higher the slope quicker the reaction time of tyre. In figure 3.7 and 3.8 can be seen the difference of these two tyres. Lateral force coefficient normalizes the lateral force vs. slip angle in Figure 3.9.

Table 3. 1 Lateral Force Coefficients comparison Sorex 28JB vs. Hoosier 20.5/7.0 – 13 R25B

Sorex 28 JB					Hoosier 20.5/7.0 - 13 R25B			
Normal Load [N]	**Mag. Slip Angle [deg]**	**Lateral Force Coefficient μ [-]**	**c_α [N/deg]**		**Normal Load [N]**	**Mag. Slip Angle [deg]**	**Lateral Force Coefficient μ [-]**	**c_α [N/deg]**
10.5	-12	1.28	2.4		1115	-7.4	2.51	859
8.5	-11	1.30	2.2		670	-6.6	2.61	681
6.5	-10	1.38	1.9		440	-5.8	2.65	503
4.5	-9	1.33	1.3		220	-4.9	2.7	250
2.5	-6.5	1.96	1					

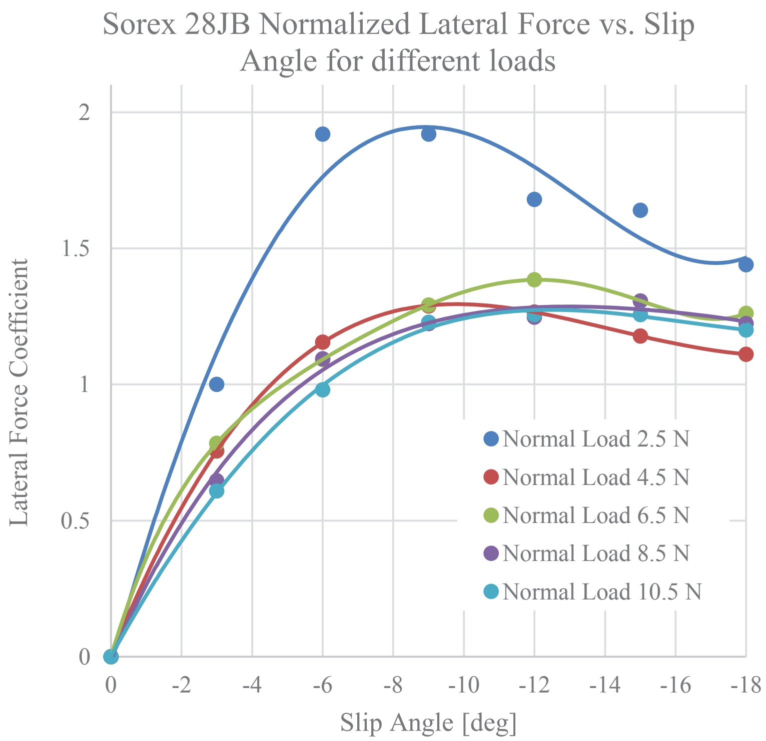


Figure 3.9 Normalized Lateral Force vs. Slip Angle for different loads.

3.1.4 CAMBER THRUST

The camber effect can be seen in figure 3.10. The negative camber produce lateral force even in longitudinal direction of travel. This is called camber thrust. It is widely used in racing as it drives the kinematic characteristic of camber change. It is important not to design the car which enables the tyre to be in positive angle of camber. As it is clearly brings disadvantage of lowering the lateral force.

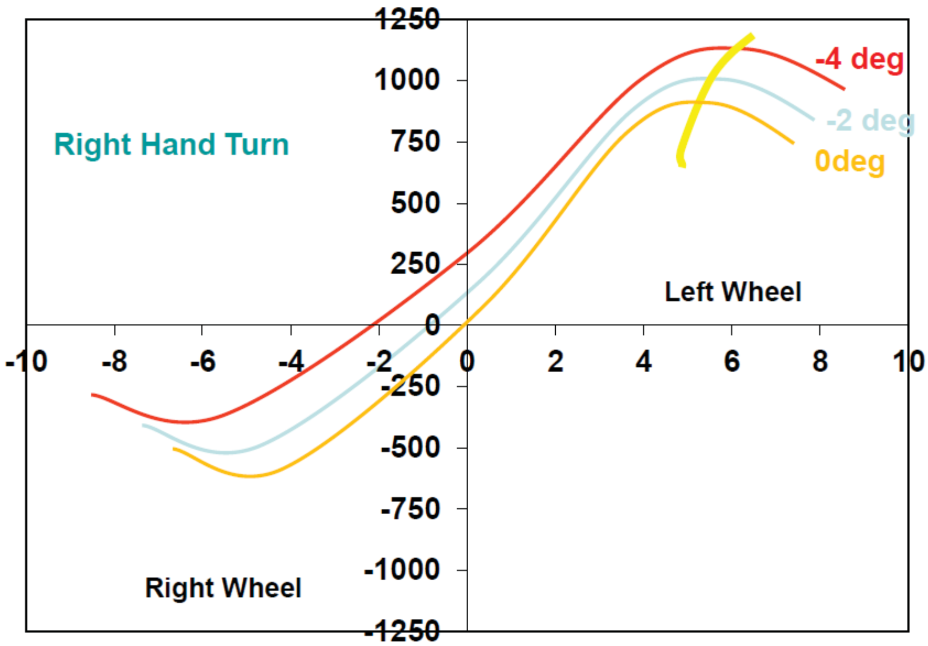


Figure 3.10 Lateral force vs. slip angle for different camber angles (Ash, 2014)

3.1.5 TYRE TEMPERATURE ANALYSIS

Tyre management is absolutely crucial during endurance races. Ultimately, the tyre has the biggest influence how the car behave during the whole race. The well-established team with quite high budget definitely should use the tyre temperature sensors. The types of sensors are beyond the scope of this diploma thesis, however, such a sensor can provide team with a lot of useful information (Segers, 2014):

- The ideal working range of the tyre
- The time needed to get the tire up to correct conditions
- Balance of the car
- Lateral load transfer
- Tire compound and construction
- Tire wear
- Camber
- Tyre pressures
- Steering and suspension geometry
- Driving style

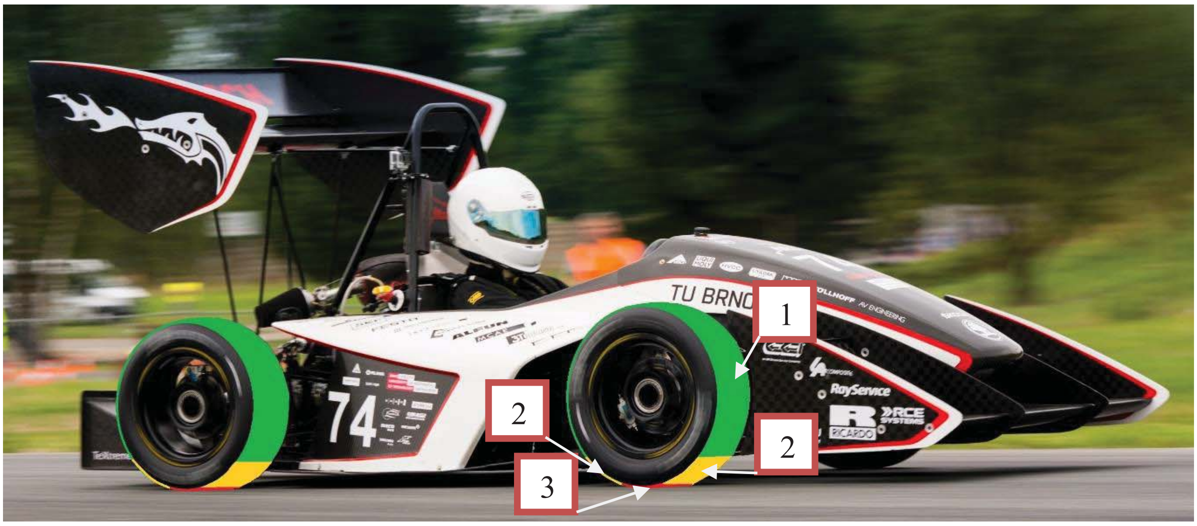


Figure 3 11 Schematic illustration of the three terms governing the speed of tyre temperature variation

The figure 3.11 shows the basic idea of how temperature is gained at the tyre surface. This approach help understand what is the most important factor to influence tyre temperature. The equation 3 explain the theory which is used in Chassissim lap time simulation software.

$$\frac{C_p * \rho_T}{HF} * \frac{\partial T}{\partial t} = \sqrt{\left(F_y * \alpha * v\right)^2 + (F_x * SR * v)^2} - \kappa * (T_T - T_{amb}) - \kappa_{track} * (T_T - T_{track}) \qquad (3)$$

ρ_T = Tyre density (kg/m3) (Approximately 900 for rubber)

C_p = Tyre specific heat (Approximately 2 for rubber)

HF = Heat factor multiplier. Correction factor to dial in tyre heat input.

Fy = Lateral tyre force (N).

Fx = Longitudinal tyre force (N).

v = Velocity of the tyre (m/s)

α = Slip angle (radians)

SR = Slip ratio

K = Thermal conductivity to air.

Ktrack = Thermal conductivity to track.

3.2 SUSPENSION

While the tyre depends on the area of its contact patch with the road, it is controlled with the suspension system which ensure this. The maintaining a large contact patch is a challenge while suspension constantly changes its position to road absorbing bumps and undulations. Suspension geometry is also defines how the unsprung mass is connected to the sprung mass and more importantly how it transform the forces between these two main part of a vehicle (Smith J. , 2013).

The most common layout of suspension in Formula Student competition is nonparallel, unequal double wishbone system with pull-rod or push-rod actuated dampers via rockers. This is the form the TU Brno Racing have been using since it first car. This enables the full control of wheel movement in huge range of damping movement. This is common solution for open-wheel cars where is a lot of space to accommodate such a suspension geometry. In road cars it is typical to use MacPherson system which is not an objective of this diploma thesis. The nonparallel, unequal double wishbone system with pull-rod actuated dampers on front and push-rod linkages on the rear axle was used on the first four generation of TU Brno Racing Dragon cars. The Dragon 4 solution is shown in Figure 3.11 and 3.12

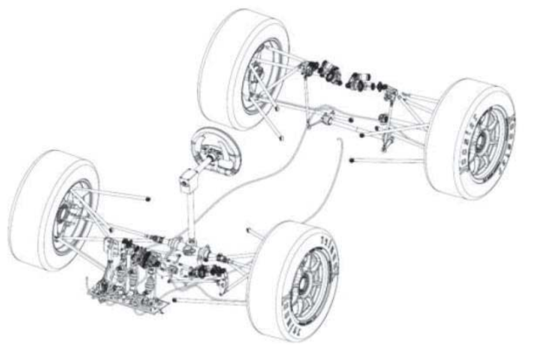


Figure 3 21 Front view Dragon 4 suspension layout. Front axle is pull-rod solution.

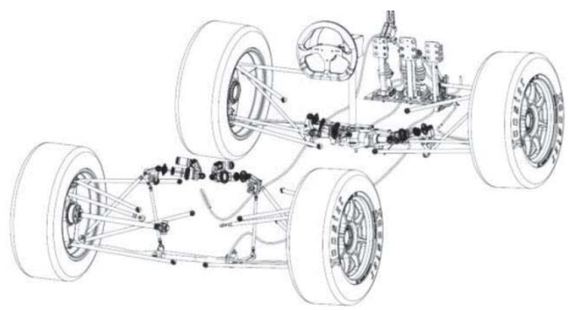


Figure 3 32 Rear view Dragon 4 suspension layout. Rear axle is push-rod solution

3.2.1 STEERING GEOMETRY

The substantial part of the whole suspension geometry takes the steering geometry. The importance is easy to imagine as the steering wheel is one of the few controllers which driver has. The steering geometry is influenced with two main factors – usage of tyre and track the car will race on. The tyre characteristics and track corner characteristics indicates the direction if the Ackerman, anti-ackerman or parallel steering geometry will be used also it help to define the castor and kingpin inclination angle as it defines the amount of mechanical trail and scrub radius. Definition of these parameters is explained in Figure 3.13.

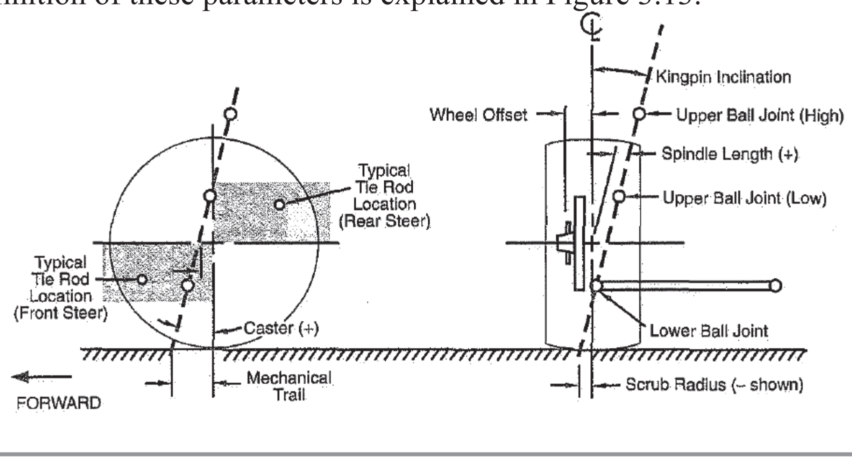
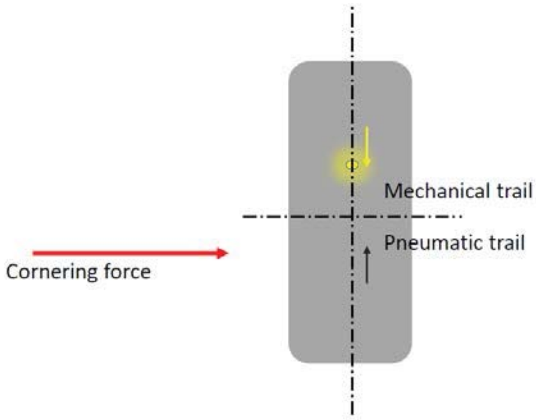


Figure 3.13 Front suspension packaging and term explanation. (Milliken & Milliken, 1995)

Figure 3.14 Restoring moment due to cornering force. (Ash, 2014)



The restoring moment due to cornering force depends on the geometry of upright (resulting amount of Mechanical trail) and on the pneumatic trail which is characteristic of tyre Figure 3.14. As the pneumatic trail is a value which is changing with slip angle (Figure 3.15) as well it is the area where to improve the final steering responsiveness. The pneumatic trail helps driver to feel the edge of the tyre capability as the resisting moment of tyre to change its direction falls to the zero. The mechanical trail decreases the amount of resulting pneumatic trail, so that it is always important to consider this two values and be aware of them.

$$Restoring\ moment = (mechanical\ trail + pneumatic\ trail) * Cornering\ Force \qquad (3)$$

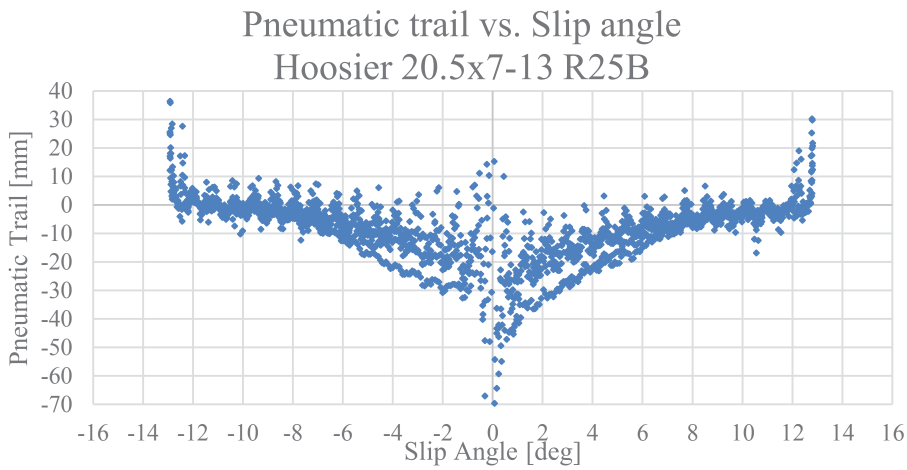
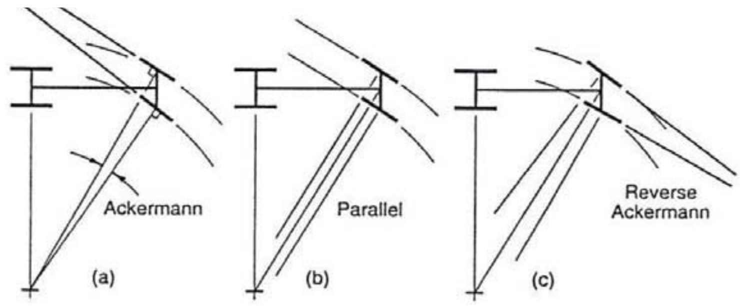


Figure 3.15 Pneumatic Trail calculated from self-aligning moment. Data measured by Calspan TIFR (Calspan, 2013)

Typical Formula Student race track is very narrow with lot of corners. This brings the decision to use Ackermann steering geometry as it improves the corner ability at small space. On the other hand with consideration of different lateral force coefficients at different values of normal force the reverse-Ackermann steering geometry would be used. The reverse-Ackermann geometry enable right the opposite than Ackermann geometry. The outer steered wheel in Reverse-Ackermann is steered with greater angle than the inner wheel. That produce greater slip angle on the outer more loaded wheel and use higher lateral force as it could be seen in figures 3.7 – 3.9.

Figure 3.16 Ackerman, Parallel and Reverse Ackerman steering geometry. (Milliken & Milliken, 1995)



The last parameter of suspension geometry to discuss is bump steer. The procedure how to ensure the desired bump steer interferes into the suspension kinematics chapter. Nevertheless the bump steer will be described in the steering geometry chapter. This characteristic describes the self-steering of a wheel while bump or roll movement of the chassis. In general, the zero change is required. While changing the suspension geometry for the next generation of Formula Student Car Dragon 5 it was another very important aspect to study as it can easy influence the vehicle handling. Whereas drivers in the TU Brno Racing team are non-professionals it is really important to bear in mind to make the car as easy to drive as possible. Hence the required zero bump steer is really important to ensure linear responsiveness while driving the car.

To explain how to design the required bump steer the instant centre should be described. The instant centre (or instant axis in three-dimensional) is the point (axis) around which the wheel assembly rotates. In Figures 3.17 – 3.19 is shown the basic principle. This could be solved with complicated mathematical equation or designed with some kinematic software. The Tie Rod is the main element which influences the bump steer. While it is located towards the instant centre (Intersection Point) it results in zero bump steer (Figure 3.17). To aim the Tie Rod underneath of instant centre brings the bump in characteristic as the wheels are steered inboards (toe out) in the case the steering is behind the axle. Otherwise location the Tie Rod axis above the instant centre shows the bump out solution.

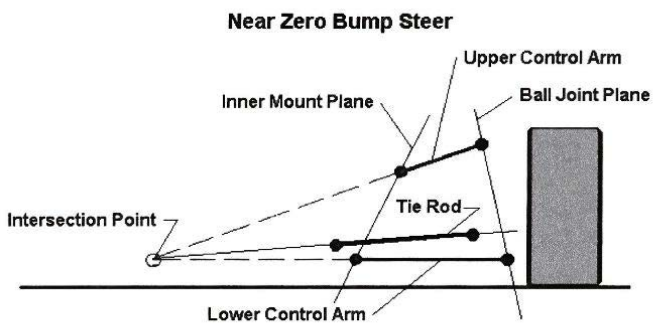


Figure 3.17 Zero Bump Steer geometry

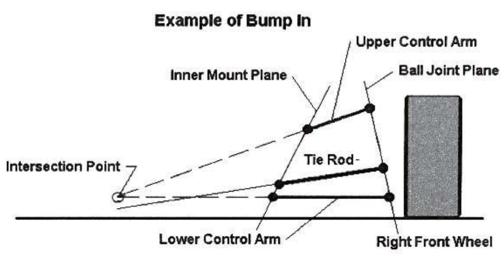


Figure 3.18 Bump In Geometry

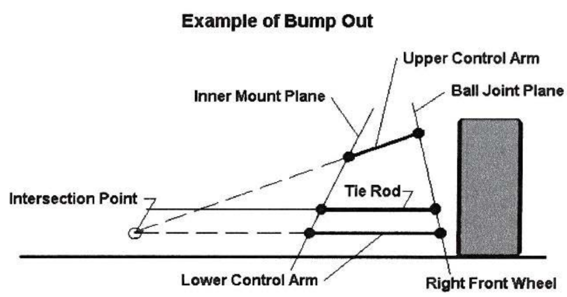


Figure 3.19 Bump Out Geometry

3.2.2 Suspension Kinematics

Suspension kinematics is discipline which study the motion of wheel against the chassis. It describes the transform of forces to chassis acting on the wheel. As anything in space even the wheel has 6 degrees of freedom described in Figure 3.20.

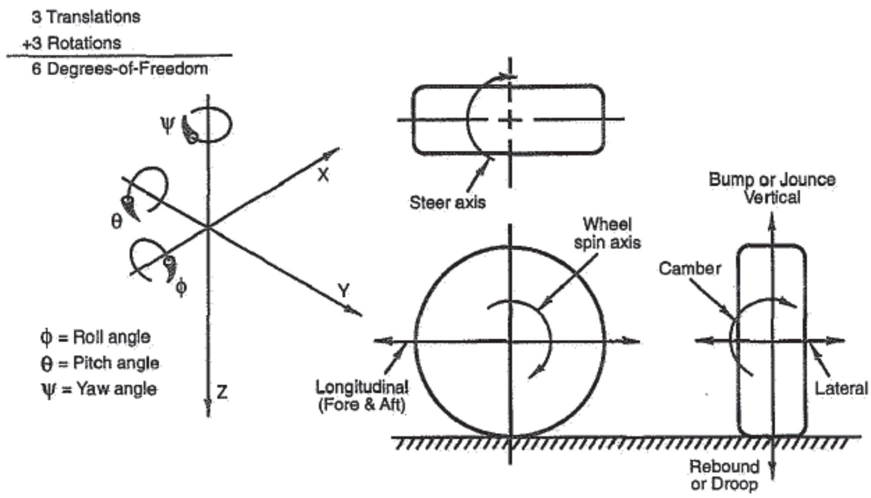


Figure 3.20 Degrees of freedom and suspension motion definition (Milliken & Milliken, 1995)

The design of suspension geometry is divided into two main areas. The geometry which can be seen in front (rear) view and in side view of vehicle. Both of view use the same concept of thoughts.

Front view was described while defining the bump steer. The upper and lower wishbone defines the axis (planes in three-dimensional) and intersect in single point (axis). This point define the rotational movement of the wheel. Connecting the centre of tyre contact with this point defines the roll centre of the suspension on the vertical axis of the car. The roll centre defines the point around which the sprung chassis will move. The roll centre moves during bump and roll of the vehicle (Figure 3.21). The vertical migration of roll centre should be reduced to ensure the car responsiveness during every manoeuvre remains the same.

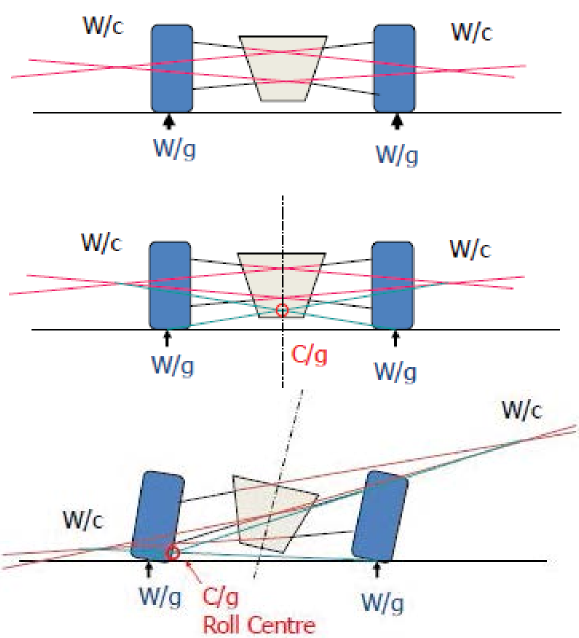


Figure 3.21 The intersection point and roll centre definition. (Ash, 2014)

The horizontal migration of the roll centre is controlled with the length of virtual swing arm length. The length of virtual swing arm also defines the camber change of the wheel. Camber change is the difference in amount of camber during bump (or roll). This enables the tyre to be in the right position to ground even in cornering.

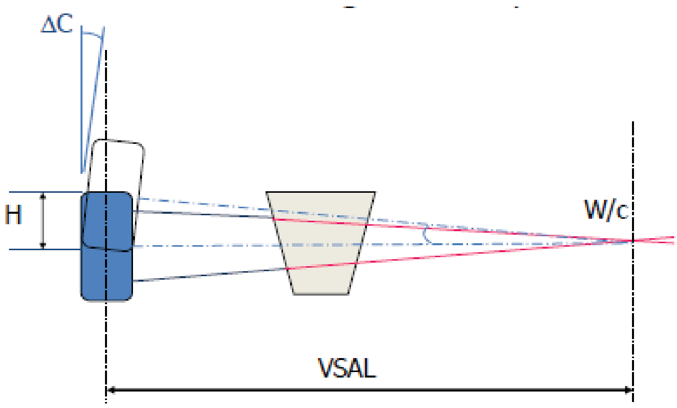


Figure 3.22 Virtual Swing Arm and Camber change Definition. (Ash, 2014)

Side view of vehicle enables to study the motions and forces in the fore/aft direction. The two most important characteristics of side view kinematics are Anti-dive and Anti-squat features. Another feature is anti-lift (for front wheel drive car).

Similarly to front view the amount of anti-dive or anti-squad is given by the virtual swing arm length (svsa) and the angle which it forms between the ground and the line connecting centre of contact patch and intersection point as in Figure 3.22. The amount of such a feature depends on its position to centre of gravity position.

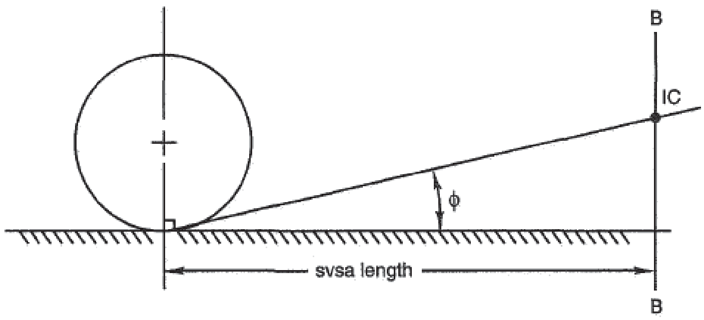


Figure 3.23 Side-view of vehicle kinematics. Definition of side-view virtual arm (Milliken & Milliken, 1995)

The very same situation but for the rear axle, that means for anti-squat feature, is described in Figure 3.24. In that figure it is once again shown the importance of Centre of Gravity position. The Centre of Gravity represents the mass of the vehicle, Intersection point is a pivot around which that mass rotates. Therefore the moment is acting on the whole car. Generally, it is used to describe amount of these anti-features in percentage. This is described in Figure 3.24.

If the designing team know the Centre of Gravity height at the beginning of kinematics design, it is possible to decide the amount of anti-features very accurately. Unfortunately, this is not the case in general as the final height of Centre of Gravity is known after the car is at least properly modelled up in a CAD software. The usual approach is to predict this height according to historical data and some prediction. The good way is to design different attachment points for wishbones to have a possibility to change this characteristics in a range.

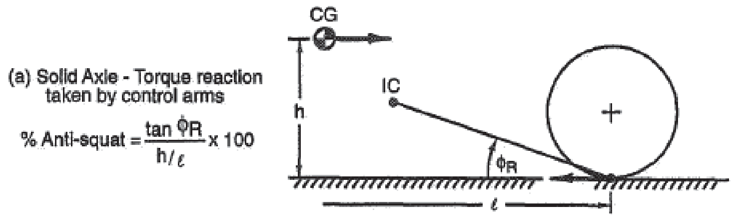


Figure 3.24 Anti-squat feature and Torque reaction definition (Milliken & Milliken, 1995)

From the definition of anti-dive or anti-squat features it is possible to design the kinematics with 100% of such a feature. That means that the whole mass of car during accelerating or braking events is transformed to a contact patch only via wishbones. The car is not pitching in another way. This could be positive from aerodynamics point of view as the ride height is absolutely crucial for aerodynamics performance. On the other hand the driver is not able to feel the car as the car becomes digital for driver. Especially in Formula Student it is necessary, as drivers are not professionals, to design the car easy to drive.

This is one of ideas which influenced the design path of Dragon 5 front wing for example. In the way the car should be responsible enough for the driver the roll gradient of the car is little bit higher compare to aerodynamic cars. Roll gradient is discussed later in this chapter.

The whole concept of racing car depends on a few compromises. The compromise of anti-features hence is to deliver good feeling for the driver with a little of movement while pitching and rolling movements.

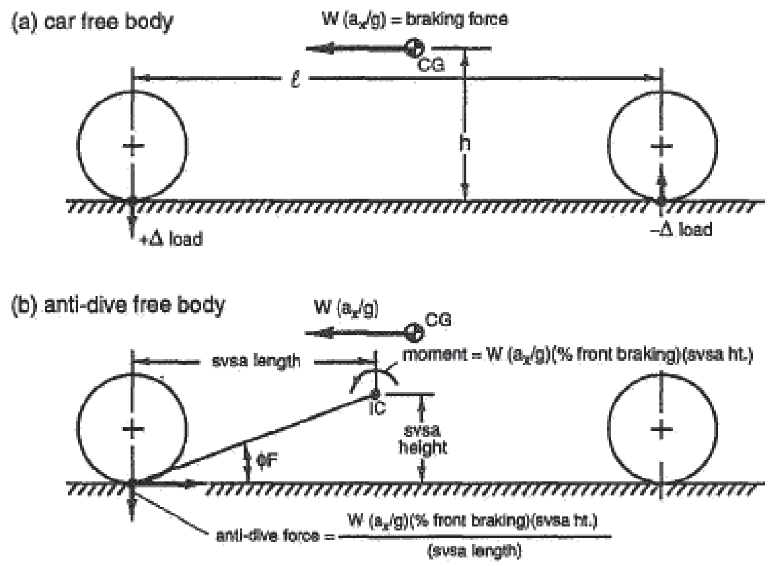


Figure 3 4.25 free body diagram of a vehicle with anti-dive feature involved (Milliken & Milliken, 1995)

3.2.3 Load transfer

In tyre theory was discussed how important is to take care about the contact patch. The contact patch is the ultimate place where the whole mass of a car is transmitted onto a road. While the tyre is load sensitive, the aim is to equal forces acting on tyre. In previous chapter the driveability of car was described.

Load transfer is closely related to both of this phenomes. From the tyres point of view it is beneficial to equal the forces especial in cornering events. In this situation the best way how to achieve this is to lower the Centre of Gravity. While the car is limited in this requirements it is useful to make the most of anti-roll bars. Anti-roll bars help to equal the forces acting in left/right tyres' contact patches.

While the centre of gravity is something which is limited by a car design. We can influence the centre of gravity height just to a point where it starts to be very difficult to get it lower. Basically, the limitation can be imagination or budget. What can be controlled is roll centre height position and its migration in bump or roll movement. The position of roll centre according to centre of gravity is important.

If roll centre is at the same height as centre of gravity all cornering forces are transformed via suspension links (wishbones). In this case are dampers, springs and anti-roll bars just added weight in roll movement. This is unintended as the car will be jacking on two wheels in corners immediately. That means that even strain gauges will measure no force in pull rods or push rods for example.

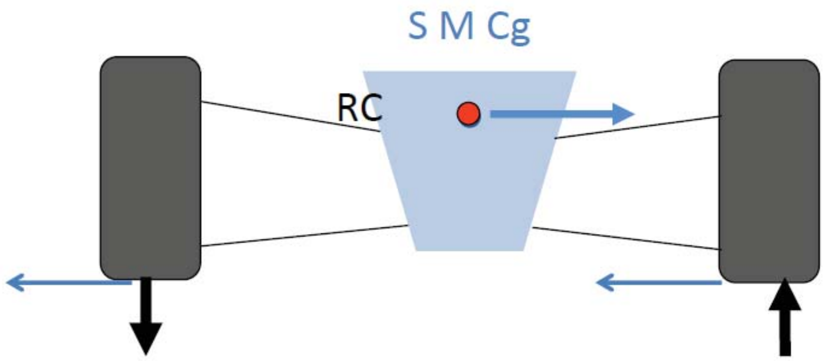


Figure 3 26 roll centre at the centre of gravity introduce only jacking effect. Movement is transferred only via wishbones. (Ash H. , 2015)

On the opposite extreme situation roll centre is below ground. Even here the jacking effect will appear – suspension will go into bump. Part roll effect is absorbed (controlled) by springs (dampers) and anti-roll bars. However, this configuration is still not the intended one.

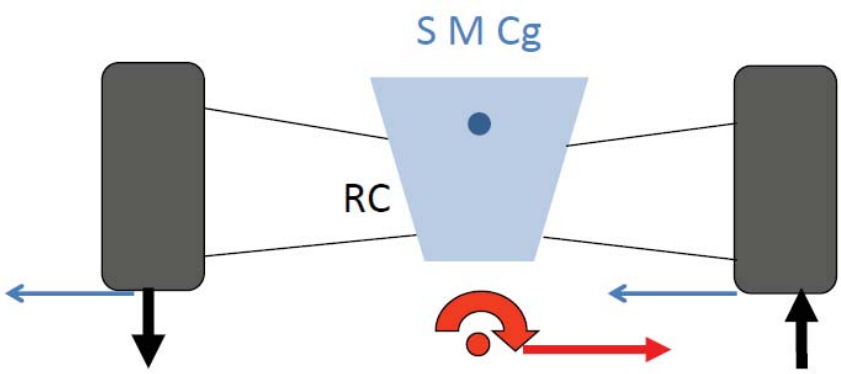


Figure 3 27 another unintended situation is roll beneath track surface. This situation brings jacking effect as well. It demonstrates as suspension bump. (Ash H. , 2015)

Caroll Smith advices in his book (Smith C. , 1978) to design roll centre to be acting as low as possible to ground but not to go under track surface. This configuration deliver as low jacking effect as possible and intended sensitivity of springs and anti-roll bars.

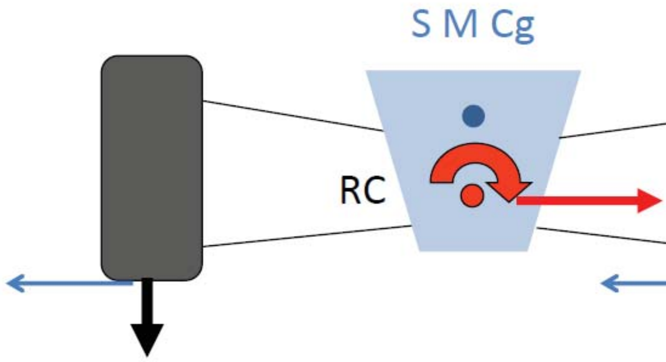


Figure 3 28 Situation while the roll centre works in range between ground and centre of gravity deliver suspended mass roll and jacking effect as well. However this situation is the best option. (Ash H. , 2015)

3.3 AERODYNAMICS

Once again the introduction about aerodynamics has to start with tyre. Racing cars are designed to produce as high acceleration as possible. After the start procedure there is no place in race where the car is at a constant movement. There are a few exceptions. Pit stop, safety car and maximum speed. In every other moment the car is accelerating somehow.

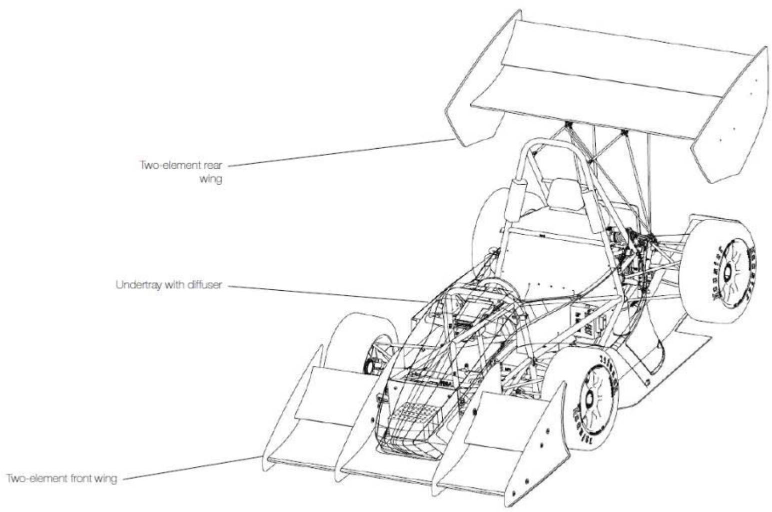


Figure 3 29 Dragon 4 aerodynamic package uses front and rear two element wings and undertray with diffuser. While the aerodynamic package is very first in TU Brno Racing history the simplicity was one of the main targets. With no experience with manufacturing of this parts the same aerofoils were used for the front and the rear wing. Diffuser tunnels has been prepared only by team members without any machine help.

While the car is increasing or decreasing speed constantly, the only thing which transfer this loads is tyre. To be precise four tyres. In the first part of this chapter tyre theory was introduced. One of the most important fact is that the tyre is load sensitive. With higher normal force the tyre can produce higher lateral or longitudinal force. One of the solution could be design a heavy car. But this is a nonsense as the car would have to be more powerful and the cornering abilities would be worse. The best possible way how to increase force in contact patch of a tyre is to deliver aerodynamic package on the car.

In this chapter the brief theory will be introduced. It is beyond this diploma thesis to present all aerodynamics theory. There will be aerodynamics parts of Dragon 4 monopost described, the importance of forces and moment analysis and CFD process which has been used to develop this package. The main interest for further analysis is in forces acting on tyres. Measurement and deep analysis are shown and explained in chapter 6 of this diploma thesis. No aerodynamics of cooling the engine or brakes are introduced in this chapter.

While the racing car run on the track, it runs through air – fluid, the Bernoulli's law can describe the aerodynamic effects. Aerofoils on racing cars are chosen to provide as high lift coefficient as possible. Formula Student tracks are based to enable roughly 50 kph velocity in average. Therefore the drag coefficient is not as important here. (Frystak, 2014)

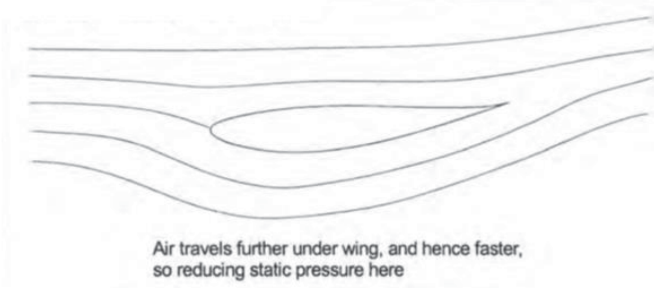


Figure 3 30 Based on Bernoulli's explanation where the air travels faster there is lower pressure. (McBeath, 2006)

Dragon 4 has two main aerodynamic parts. Wings and undertray with diffusors. Two element wings try to achieve high pressure difference around the aerofoil. On racing cars the configuration is to provide as negative lift coefficient as possible (downforce) Figure 3 31.

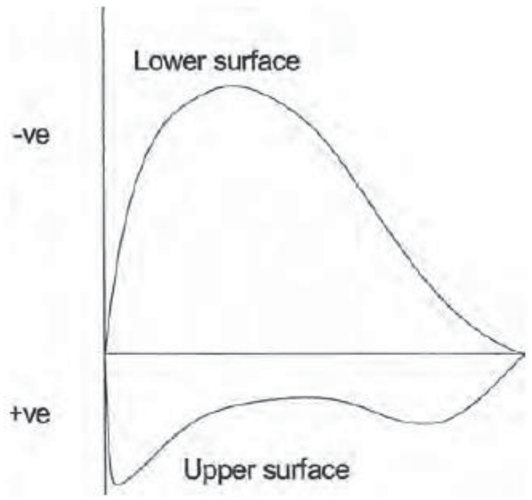


Figure 3 31 pressure distribution on the surfaces of a wing. In overall the lower surface provides higher pressure. Hence the resulting pressure (force) aims towards the ground and generates downforce. (McBeath, 2006)

Undertray with diffusors can be explained with Bernoulli's law as well. Specifically it can be described as a venturi tube shown in Figure 3 32. With the same explanation from aerofoils that higher speed means lower pressure the venture effect can be understand.

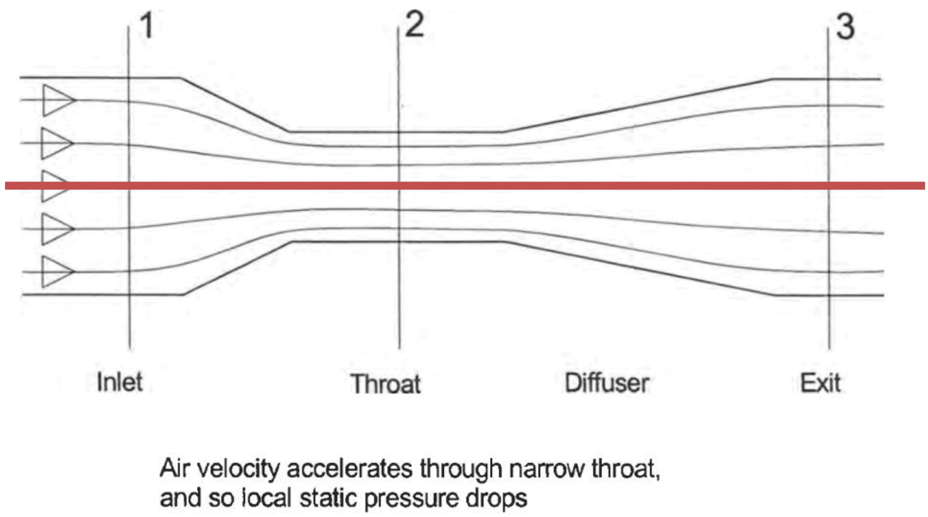


Figure 3 32 Schematic of venturi tube, this configuration can be found in a carburettor choke tube. We can imagine that race car undertray is half of this tube as is shown with red line. (McBeath, 2006)

For purpose of this diploma thesis the aerodynamic balance is the most important parameter. On racing car there is very important to deliver exact added weight (downforce) in respect of weight distribution. In chapter 6 the aerodynamic measurement are shown and explained. On the race car under real condition the only way how we could measure the downforce are damper position sensors. While we know installation ratio of dampers and spring stiffness it is possible to calculate force which is acting in tyre contact patch.

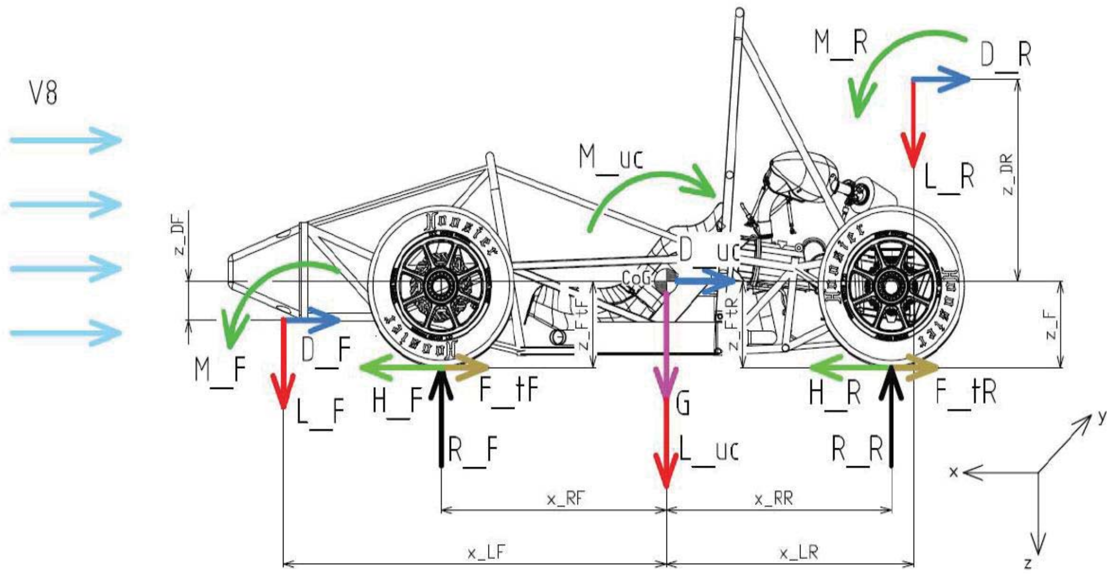


Figure 3 33 Moments and forces which are acting on a car with aerodynamic package. The most important are the resulting force in tyres contact patch. This force can be measured with damper position sensors.

The only possible way for such a small Formula Student team to develop aero package is to make the most of CFD. Computational Fluid Dynamics. This method enables to test the aerodynamic behaviour of the car without necessity to go to wind tunnel. It cannot replace the real measurement, however, lot of steps can be simulated with this tool.

There should be correlation between CFD simulations and wind tunnel test provided. Nonetheless, TU Brno Racing do not have any possibility to undertake a wind tunnel test. This led to correlate the data in real condition at local agricultural airport.

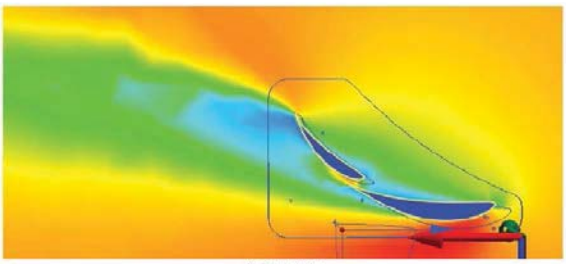
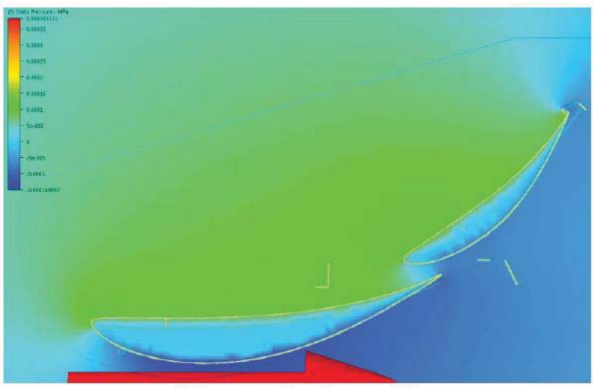


Figure 3 34 2D CFD simulation of two element wings. On the right Figure 3 35 the static pressure with gurney flap on the wing is shown.



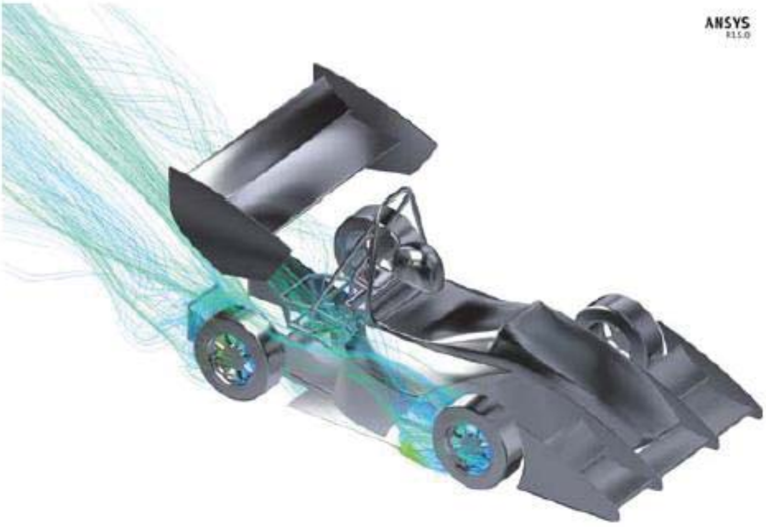


Figure 3 36 Dragon 4 CFD simulation in 3D. The visualization of 3D air flow enables to understand how the aerodynamics influence the whole car.

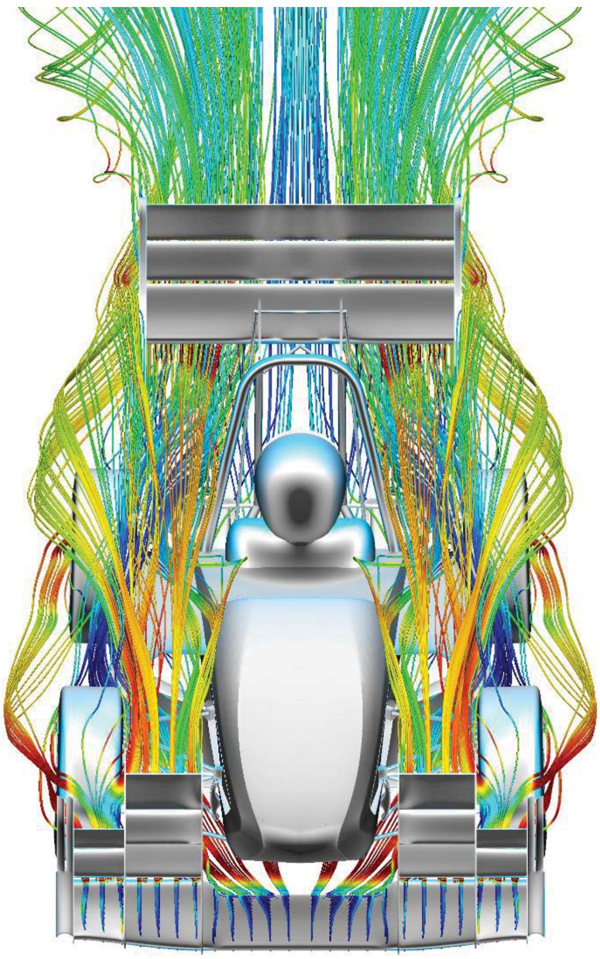


Figure 3 37 Dragon 4 has undertaken extensive development according to new rules. Flow visualisation is coloured with pressure distribution

4 KINEMATICS

The kinematics have always been a strong part of TU Brno Racing cars. The reason why the concept had been the same before the Dragon 5 was lack of test kilometres and therefore lack of experience and data. Hence the decision to change rapidly anything on the car was inappropriate. Dragon 4 run more than 700 kilometres in 2014 season. With a great amount of analysed data the decision could be made.

4.1 DRAGON 1 – 4 CONCEPT

Since the beginning of TU Brno Racing history the concept of suspension had been the same. Non-parallel unequal double wishbone layout with pull-rod on front suspension and push-rod on the rear.

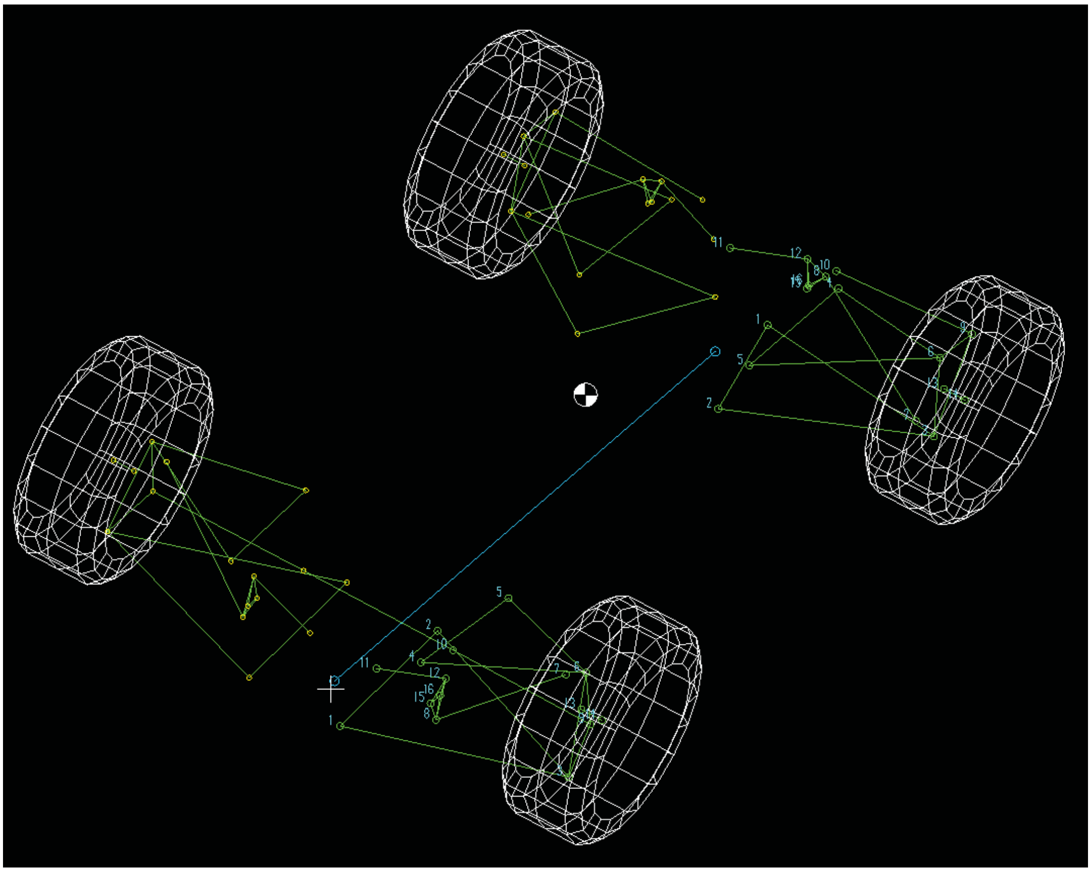


Figure 4 1 Suspension layout of Dragon 1 - 4 monopost

The reason was to lower centre of gravity as much as possible on the front and to make use of the space at the rear side of the car above the engine.

Main idea of this kinematic layout was to deliver responsible car which is easy to drive for any driver. In Formula Student there are non-professional racing drivers which means the car should be easy to control and easy to read for such a drivers.

Both concepts were analysed in Lotus Suspension analysis software Shark. While the tyres remain the same for every concept the initial parameters are shown in Figure 4.2.

GENERAL DATA VALUES		D1 – D4
TYRE ROLLING RADIUS	(mm)	264.16
WHEELBASE	(mm)	1600
C OF G HEIGHT	(mm)	310

BUMP TRAVEL	(mm):	27.5
REBOUND TRAVEL	(mm):	42.5
ROLL ANGLE	(deg):	3.5
STEERING TRAVEL	(mm):	42.75

Figure 4 2 General Data Values of Dragon 1 - 4 concept

FRONT SUSPENSION

STATIC VALUES		D1 – D4
Camber Angle	(deg)	0
Toe Angle {Plane}	(deg)	0
Toe Angle {SAE}	(deg)	0

Castor Angle	(deg)	7.98
Castor Trail (hub)	(mm)	12.55
Castor Offset (grnd)	(mm)	24.47
Kingpin Angle	(deg)	8.04
Kingpin Offset (w/c)	(mm)	52.75
Kingpin Offset (grnd)	(mm)	15.43
Mechanical Trail (grnd)	(mm)	24.23
ROLL CENTRE HEIGHT	(mm)	23.01

Figure 4 3 Front Suspension static values of Dragon 1 - 4 concept

REAR SUSPENSION

STATIC VALUES		D1 – D4
Camber Angle	(deg)	0
Toe Angle {Plane}	(deg)	0
Toe Angle {SAE}	(deg)	0

Castor Angle	(deg)	-12.93
Castor Trail (hub)	(mm)	-28.41
Castor Offset (grnd)	(mm)	-32.22
Kingpin Angle	(deg)	2.1
Kingpin Offset (w/c)	(mm)	53.78
Kingpin Offset (grnd)	(mm)	44.52
Mechanical Trail (grnd)	(mm)	-31.4
ROLL CENTRE HEIGHT	(mm)	62.35

Figure 4 4 Rear Suspension static values of Dragon 1 – 4

4.1.1 FRONT SUSPENSION BUMP CHARACTERISTICS

Figure 4 6 Camber change Dragon 1 - 4

Figure 4 5 Bump steer characteristic - less is better as the driver can feel the steering still the same

Figure 4 9 Castor angle change

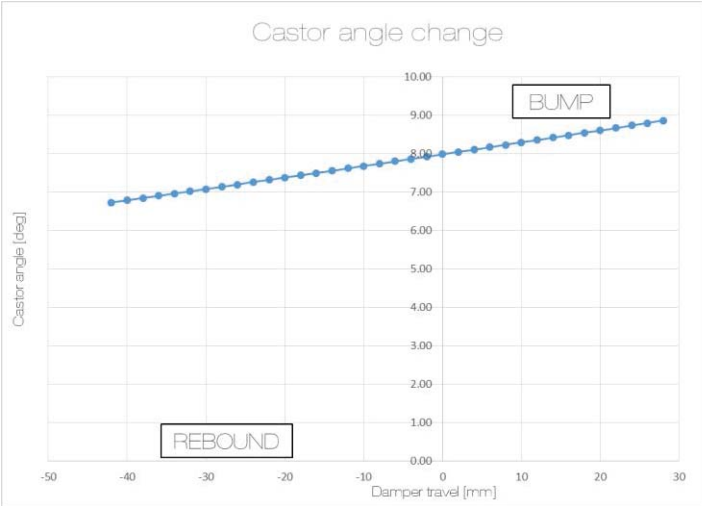
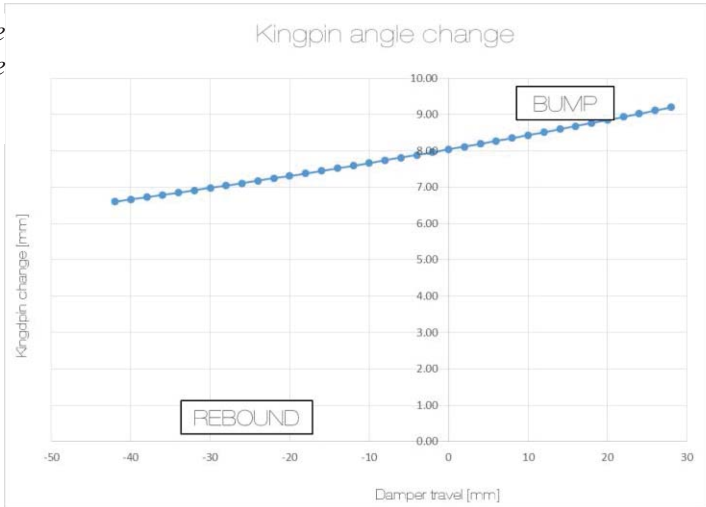


Figure 4 8 Kingpin angle change



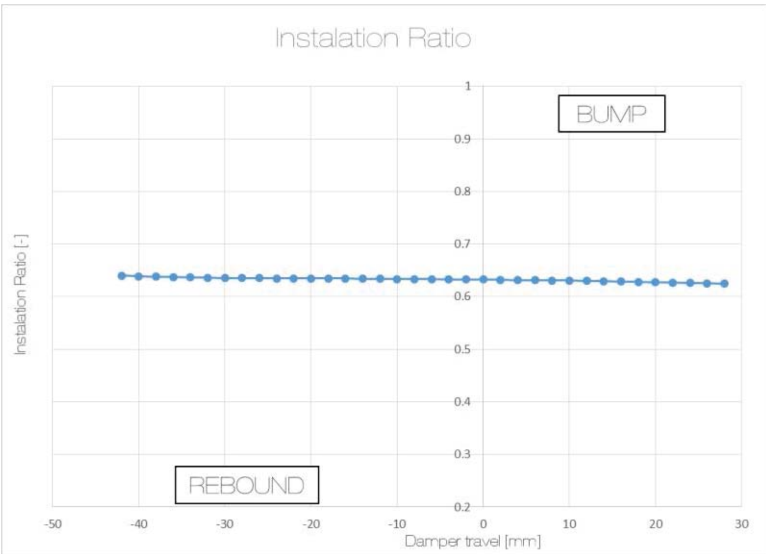


Figure 4 7 Installation Ratio is crucial from the beginning of suspension design. It controls the amount of wheel force to dampers transfer. That means the IR (or motion ratio) determines ride rates (frequencies of suspension).

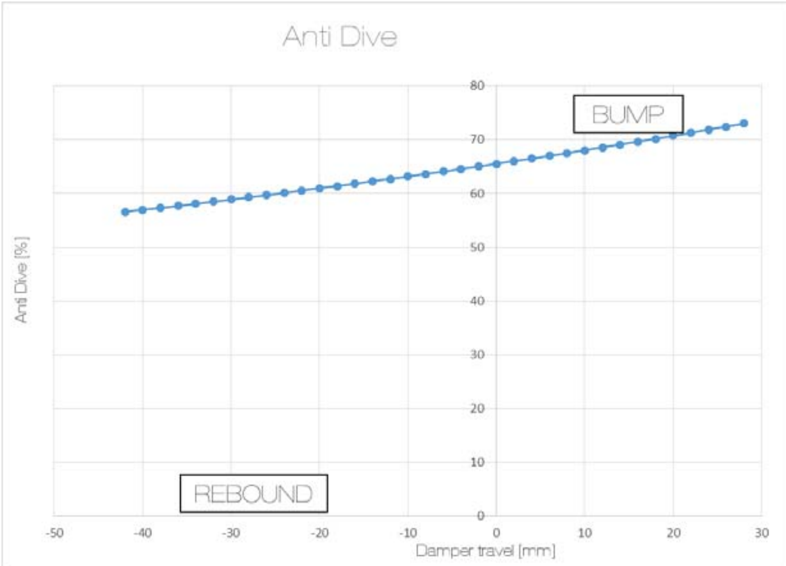


Figure 4 10 Anti Dive characteristics show how the car is sensitive to load transfer during braking event. The total amount of load transfer remains always the same. Anti-dive controls how much of weight is transferred via suspension or just via chassis (wishbones).

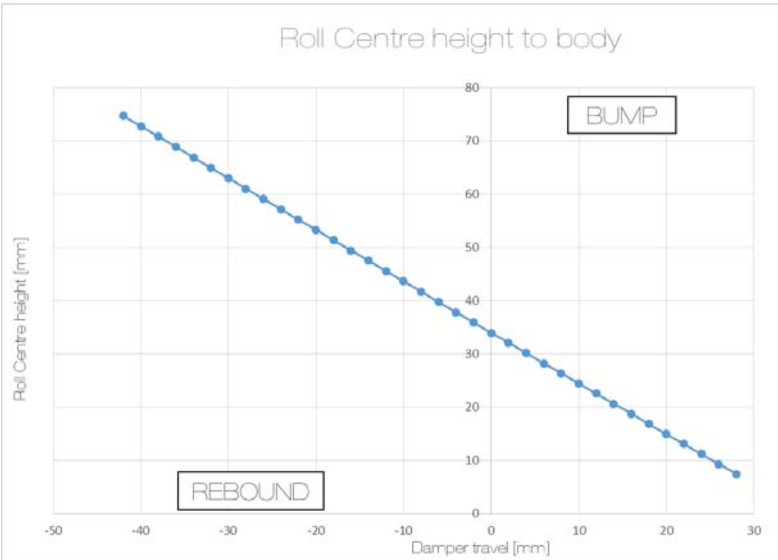


Figure 4 11 Roll Centre height to body

4.1.2 FRONT SUSPENSION ROLL CHARACTERISTICS

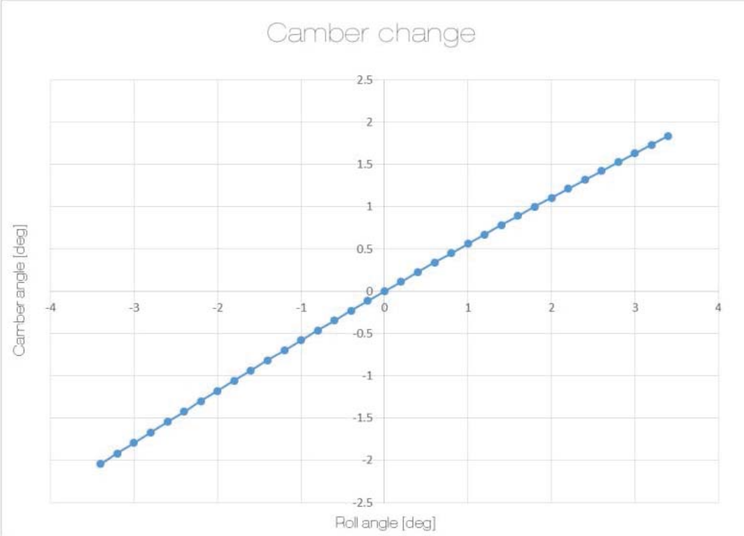


Figure 4 14 Chamber change of suspension is important from the tyres point of view. It is important to keep the tyre in the ideal position as much as possible. Here the camber trust is taken into account as well.

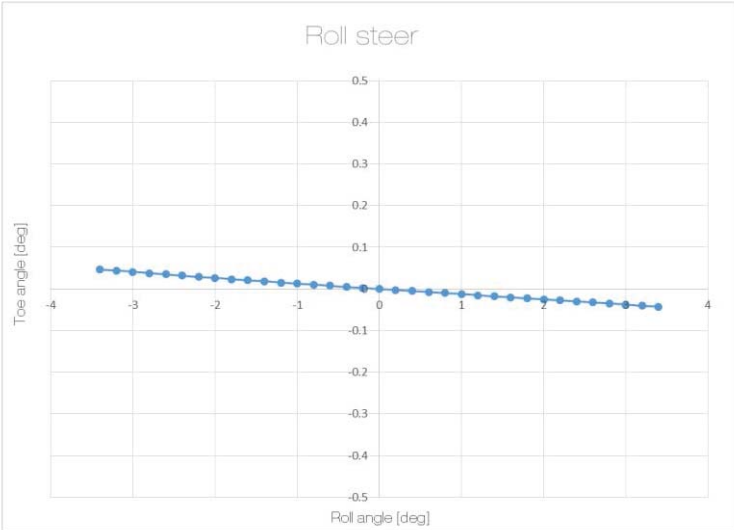


Figure 4 13 Similarly to bump steer - it is important to reduce this change as much as possible to deliver driver confidence in steering during cornering

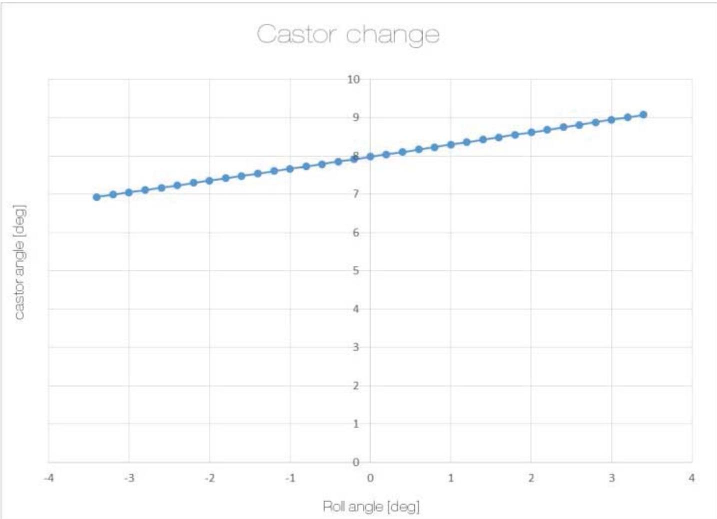


Figure 4 12 Castor Change

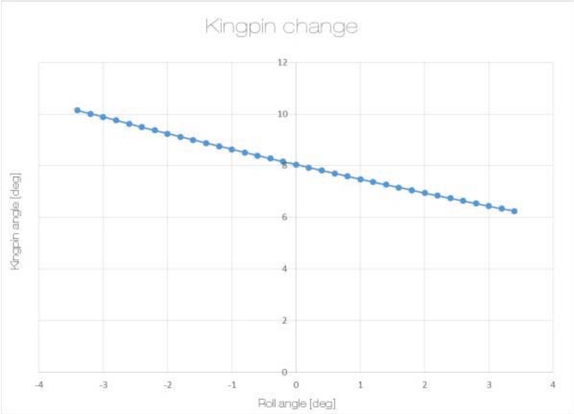


Figure 4 19 Kingpin change

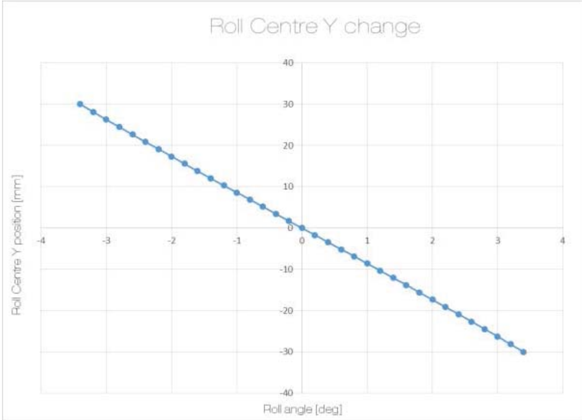


Figure 4 18 Change of roll centre position in Y direction

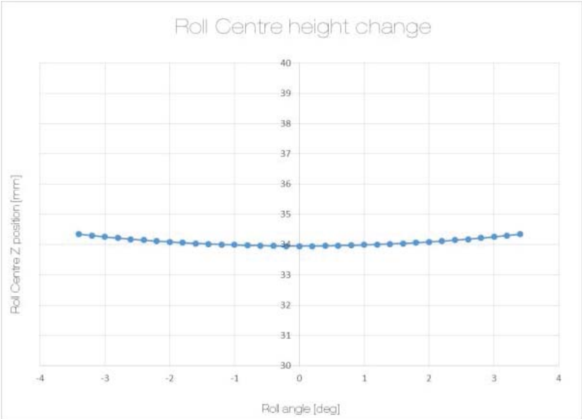


Figure 4 16 to deliver stable roll centre height is very important. If this characteristic is stable it means that load transfer during cornering phase remains the same. Hence the driver can believe the car as it responses constantly same

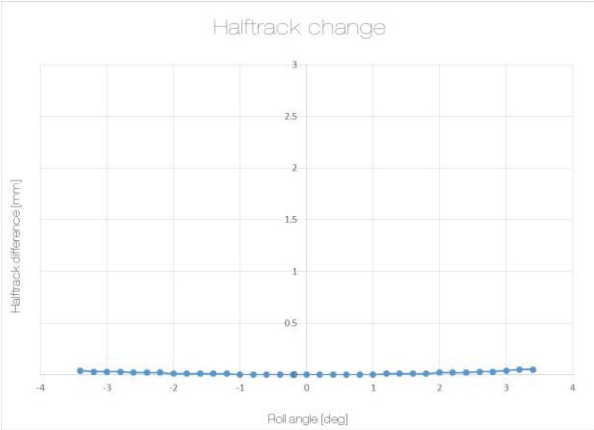


Figure 4 15 during cornering even the halftrack is changed little bit. In this case it is very small change.

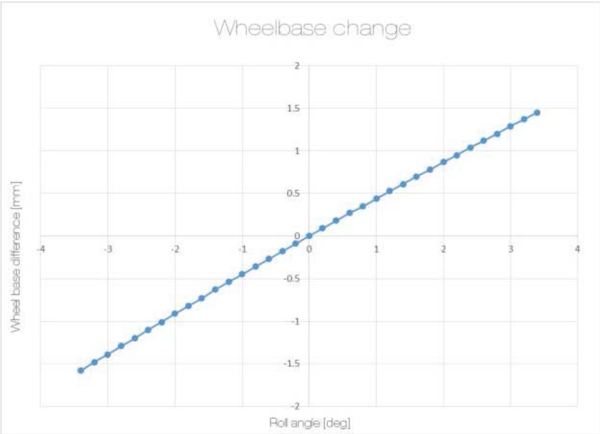
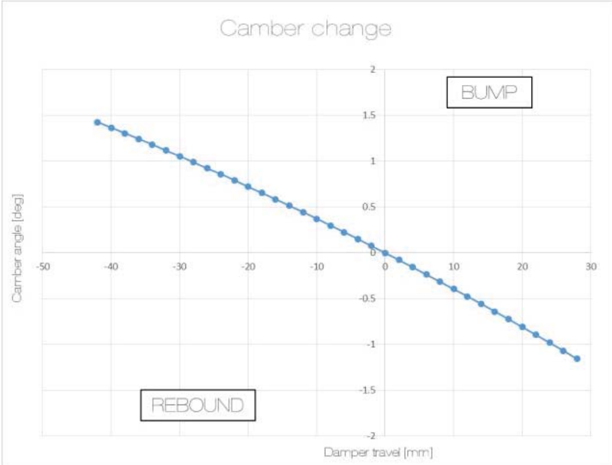


Figure 4 17 Wheelbase is changed little during roll movement

4.1.3 Rear Suspension Bump Characteristics

Figure 4 22 Camber change of the rear suspension could be smaller according to smaller load transfer during braking into a corner and cornering phase itself



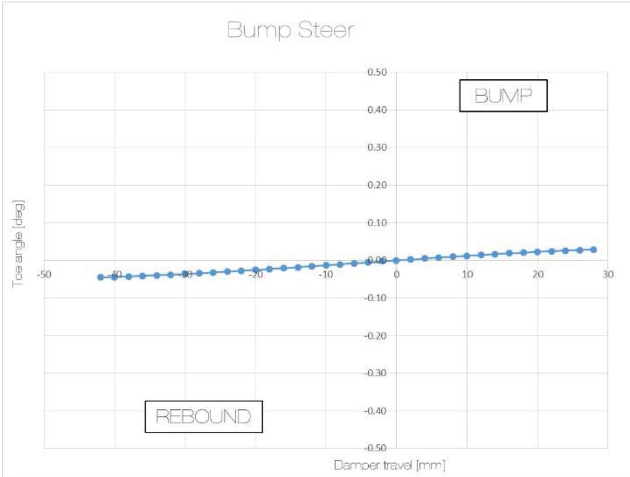


Figure 4 20 Even at rear suspension it is important to deliver as small bump steer as possible.

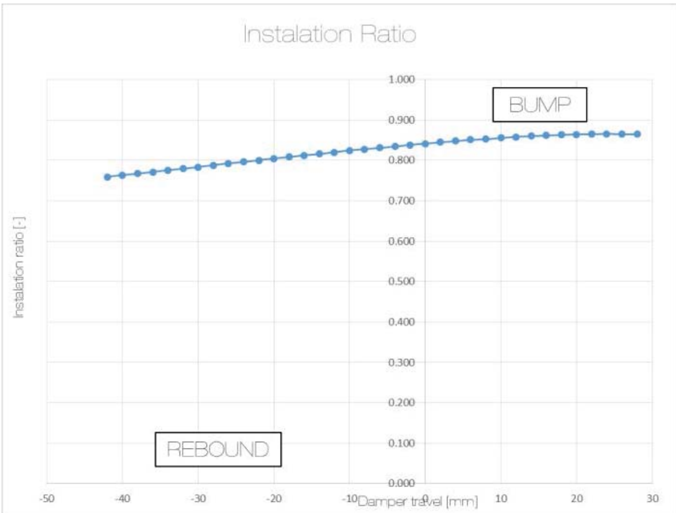


Figure 4 21 Installation ratio of rear suspension. Higher ride frequency deliver easier driveability through bumps for driver.

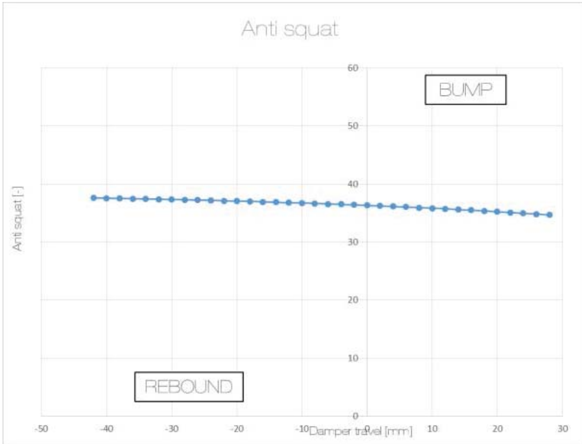


Figure 4 24 Anti squat characteristics are important for load transfer under acceleration.

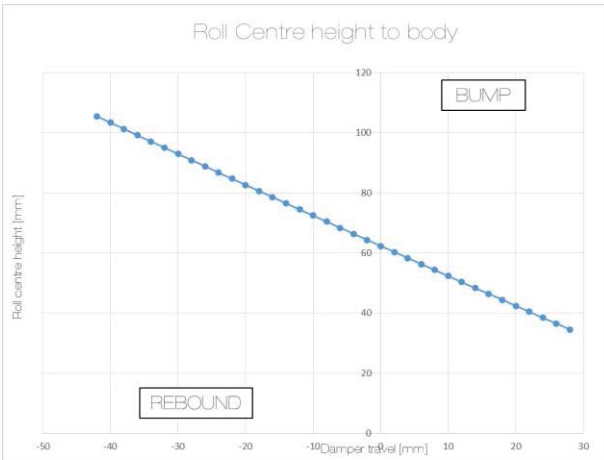


Figure 4 23 Roll centre height to body characteristics

4.1.4 Rear Suspension Roll Characteristics

Figure 4 26 Camber change in roll. This characteristic has to enable the tyre to be in ideal position according to road surface

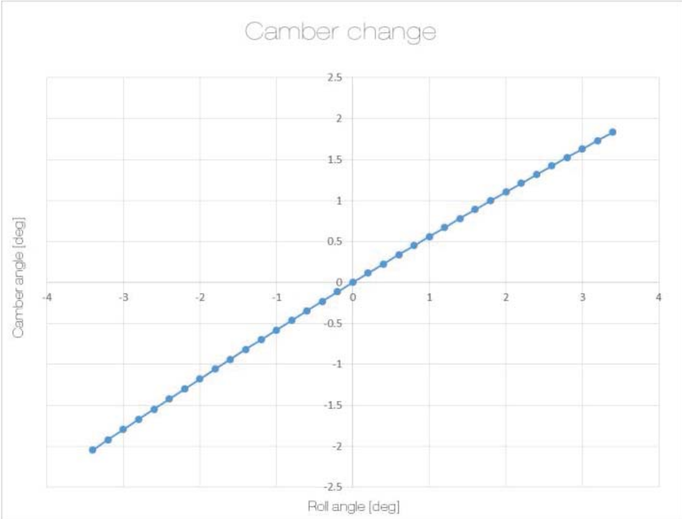
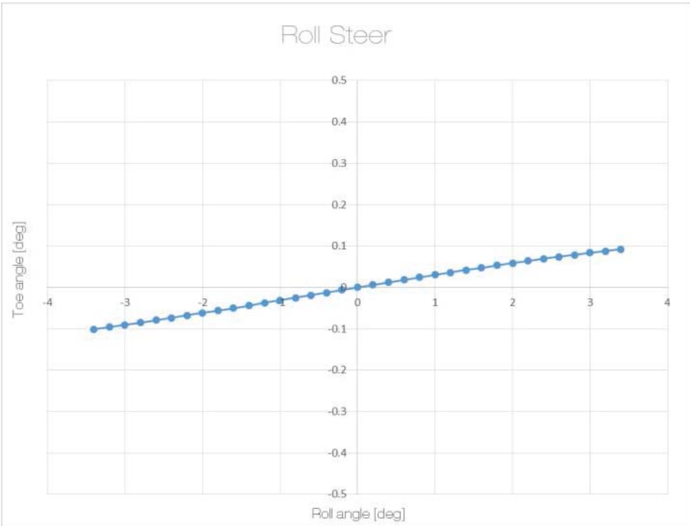


Figure 4 27 Roll steer characteristic has to be as small as possible to give the driver confidence in stable cornering behaviour



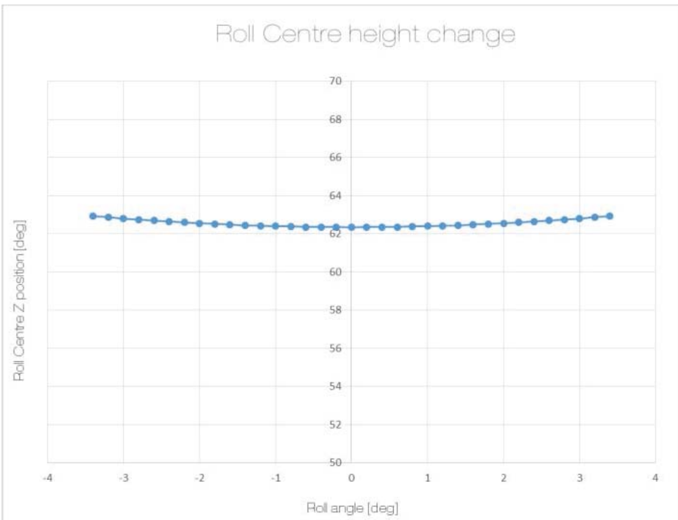


Figure 4 25 same as at front suspension it is very important to deliver as small change of roll centre height as possible. This deliver the constant load transfer characteristics in cornering.

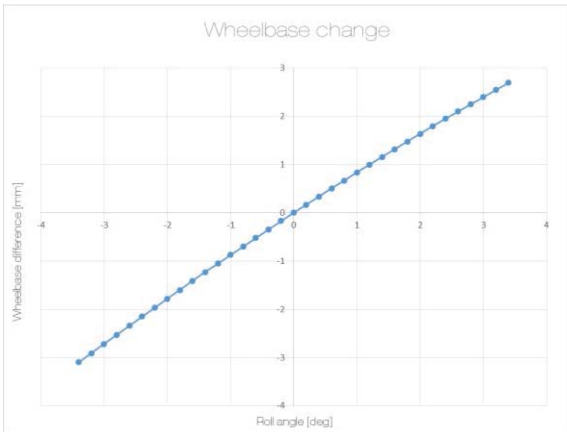


Figure 4 29 Wheelbase change of rear suspension while rolling

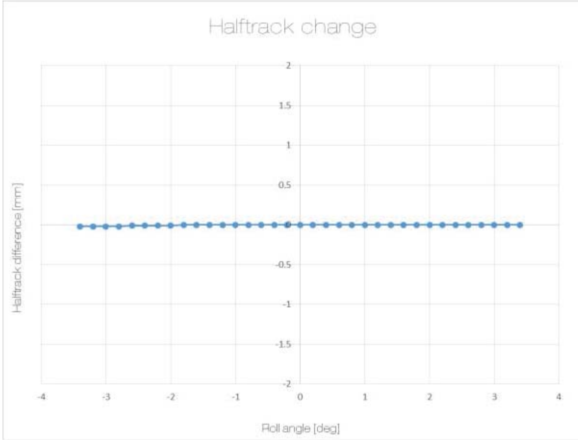


Figure 4 28 Halftrack change of rear suspension while rolling

4.1.5 Steering characteristics

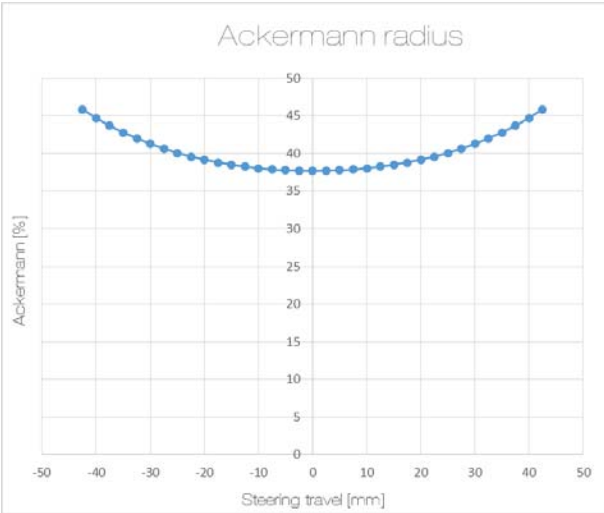


Figure 4 31 Ackermann radius determines how much is inner wheel steer differently compare to outer wheel.

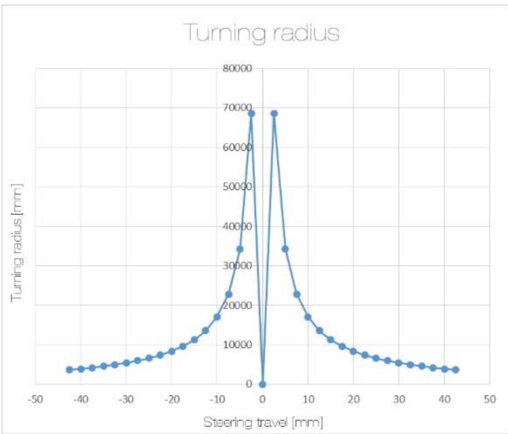


Figure 4 30 Turning radius in mm

4.2 DRAGON 4 ISSUES

During 2014 season Dragon 4 run more than 700 km. The car was tested a lot before the first competition at Formula Student Germany. One of the features of Dragon cars are different mounting points of wishbones. That means different characteristics could be tested. During testing team could understood more the tyres. The basic setup from 2013 season was improved a lot.

One of the issues was turn-in movement. The car had difficulties with turn-in understeer. As the brake balance was tested and results was satisfying team decided to try different toeing characteristics. Eventually the toe-out of front wheels was 10 mm of difference. This is quite a lot. That resulted in decision to consider different Ackermann radius for next generation.

Almost every setup possibility was tried during the test season. The car was easy to drive for every driver but there were some limitations. Racing car is very complex machine. Everything influences everything else. From kinematic point of view the biggest challenge was rear inner wheel lift during cornering phase.

The rest of problems were connected to vehicle centre of gravity. At Formula Student Hungary the car found its edge as the track surface is concrete. Probably the height of roll centres hand in hand with relatively high centre of gravity caused the high jacking effect. In other words, every single corner the car was running on two wheels.

Figure 4 32 Formula Student Hungary 5th place in Endurance while the car was cornering only on two wheels.

Even with this limitation the TU Brno Racing finished 5th in Endurance event. That was the reason to think about new configuration of suspension for next generation of Dragon 5 mainly from weight reduction point of view.

4.3 DRAGON 5

Dragon 5 aims and targets were done at the beginning of the new season. According to new engine with turbocharger, the whole powertrain unit position could be changed. Dragon 4 had spaced frame around the whole differential unit as in Figure 4.26. This configuration influenced the weight quite a lot. In the same Figure it is visible that the last part of chassis were toe-link pickup point.

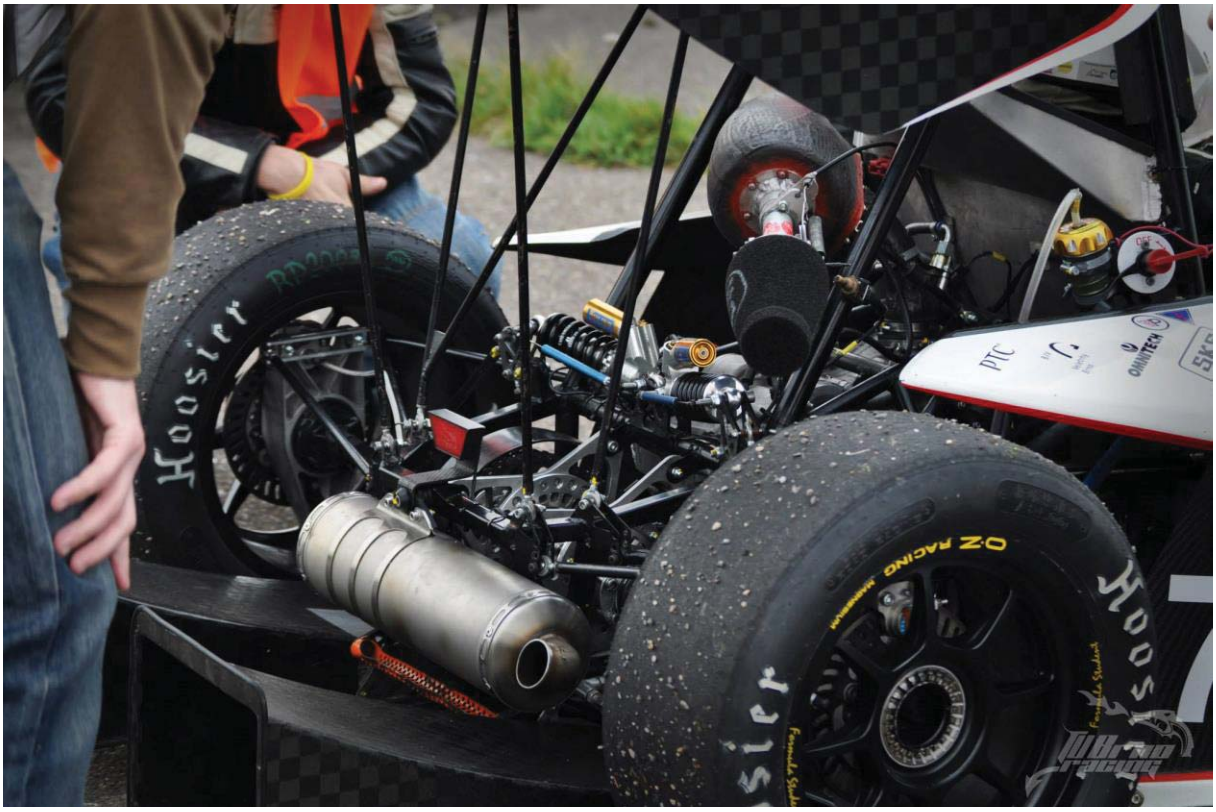


Figure 4 33 Dragon 4 rear suspension layout. The mass of space frame around differential unit was eliminated for Dragon 5

Decision to change the rear suspension from the scratch enables to reduce the weight a lot. The whole powertrain unit of Dragon 5 is hold together with aluminium mountings. Therefore the whole suspension layout could been changed. Due to centre of gravity reduction, the push rod configuration was changed to pull rod. Thanks to 13” wheels dimension it was not a big problem to find the right position of pull rod and rocker pick up points.

Whole configuration of rear suspension is visible in Figure 4.35. There is visible that even the whole upright kinematics points were changed significantly. The aim was to deliver the highest possible strength of uprights. Therefore the pickup points were chosen as close to wheel rim as possible.

There is only one compromise which was necessary to undertake. That is the toe rod chassis pickup point. Unfortunately there was no space to attach the toe rod into the chassis in a better way. Therefore the tube in that place has different dimensions (bigger thickness) and chassis team analysed the deflection in FEM. Results shown that under 3 G of cornering the deflection is less than 0.1 mm.

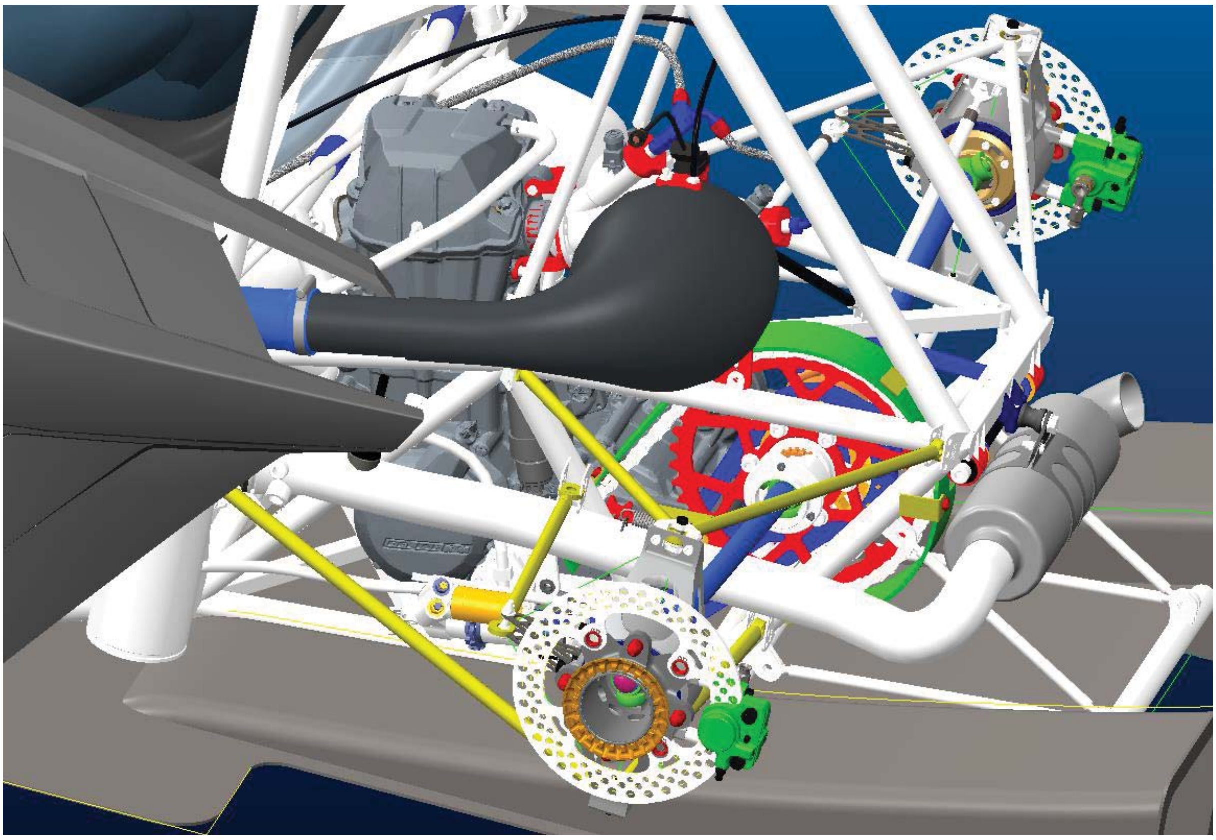


Figure 4 35 Rear Suspension Layout of Dragon 5. Everything was moved forward and the weight was reduced.

Figure 4 34 the powertrain unit of Dragon 5 is mounted into aluminium holders. This prevents to transform the biggest forces of chain into the chassis.

In Figure 4.35 is visible that except of toe link chassis pickup point all wishbones pick up points are well designed. It is always challenge to deliver such a solution which is good from kinematics and even from force transformation into the chassis point of view.

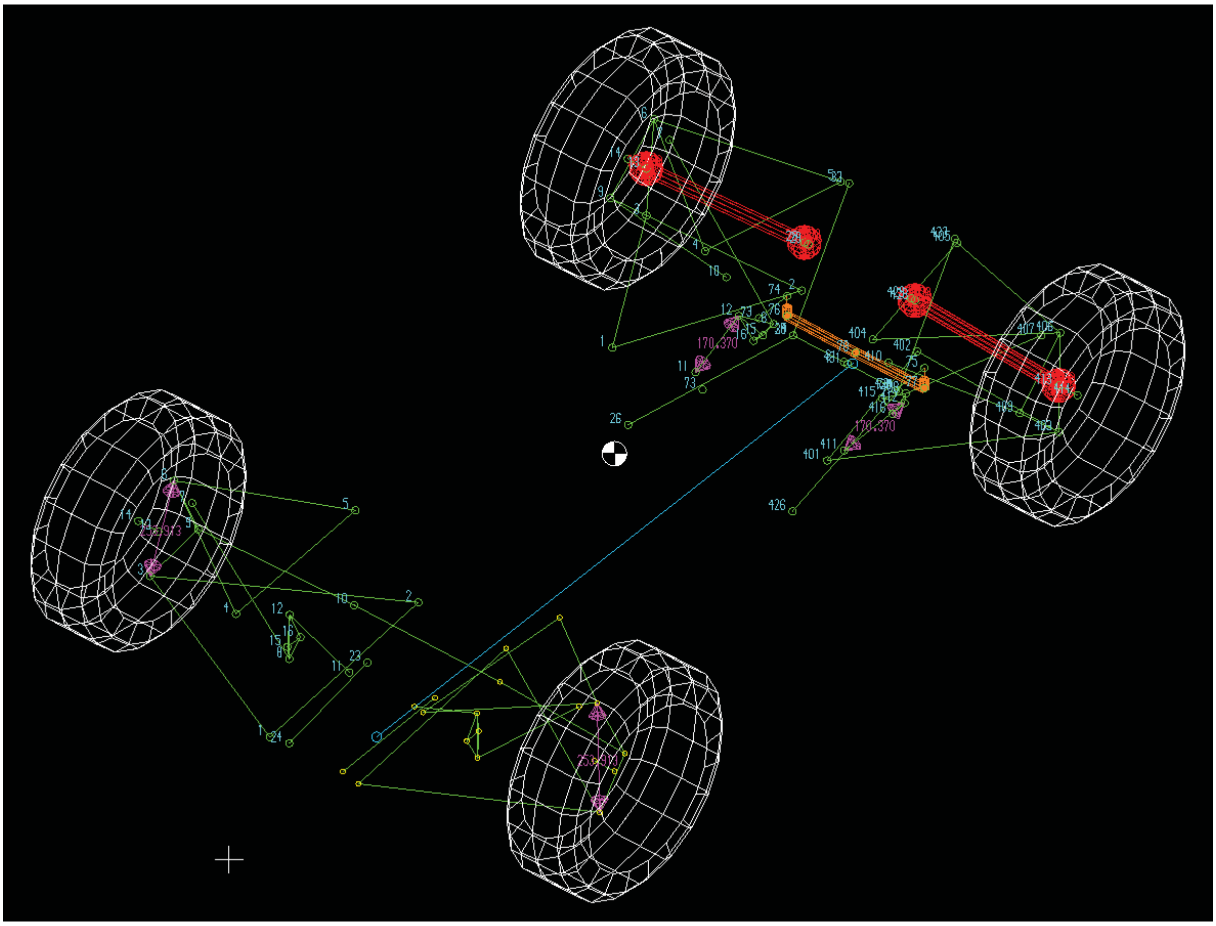


Figure 4 36 Dragon 5 suspension layout in Lotus Analysis software.

One of the decision which were made during the development and design part of the season was the wheelbase change. Based on the weight distribution measured in CAD system the wheelbase was shorten to deliver sufficient 50/50 ratio. This could bring less stable car while changing the direction but the equal weight distribution was much more important. Moreover while the research showed that the previous wheelbase was one of the longest in Formula Student competition.

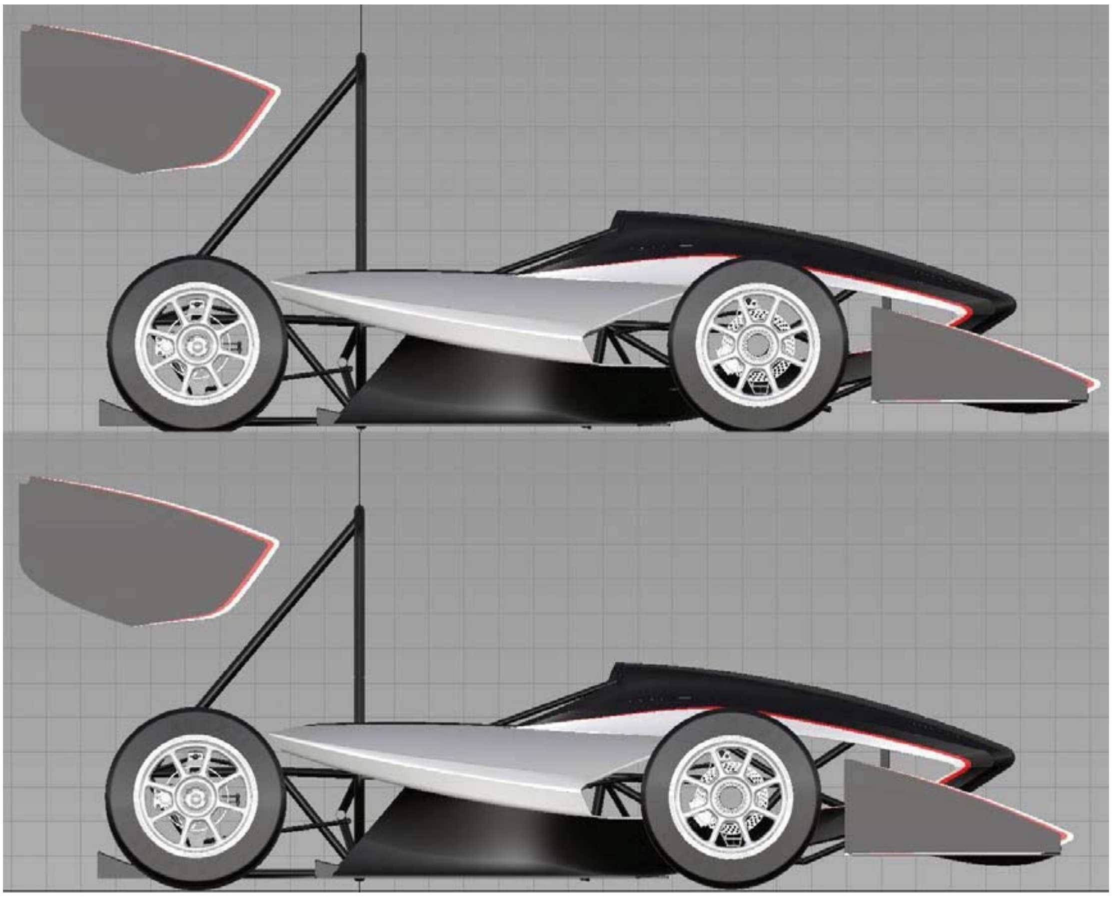


Figure 4 37 Dragon 5 different wheelbase visual comparison. Wheelbase was shorten from 1600 mm to 1527mm. Rules stipulate the 1525 mm as minimum.

4.3.1 Dragon 5 Kinematics overview

GENERAL DATA VALUES		D 1-4	Dragon 5
TYRE ROLLING RADIUS	(mm)	264.16	264.16
WHEELBASE	(mm)	1600	1527
C OF G HEIGHT	(mm)	310	290
BUMP TRAVEL	(mm):	27.5	27.5
REBOUND TRAVEL	(mm):	42.5	42.5
ROLL ANGLE	(deg):	3.5	3.5
STEERING TRAVEL	(mm):	42.75	42.75

Figure 4 38 Dragon 5 General Data Values in comparison with Dragon 1 - 4 concept

FRONT SUSPENSION

STATIC VALUES

		D 1-4	Dragon 5
Camber Angle	(deg)	0	0
Toe Angle {Plane}	(deg)	0	0
Toe Angle {SAE}	(deg)	0	0
Castor Angle	(deg)	7.98	7.98
Castor Trail (hub)	(mm)	12.55	12.55
Castor Offset (grnd)	(mm)	24.47	24.47
Kingpin Angle	(deg)	8.04	8.04
Kingpin Offset (w/c)	(mm)	52.75	52.75
Kingpin Offset (grnd)	(mm)	15.43	15.43
Mechanical Trail (grnd)	(mm)	24.23	24.23
ROLL CENTRE HEIGHT	(mm)	23.01	23.01

Figure 4 39 Dragon 5 front suspension static values in comparison with Dragon 1 - 4 concept.

REAR SUSPENSION

STATIC VALUES

		D1-4	Dragon 5
Camber Angle	(deg)	0	0
Toe Angle {Plane}	(deg)	0	0
Toe Angle {SAE}	(deg)	0	0
Castor Angle	(deg)	-12.93	3.42
Castor Trail (hub)	(mm)	-28.41	7.4
Castor Offset (grnd)	(mm)	-32.22	8.39
Kingpin Angle	(deg)	2.1	1.9
Kingpin Offset (w/c)	(mm)	53.78	53.56
Kingpin Offset (grnd)	(mm)	44.52	44.77
Mechanical Trail (grnd)	(mm)	-31.4	8.37
ROLL CENTRE HEIGHT	(mm)	62.35	34.6

Figure 4 40 Dragon 5 Rear suspension static values in comparison with Dragon 1 - 4 concept.

The Figure 4.39 shows that even the wishbones chassis pickup points were changed the overall characteristics remains the same. The biggest decision was with roll centre height. The aim was to reduce it at the very beginning. Fortunately the mistake in tyre configuration showed that the real height is the same which were wanted for Dragon 5.

The Figure 4.40 shows how different the rear axle is. The most important is the roll centre height. It is believed that the roll centre height at rear was too high and it delivered the problem with rear inner wheel lift during corners. Still the rear roll centre remains higher than front. It is due to narrower rear axle and the Centre of gravity centroid – the centre of gravity at rear is higher than on the front axle.

4.3.2 FRONT SUSPENSION BUMP CHARACTERISTICS

Figure 4 43 Camber change of Dragon 5 is basically identical as Dragon 4 version

Figure 4 42 Bump steer remains as small as possible even at Dragon 5

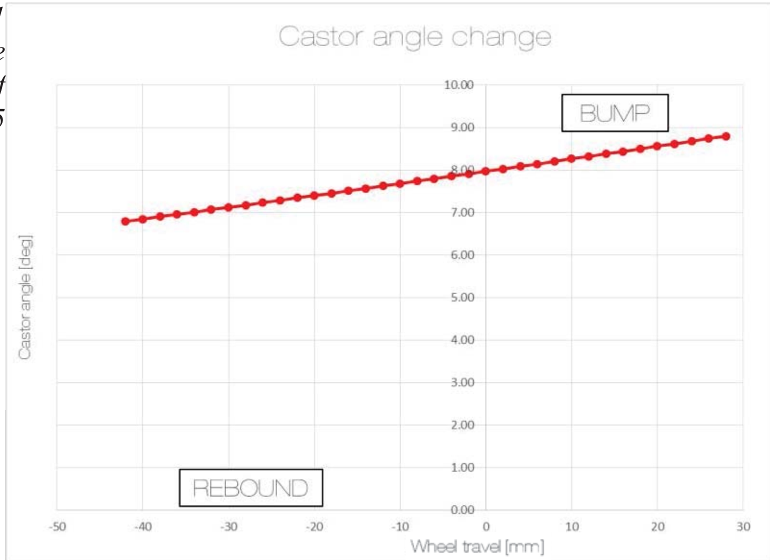


Figure 4 41 Castor angle change of Dragon 5

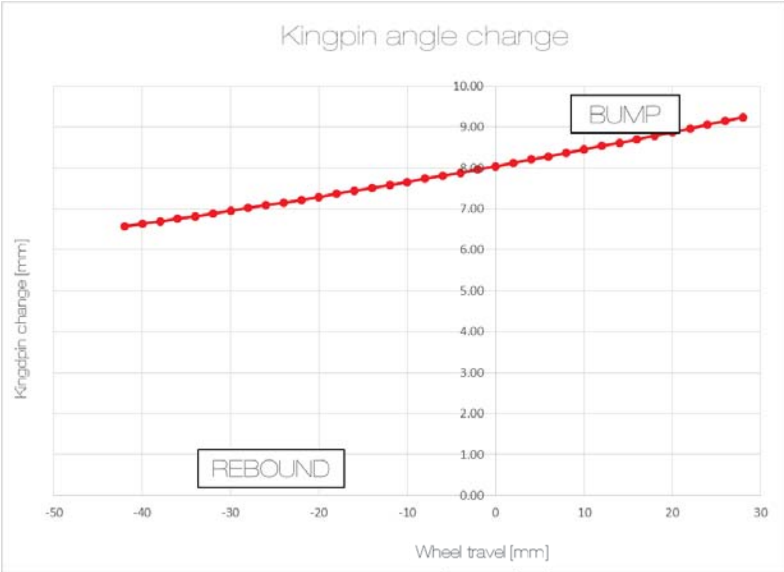


Figure 4 46 Kingpin angle change

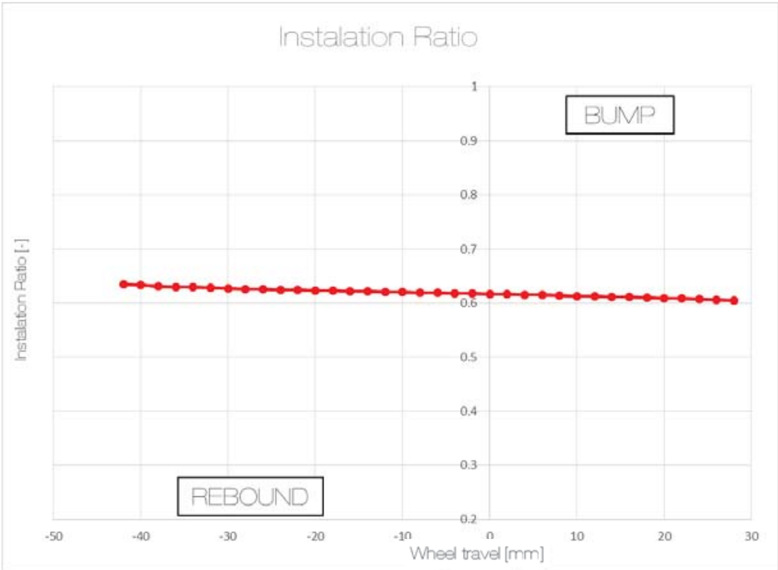


Figure 4 45 Instalation Ratio of Dragon 5 Front suspension

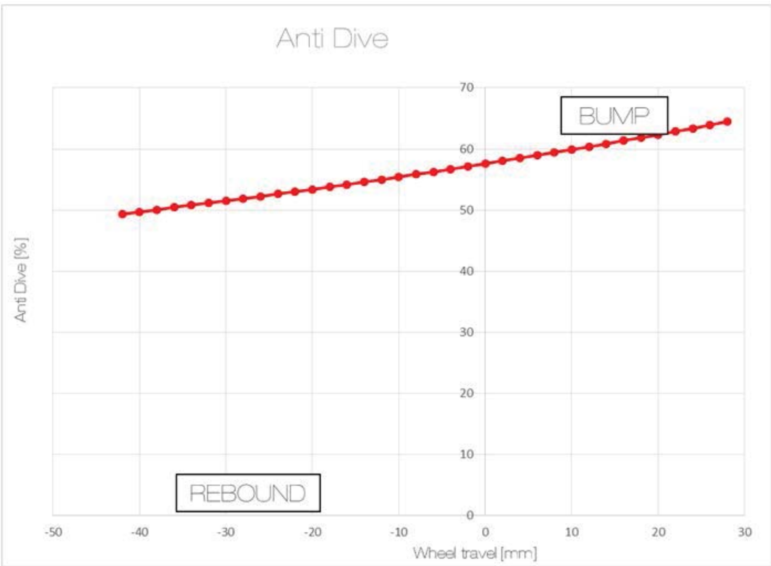


Figure 4 44 Anti Dive characteristics remain the same. If necessary from aerodynamics point of view it can be adjusted

Figure 4 49 Roll centre height to body

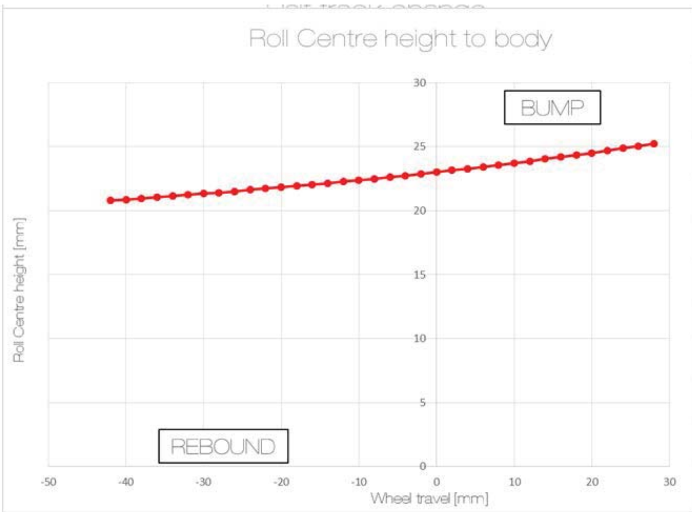


Figure 4 48 Halftrack change

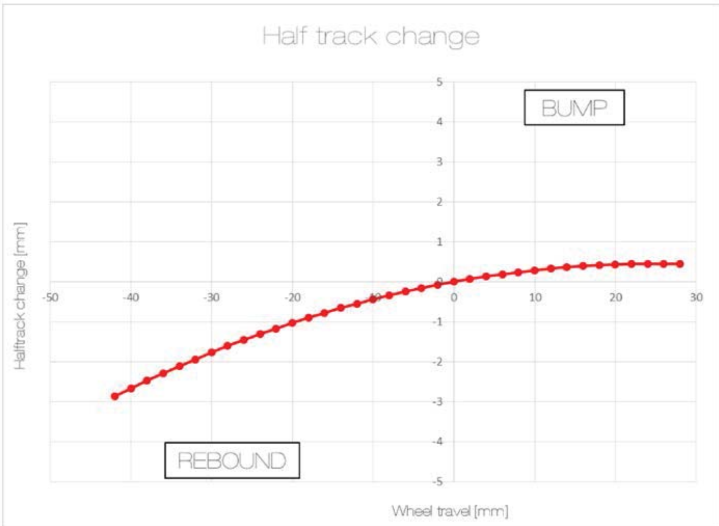
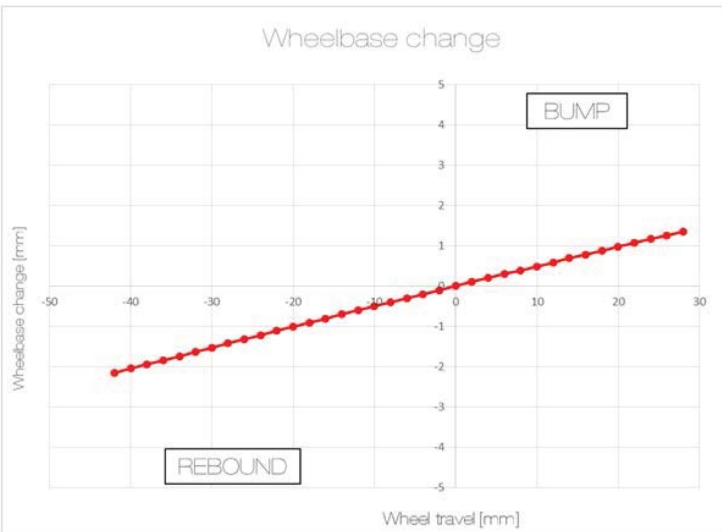


Figure 4 47 Wheelbase change



4.3.3 Front Suspension Roll Characteristics

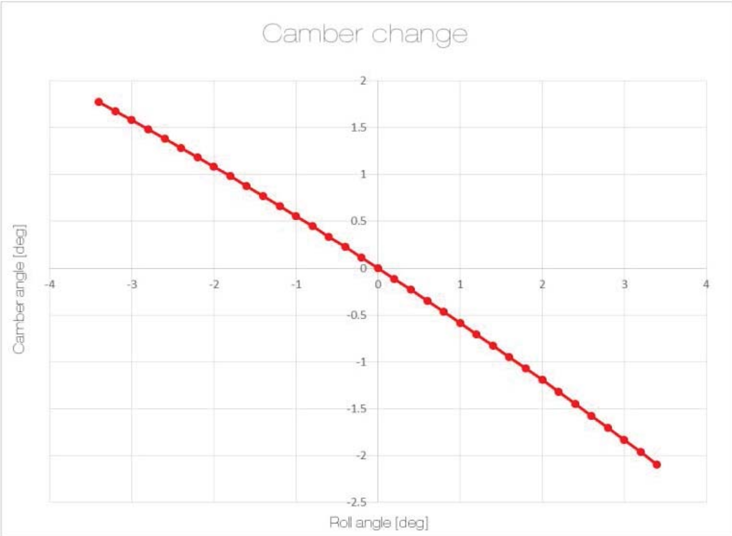


Figure 4 50 In roll it is important to allow tyre to have as big as possible contact patch all the time.

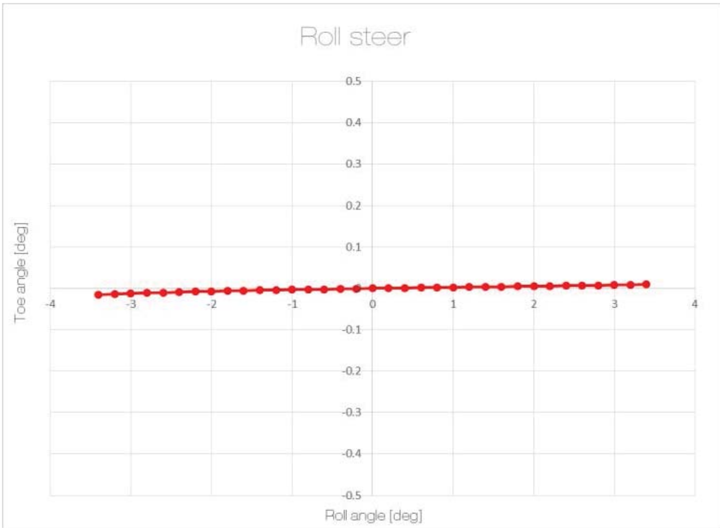


Figure 4 51 during cornering it is important to deliver driver confidence while steering. That means to deliver stable response from steering wheel within the whole range of roll

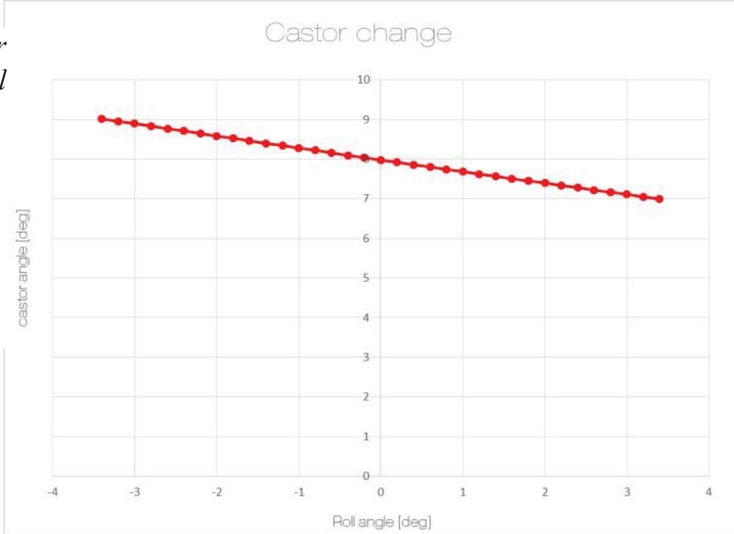


Figure 4 54 castor change in roll

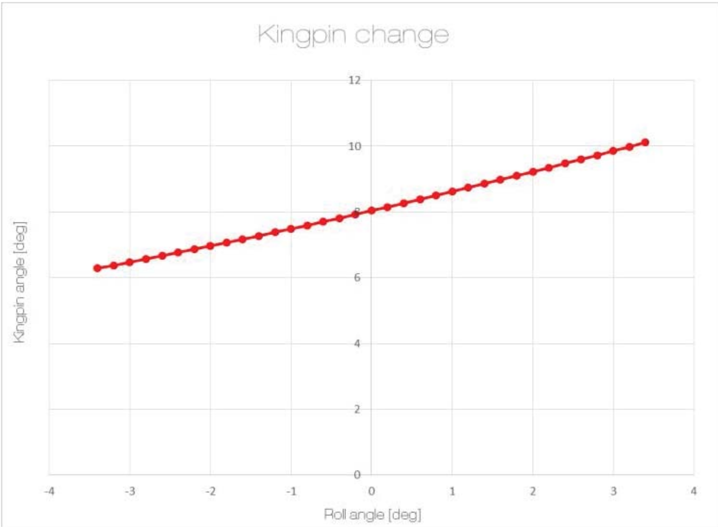


Figure 4 53 Kingpin angle change in roll

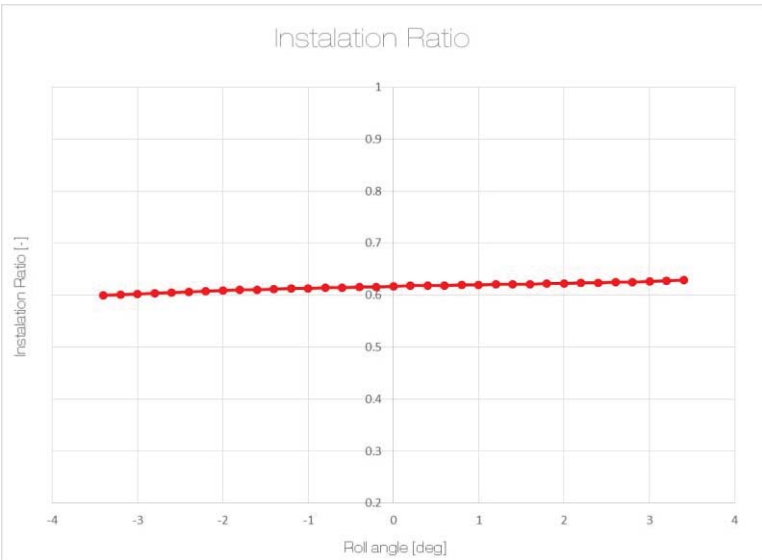


Figure 4 52 Installation Ratio remains the same in bump and in roll movement.

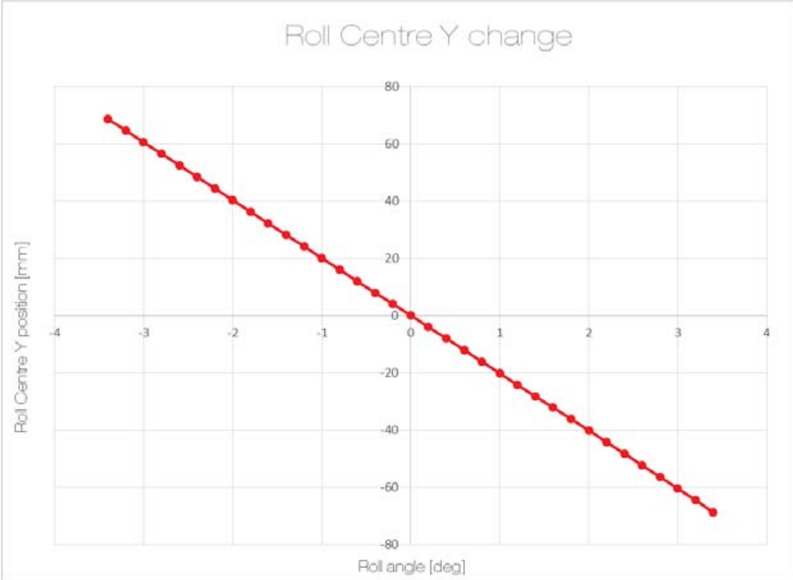


Figure 4 57 Roll centre migration in Y axis. This does not influence load transfer during cornering.

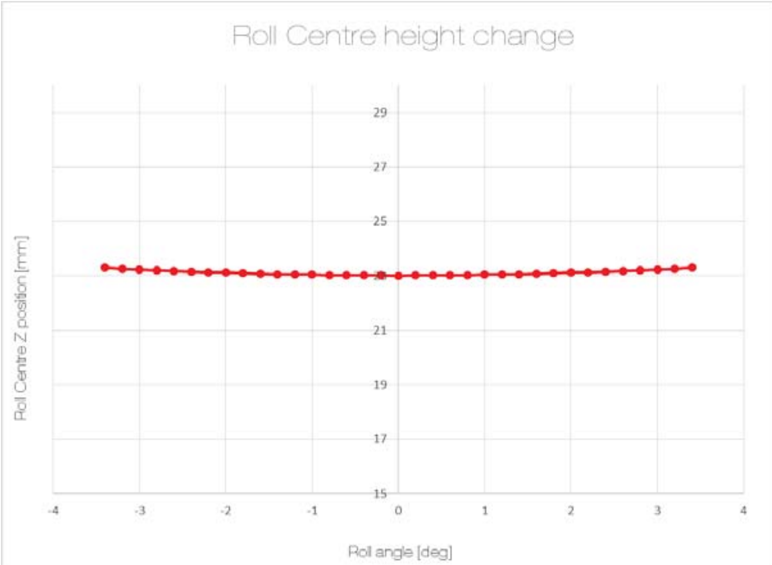


Figure 4 56 One of the most important characteristics. It is necessary to deliver consistent height of roll centre. This ensures the constant amount of load transfer in cornering action.

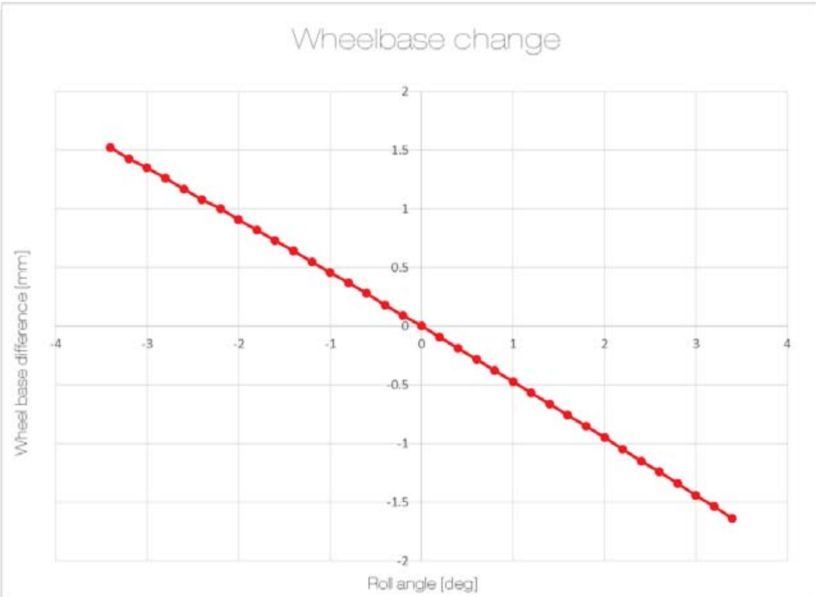


Figure 4 55 wheelbase change in roll

4.3.4 REAR SUSPENSION BUMP CHARACTERISTICS

Figure 4 60 Camber change or rear suspension

Figure 4 59 Bump Steer characteristic. It is important to design this feature as small as possible as it makes driveability of the car in corners convenient..

Figure 4 58 Rear Suspension installation ratio changed little bit. The whole unit was changed from push rod to pull rod configuration.

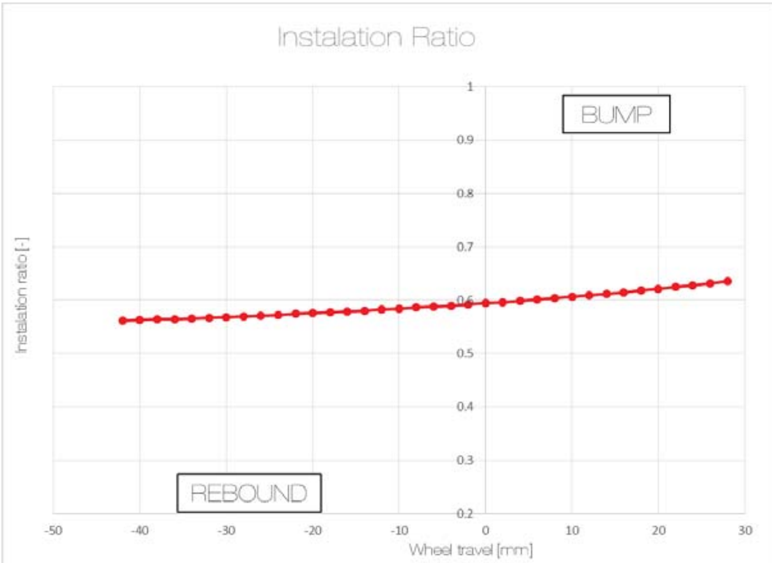


Figure 4 62 Anti squat feature determines the amount of load transfer acting on rear axle via suspension or via chassis (wishbones)

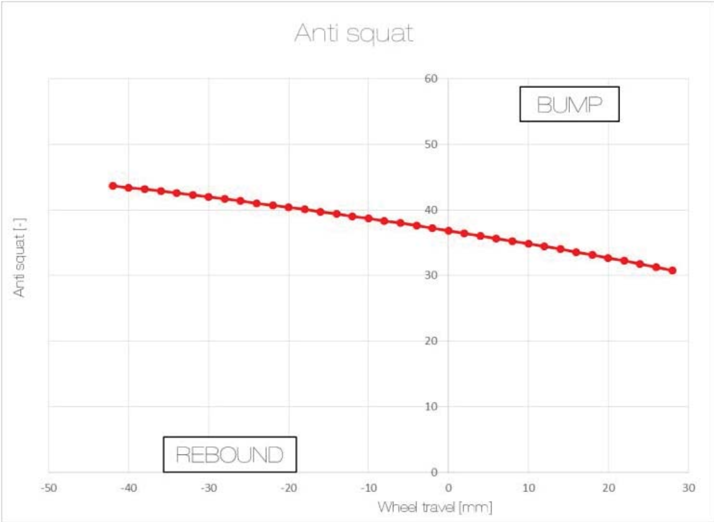
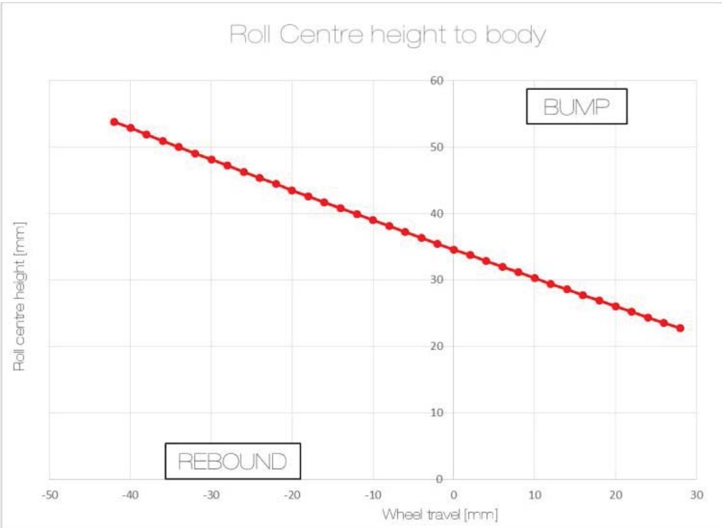


Figure 4 61 Roll Centre height according to body



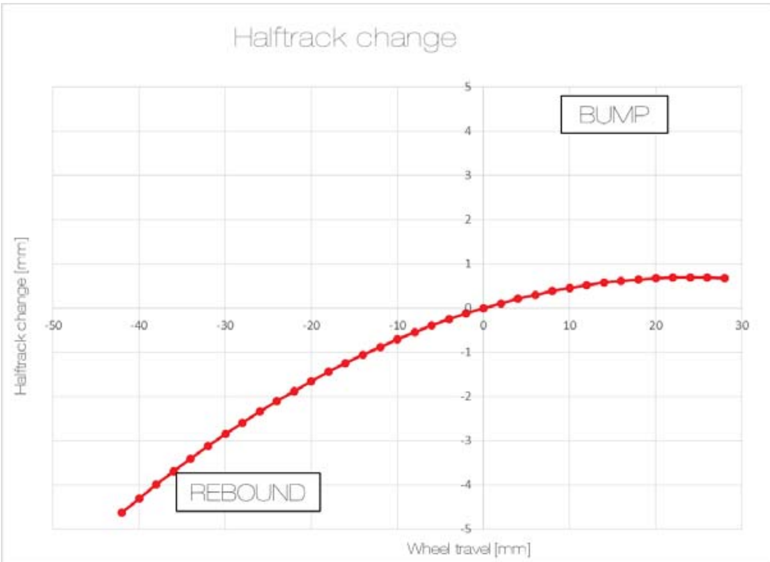


Figure 4 63 Halftrack change

4.3.5 Rear Suspension Roll Characteristics

Figure 4 66 Camber change in roll. This try to satisfy tyre characteristics.

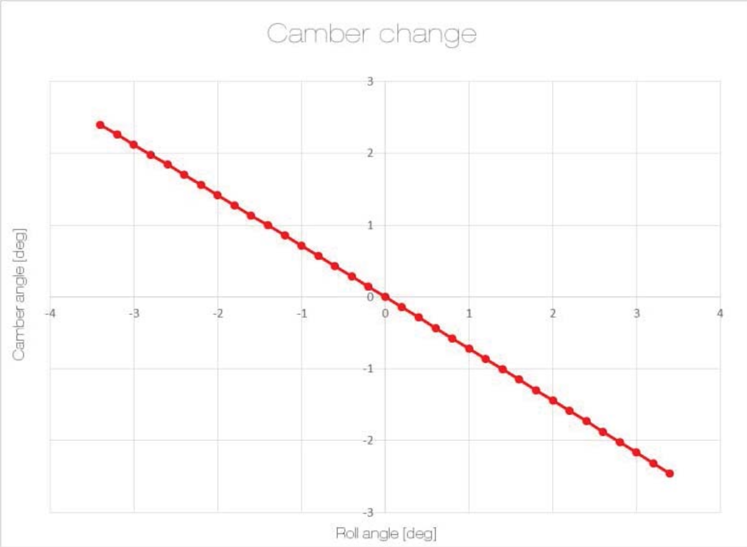


Figure 4 65 Roll steer should be zero ideally as it ensures stable response to driver while cornering.

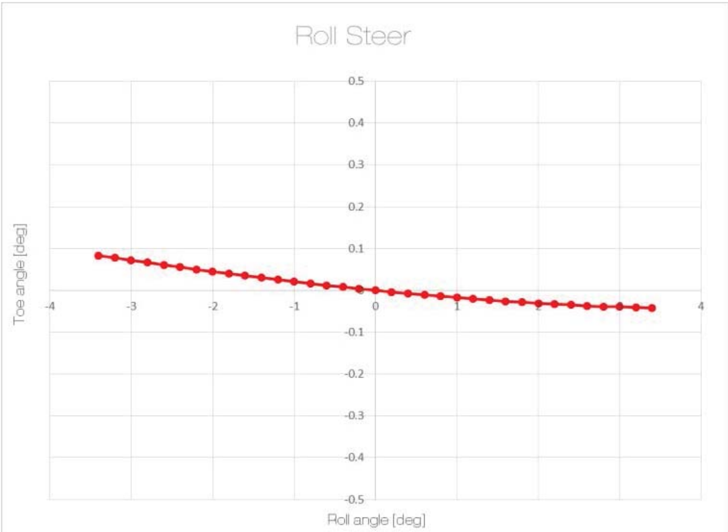


Figure 4 64 Roll centre height change should be as small as possible. In this case it is around 3 mm in operative range.

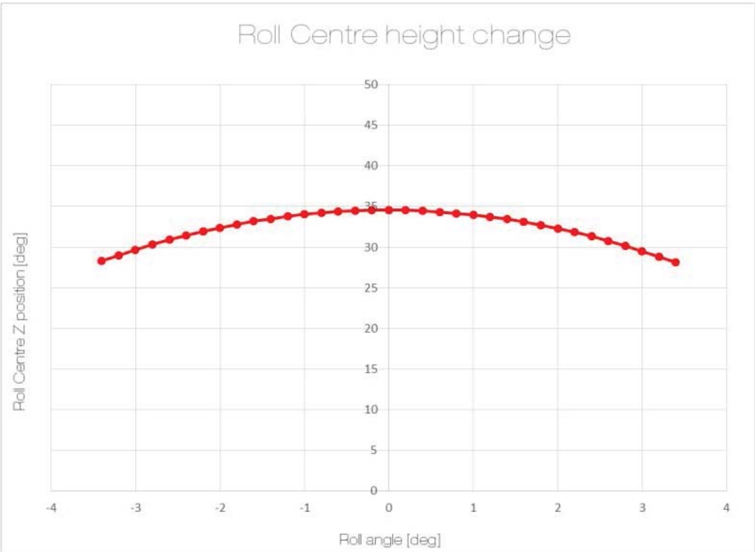
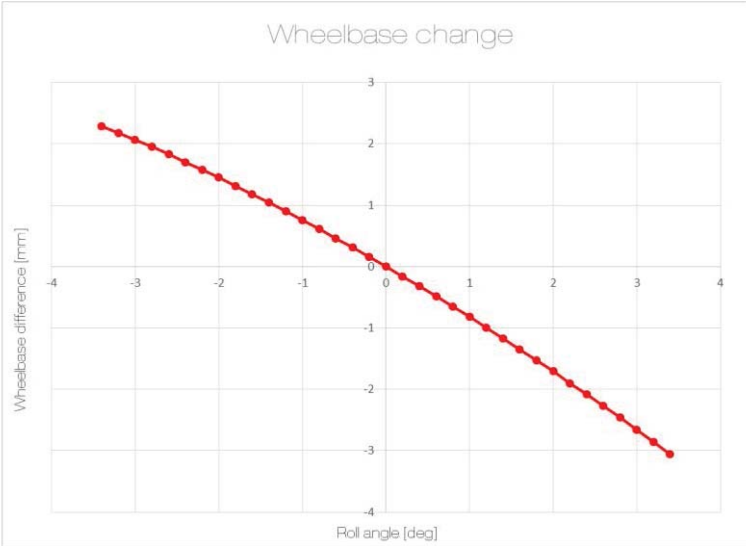


Figure 4 68 wheelbase change in roll



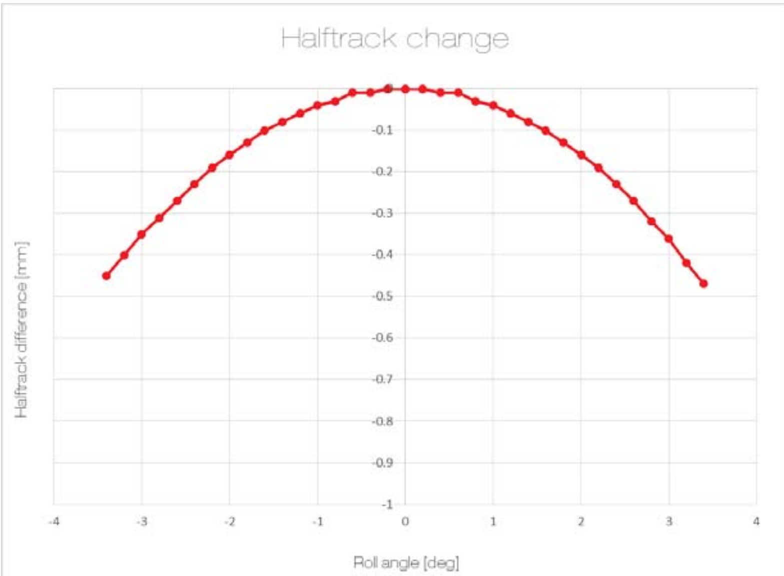


Figure 4 67 in roll movement the halftrack is changed. In this case it is roughly 0.2 mm in operative range

4.3.6 STEERING CHARACTERISTICS

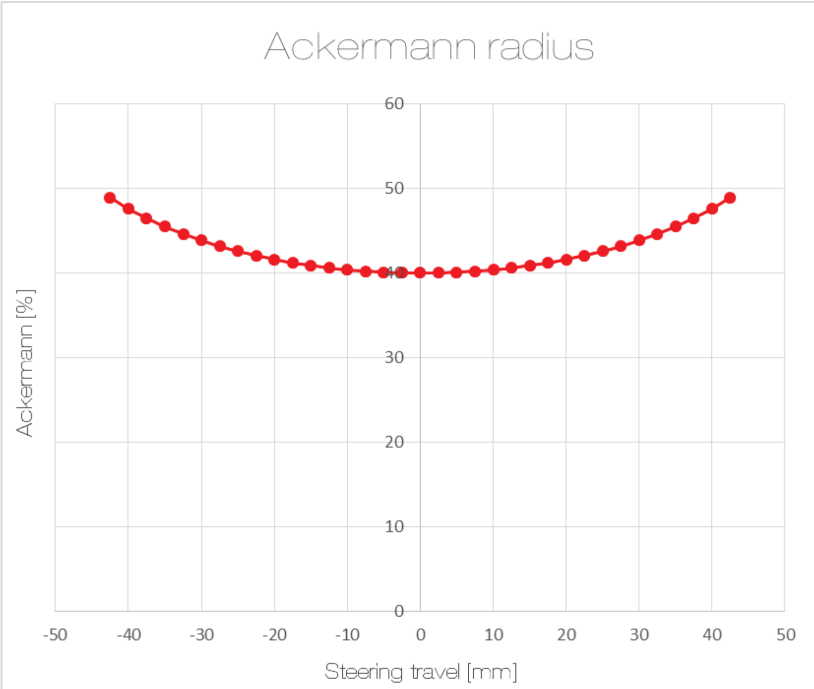


Figure 4 69 Ackermann Radius is one of features which was changed to deliver better turn-in response.

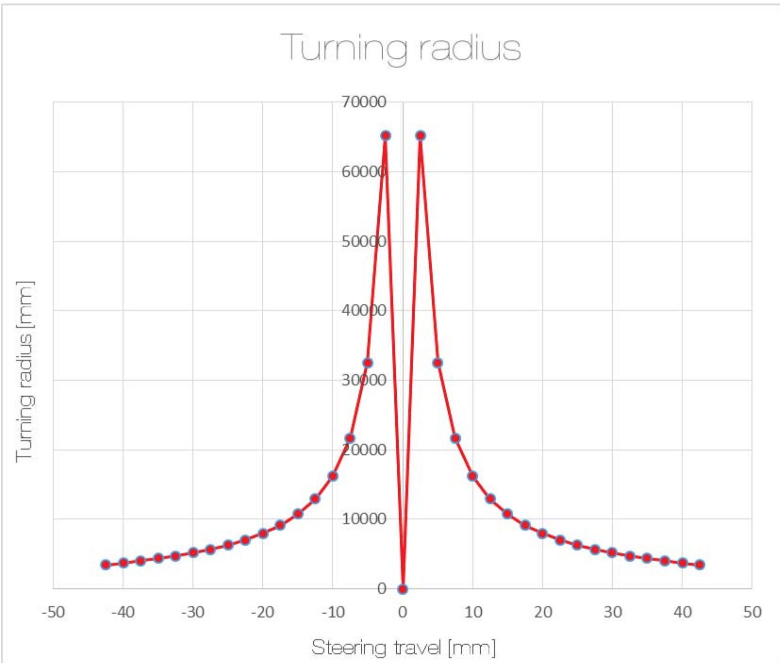


Figure 4 70 Turning radius

4.4 DRAGON 1 – 4 COMPARED WITH DRAGON 5 CHARACTERISTICS

While the team was satisfied with the most of kinematic characteristics with Dragon 4 the aim was to deliver very similar characteristics for Dragon 5. As was mentioned previous, the rear suspension was changed dramatically. The compromise which was necessary at the rear axle in connection with powertrain unit change changed a little rear characteristics. The rear roll centre height was changed on purpose as it should deliver better cornering behaviour.

4.4.1 FRONT SUSPENSION BUMP CHARACTERISTICS

Figure 4 72 Camber angle remains equal

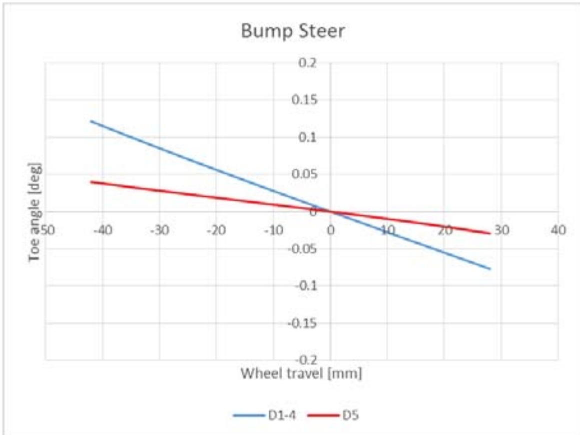


Figure 4 71 the great characteristic of Dragon 1 - 4 bump steer has been even improved.

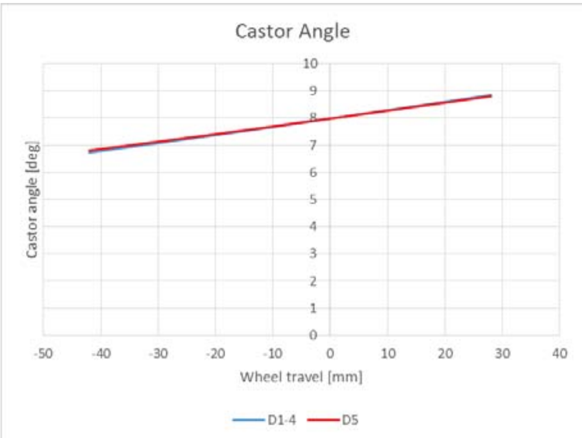


Figure 4 74 There was no reason to change front uprights pickup points. Therefore the castor angle of Dragon 5 uses the same value as its predecessors.

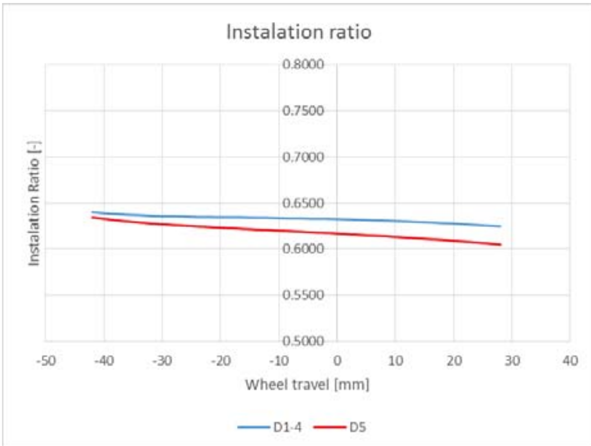


Figure 4 73 According to Y axis range the change of installation ratio is absolutely minimal.

4.4.2 Front Suspension Roll Characteristics

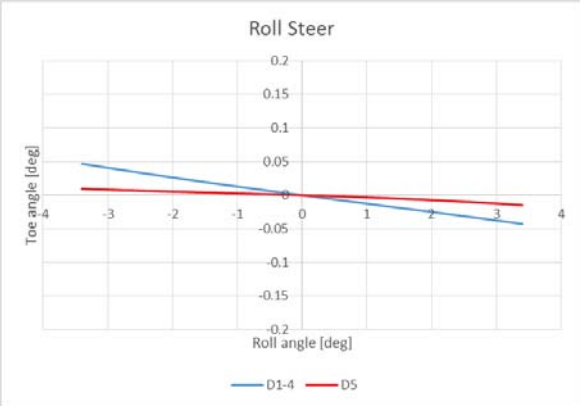


Figure 4 76 Roll steer is really important factor. While TU Brno Racing don't have professional drivers it is important to design suspension which is really easy to drive. This improvement could help this demand.

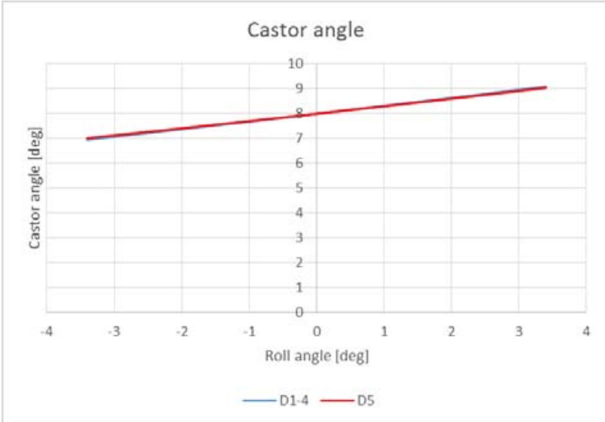


Figure 4 77 Castor angle is still the same as the upright pickup points remain the same as well. The only change was with toe link pickup point. However this change cannot be visible in this graph.

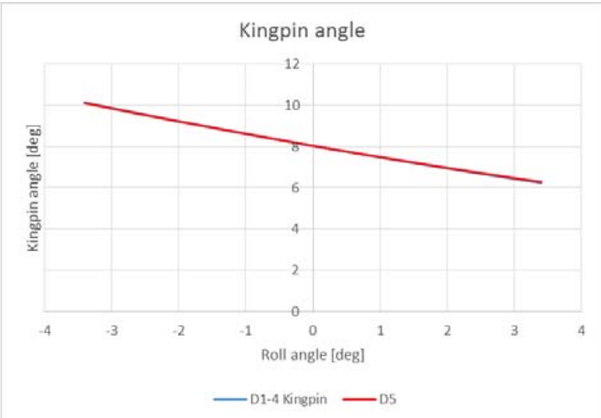


Figure 4 78 Kingpin angle is determined with the upright pickup points geometry which remains the same for Dragon 5

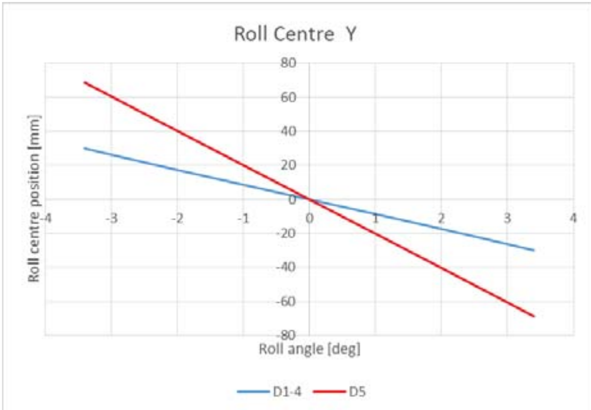


Figure 4 75 Migration of roll centre in Y axis does not influence the load transfer. Therefore this compromise was undertaken.

4.4.3 Rear Suspension Bump Characteristics

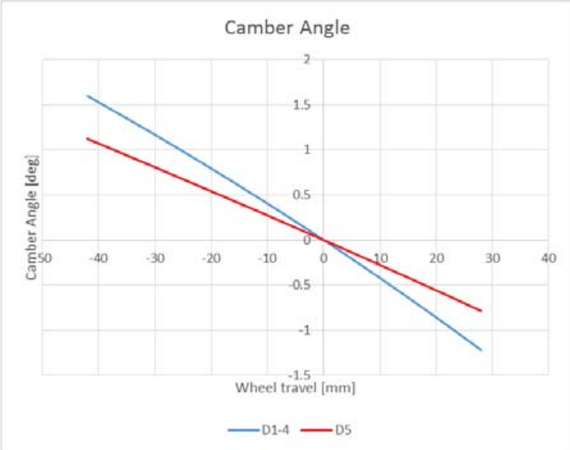


Figure 4 80 Camber angle characteristics are slightly different as the chassis compromises had to be done.

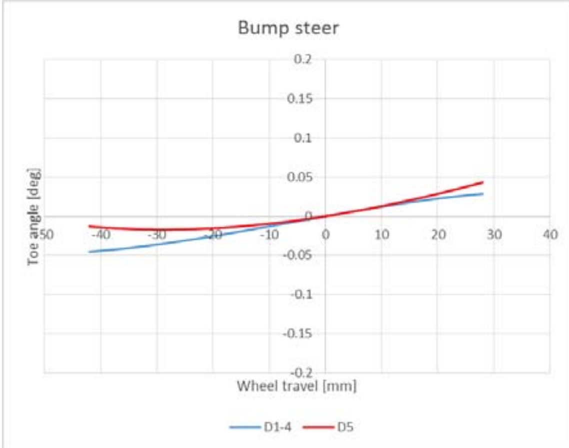


Figure 4 79 Bump steer characteristic is truly important. Comparison between the Dragon 1 - 4 and Dragon 5 shows small improvement in new generation. But the change is really small

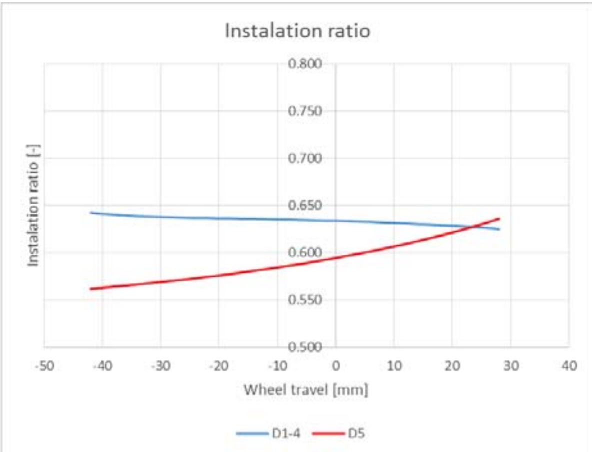


Figure 4 82 absolutely new position and configuration of rockers delivers slightly different installation ratio. In bump the Installation ratio raises. This is purpose as this prevents the tough contact at damper stop.

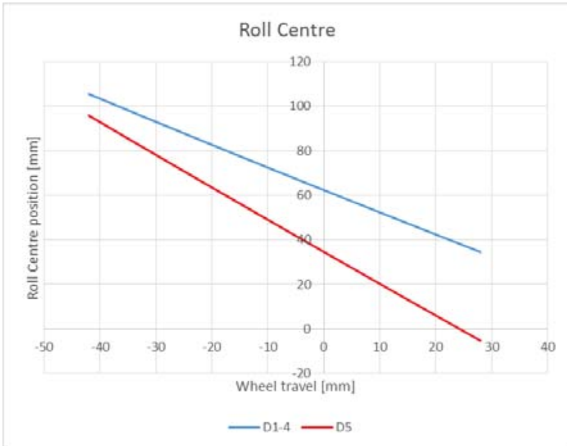


Figure 4 81 Roll centre height was reduces quite significantly. The reason was to get rid of jacking effect in cornering.

4.4.4 Rear Suspension Roll Characteristics

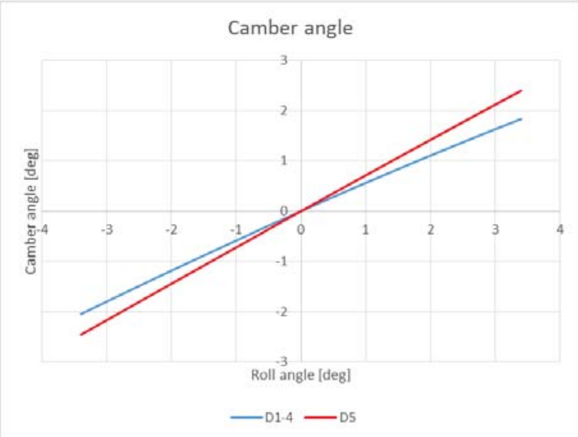


Figure 4 84 camber angle in roll is very similar. That was purpose.

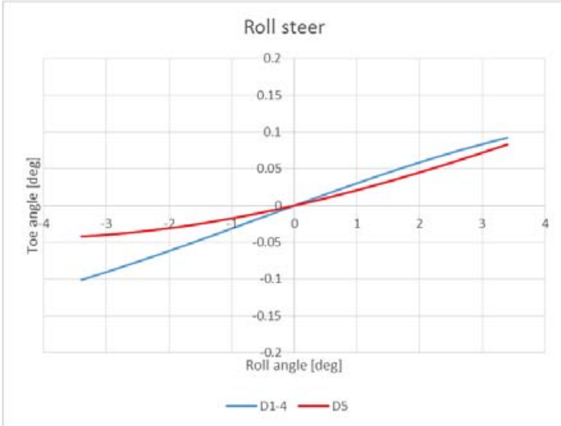


Figure 4 85 Roll steer characteristics were improved little bit even at rear axle.

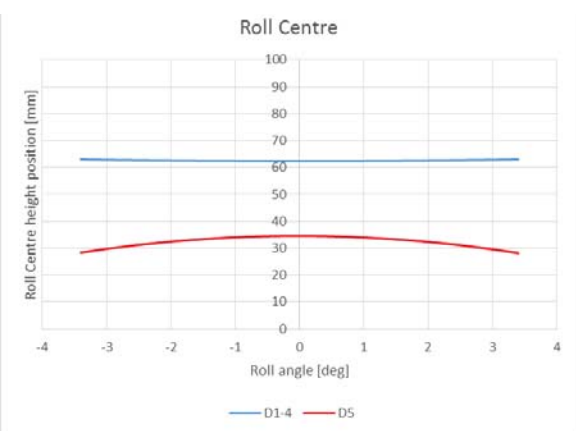


Figure 4 83 Roll centre height of Dragon 4 is slightly different than it was intended to be. This is done by compromises with chassis layout. However the change in operational range is 3 mm in maximum. This should not be any problem in real racing situation.

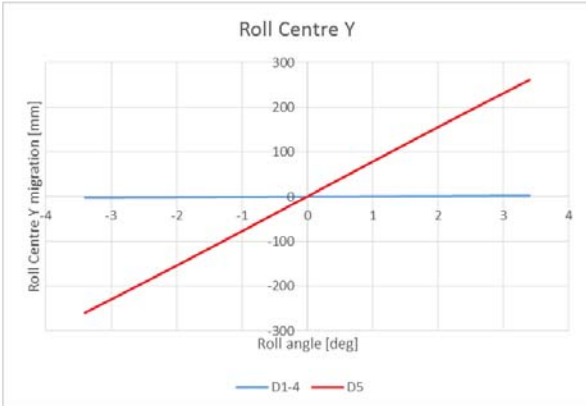


Figure 4 87 migration of roll centre in Y axis was zero at Dragon 1 – 4 concept. This characteristic was changed according to new layout of rear suspension. In general it is said that only height influences load transfer a lot. Migration in Y axis was not considered as a problem.

Figure 4 86 wheelbase change is almost identical.

4.4.5 Steering Characteristics

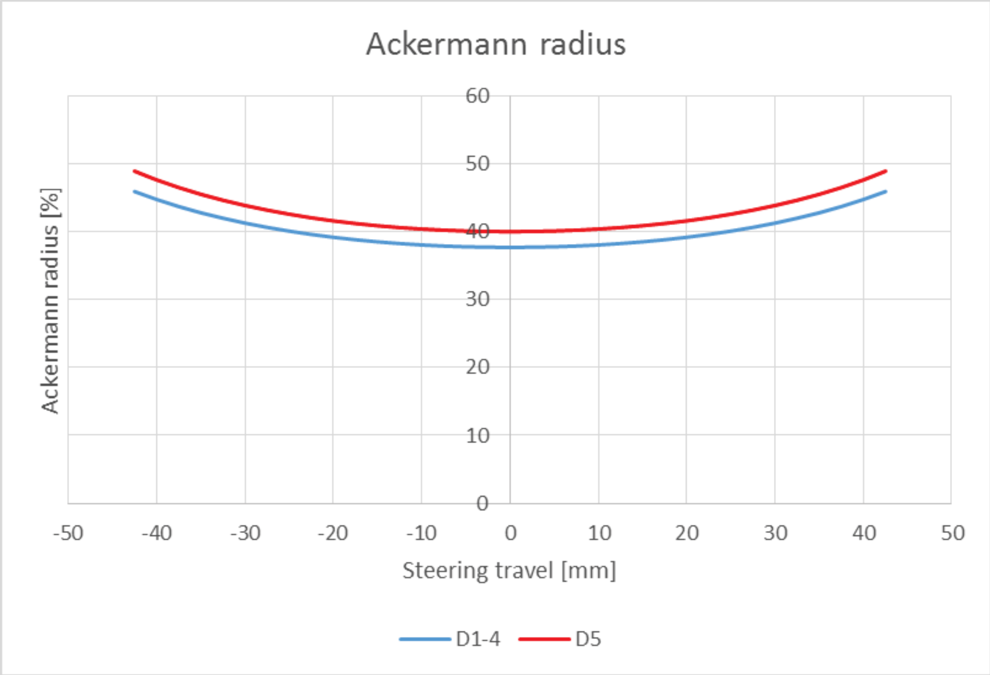


Figure 4 88 Based on experience with turn-in behaviour problems the Ackermann radius was changed. This should prevent of having such a huge amount of toe-out as with Dragon 4. Dragon 4 run 10 mm of toe-out.

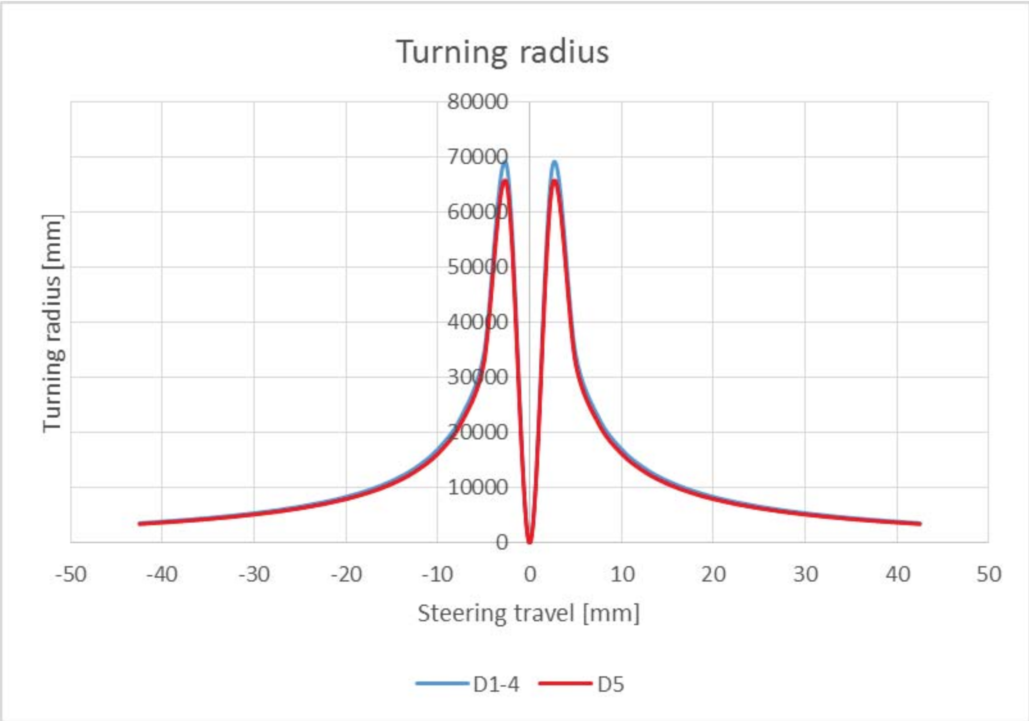


Figure 4 89 Turing radius of Dragon 1 - 4 and Dragon 5.

4.5 UH 18 KINEMATICS

Author of this diploma thesis participated on kinematics design in UH Racing – Formula Student team of University of Hertfordshire while his Erasmus studies there. The experience has been priceless as UH Racing run 10 inch tyres compared to 13 inch of TU Brno Racing.

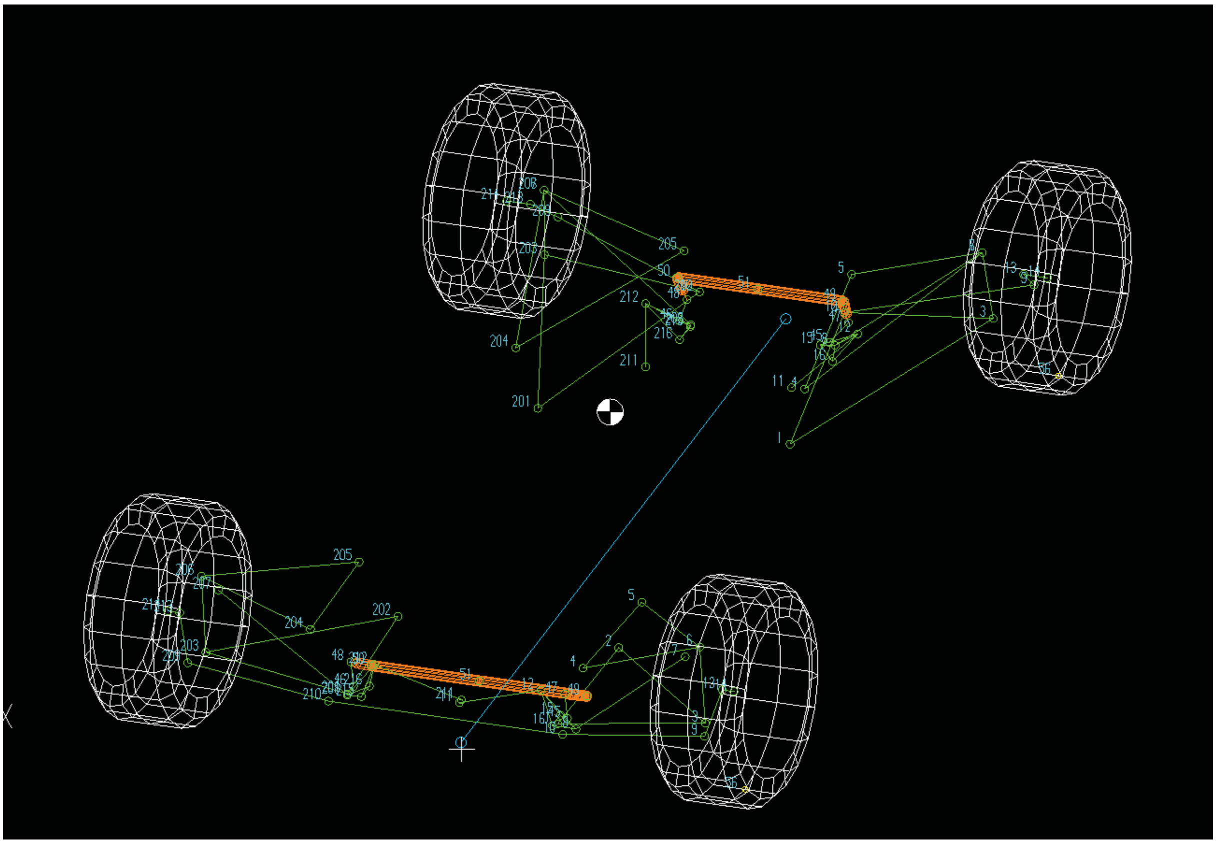


Figure 4 91 UH 18 FS monopost has very similar suspension layout to Dragon 5 car. Both - front and rear axles are pull-rod actuated. Front axis has not been changed for UH 18. Rear axle has been changed significantly. Final layout is basically same as Dragon 5 solution. UH 18 uses 10 inch rims. This aspect makes the packaging more challenging.

		Dragon 5	UH 18				Dragon 5	UH 18
TYRE ROLLING RADIUS	(mm)	264.16	220					
WHEELBASE	(mm)	1527	1580					
Castor Angle	(deg)	7.98	5		Castor Angle	(deg)	3.42	2.81
Castor Trail (hub)	(mm)	12.55	10.19		Castor Trail (hub)	(mm)	7.4	-53.44
Castor Offset (grnd)	(mm)	24.47	9.05		Castor Offset (grnd)	(mm)	8.39	64.24
Kingpin Angle	(deg)	8.04	0.38		Kingpin Angle	(deg)	1.9	4.41
Kingpin Offset (w/c)	(mm)	52.75	71.03		Kingpin Offset (w/c)	(mm)	53.56	102.6
Kingpin Offset (grnd)	(mm)	15.43	69.57		Kingpin Offset (grnd)	(mm)	44.77	85.63
Mechanical Trail (grnd)	(mm)	24.23	9.02		Mechanical Trail (grnd)	(mm)	8.37	64.16
ROLL CENTRE HEIGHT	(mm)	23.01	14.8		ROLL CENTRE HEIGHT	(mm)	34.6	41.25

Figure 4 90 table of basic comparison of UH 18 and Dragon 5 cars. Front axle has different design approach. UH Racing has changed tyre using a lot few years ago as the mechanical trail was reduced a lot. Another significant difference is in kingpin angle. Therefore the scrub radiuses are very different.

While the front axle of the UH 18 has not been changed a lot compare to its predecessor, rear axle has been completely rebuilt. Author of this diploma thesis participated mainly on the rear axle modifications. Interesting fact is that at the end of the design development both cars – UH 18 and Dragon 5 have very similar suspension layout.

The main idea of the rear suspension modification were to reduce weight and centre of gravity of rear axle. Hence the damper position was moved as low as possible and pull rod configuration has had to be used. The biggest challenge of these modifications were to deliver nice package according to available mount position of the prepared space frame around the engine and the smaller wheel diameter.

Smaller wheel diameter limits the design space a lot in respect of pull rod – rocker – damper configuration. While the angle between ground and pull rod is fairly small, it was difficult to bring the right rocker dimensions. The target was to have as small rocker as possible with the best possible kinematics results. That means installation ratio curve.

Another aspect which was analysed was bump and roll steer. Unfortunately, the front axle is not ideal, however, the rear axle has been significantly improved. All the kinematics data are shown in Figures 4.92 – 4.96.

4.5.1 FRONT SUSPENSION BUMP CHARACTERISTICS

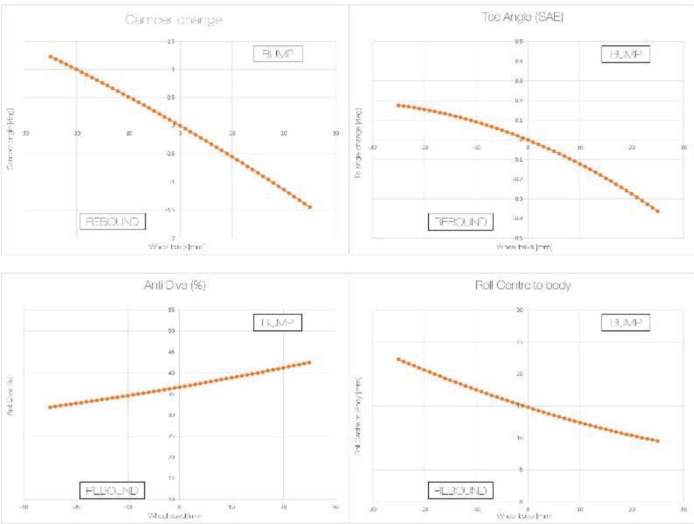
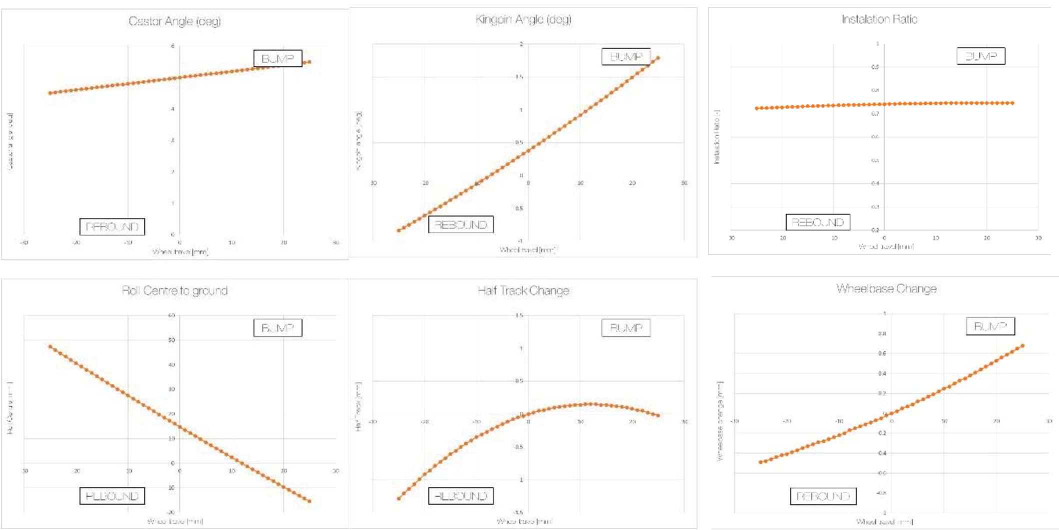


Figure 4 92 front suspension characteristics of UH 18. Camber change is higher than Dragon 5, Bump steer should be improved next years to deliver straight response for drivers. Anti-dive characteristic is quite low. Detailed comparison of UH 18 and Dragon 5 is in chapter 4.6



4.5.2 REAR SUSPENSION BUMP CHARACTERISTICS

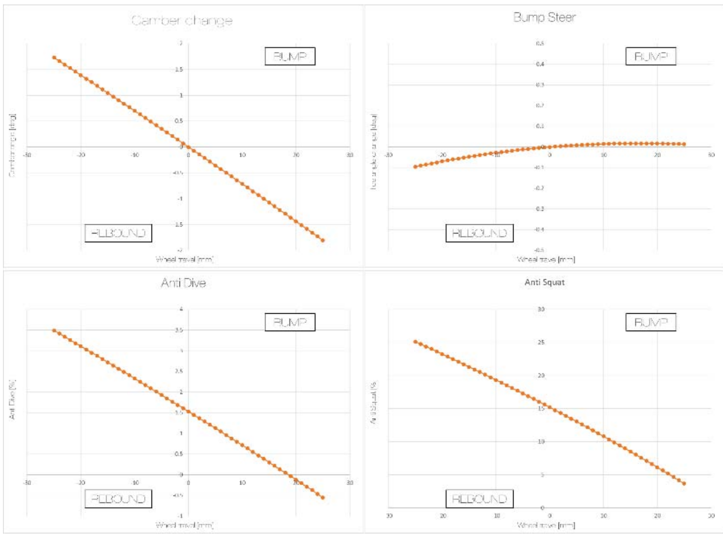
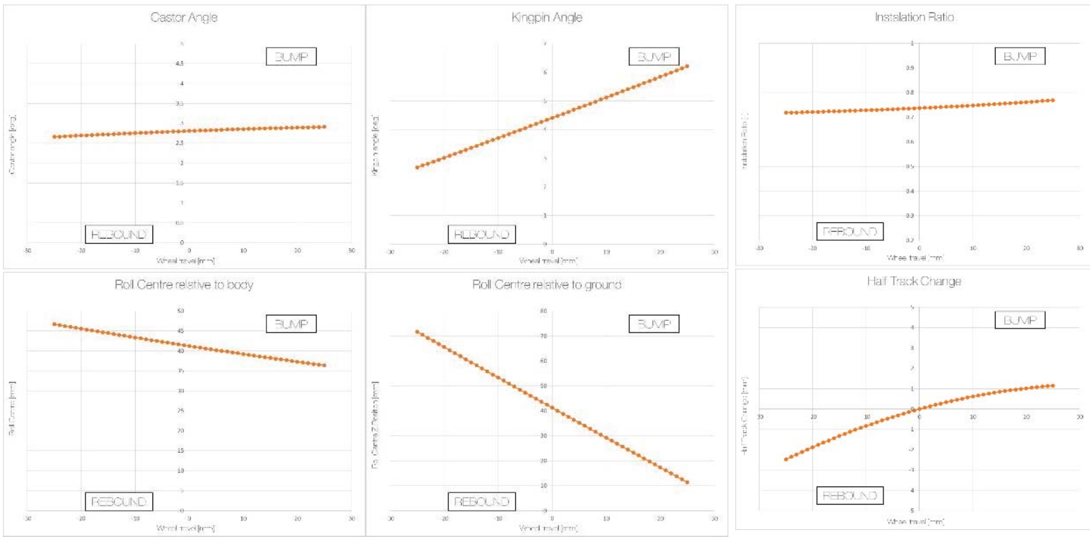


Figure 4 93 Rear suspension bump characteristics. The anti - dive feature and static installation ratio and upright features have not been changed as it was one of the restriction in design at beginning. The rest of characteristics has been modified. Quite big improvement is in bump steer characteristic and installation ratio curve.



4.5.3 STEERING CHARACTERISTICS

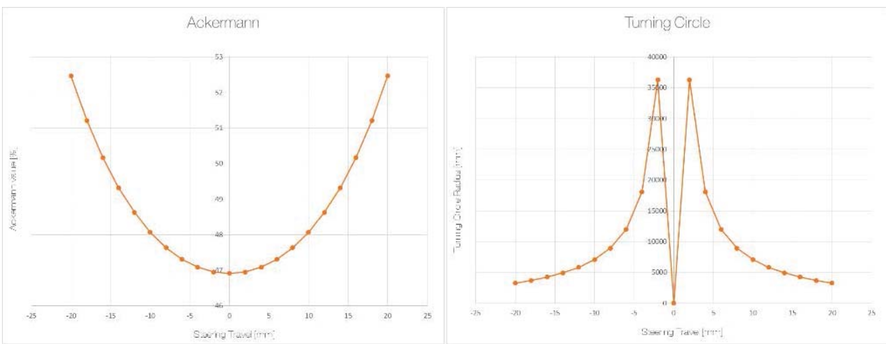


Figure 4 94 Ackermann and Turning Radius of UH 18

4.5.4 FRONT SUSPENSION ROLL CHARACTERISTICS

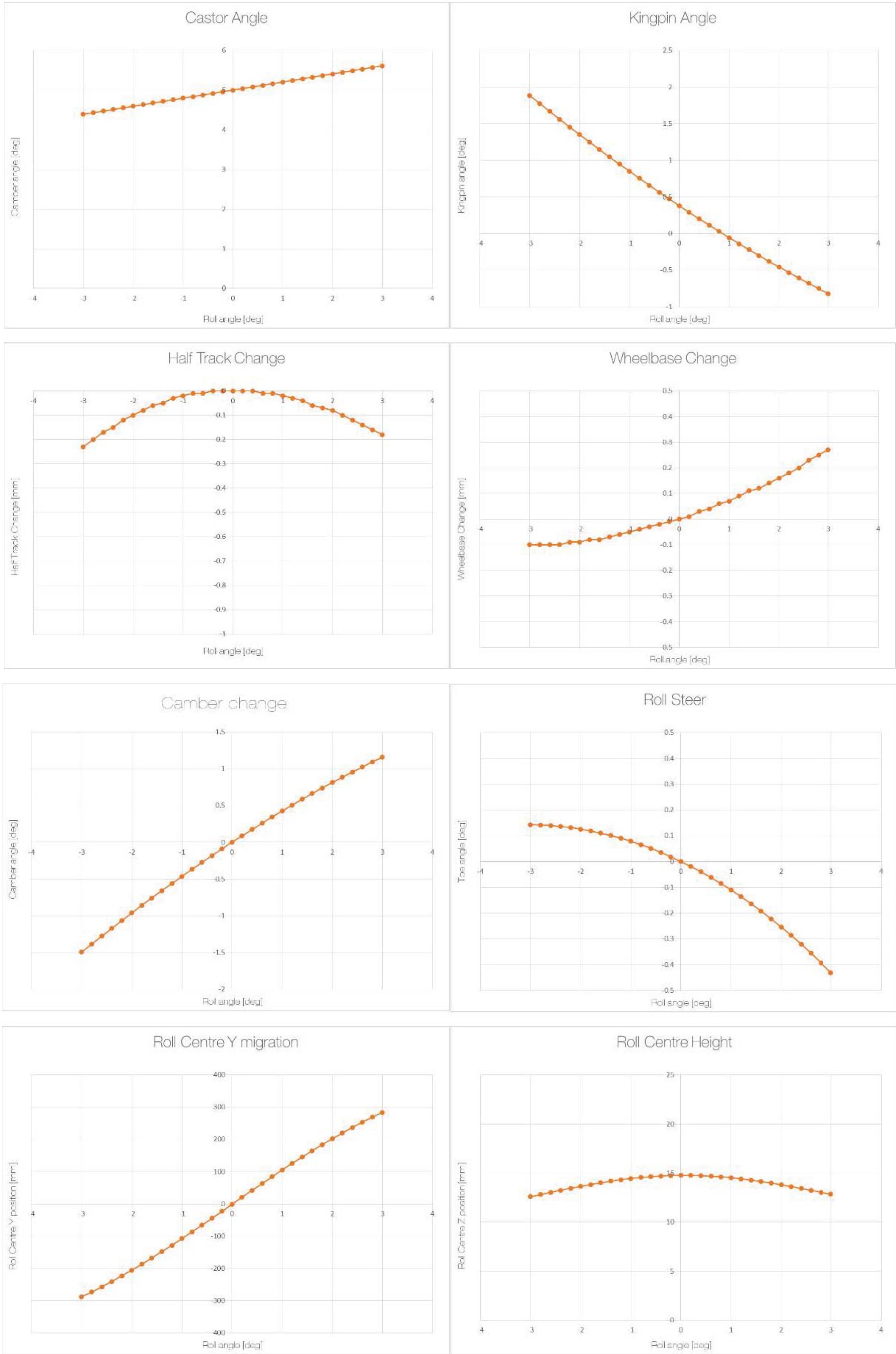


Figure 4 95 Front suspension roll characteristics. While the roll steer characteristic could have influence in drivers' feedback, rest of characteristics are satisfying. Roll centre height migration is changing in working range less than 1 mm, which should cause absolutely no problem.

4.5.5 Rear suspension roll characteristics

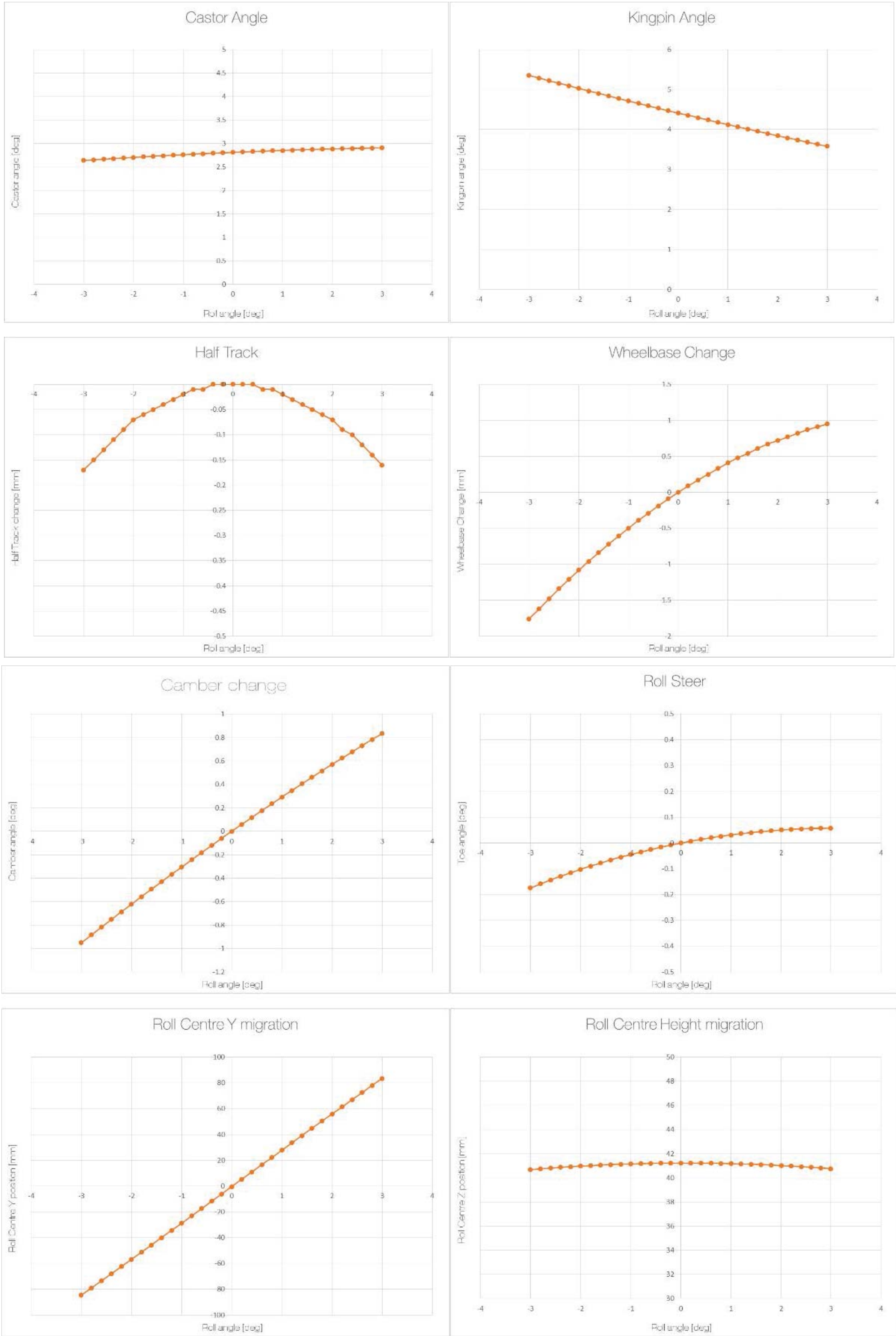


Figure 4 96 rear suspension roll characteristics has been modified for UH 18. Design intent was to deliver good response for driver. Therefore the roll steer and roll centre height migration has been significantly reduced.

4.5.6 UH 18 vs. Dragon 5 comparison

UH 18 and Dragon 5 cars have very similar suspension layout. However the wheel difference (10 vs. 13 inch) delivers different results. The design approach is slightly different. In respect of tyre using the front axle characteristics are not similar. The biggest dissimilarity is in respect of bump steer and anti – dive feature. Installation ratio of UH 18 is slightly higher as the suspension run at higher frequencies. The car is stiffer. On the other hand Dragon 5 approach is to have higher percentage of anti – features which help the car to be stiffer in respect of weight transfer. On the other hand lower frequencies (smaller installation ratio) enable wheel to be used in higher range.

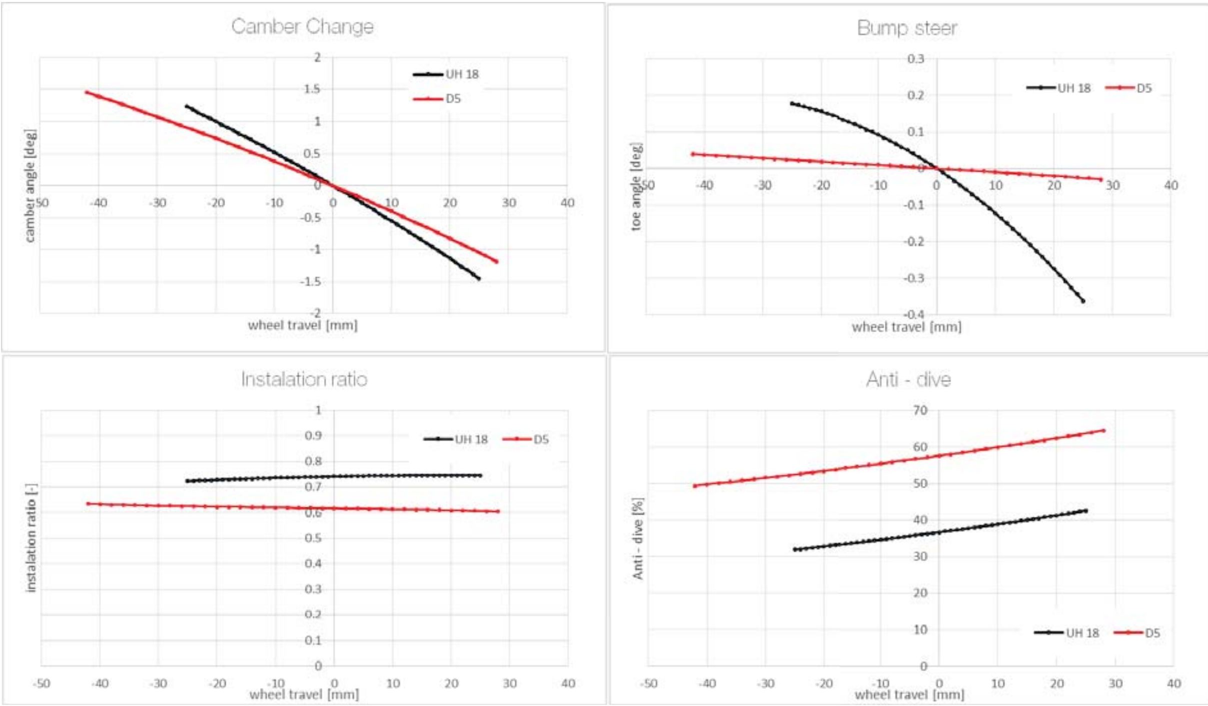
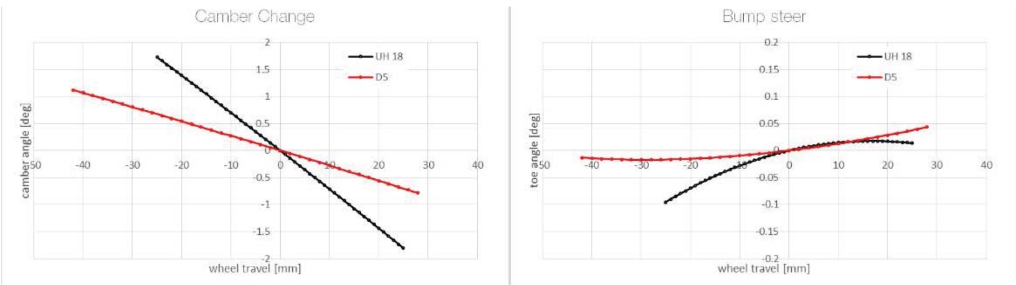


Figure 4 98 shows comparison of front suspension bump characteristics of UH 18 and Dragon 5. Camber change of UH 18 is higher – this helps tyre to be in ideal contact with ground probably better than at Dragon 5. However driver response should be better in Dragon 5 as the bump steer its' significantly lower.



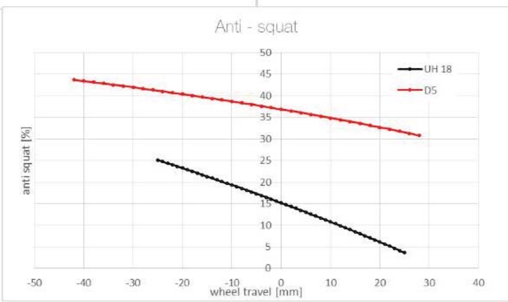


Figure 4 97 Rear suspension bump characteristics comparison shows similar results as the front. Rear bump steer of UH18 is better than the front. Anti – squat is again smaller than Dragon 5 as the car runs higher ride rates. Camber change is higher at UH 18 – tyre contact patch should be very good.

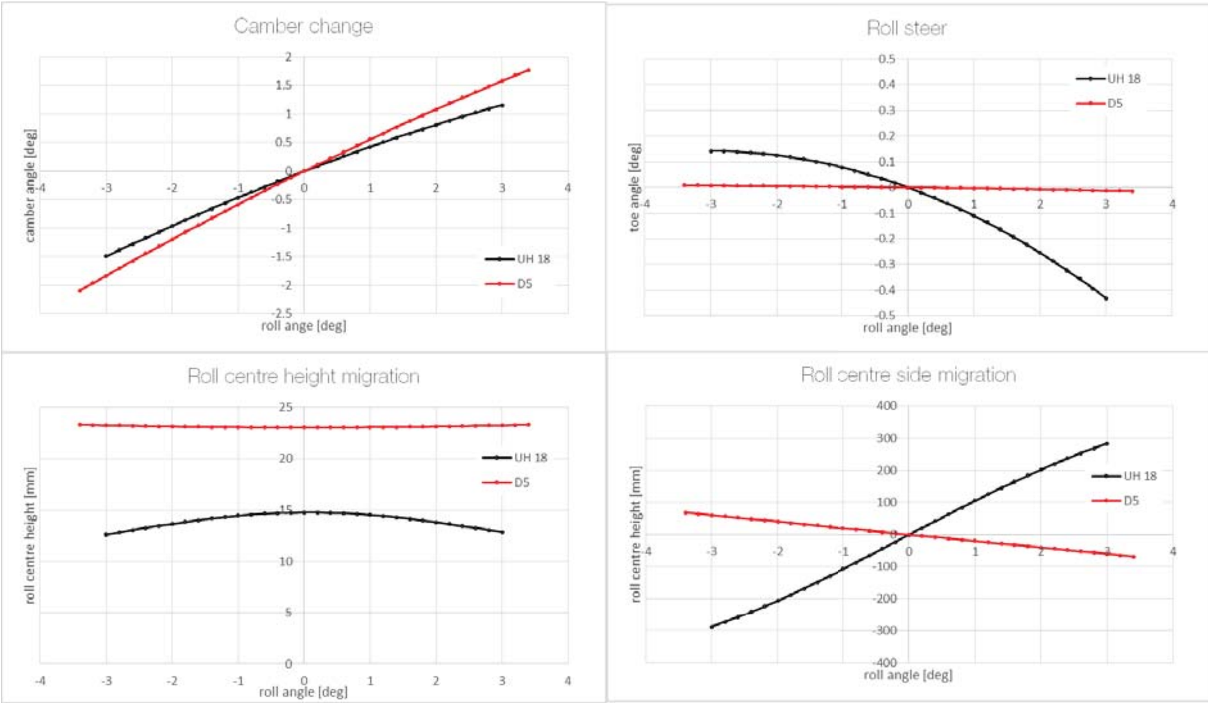


Figure 4 100 Front suspension roll characteristic comparison of UH 18 and Dragon 5. Roll centre height migration is sufficient at both cars. Camber change is very similar but the roll steer issue of UH 18 is visible. UH 18 car response for driver could be tough as the progression is significant.

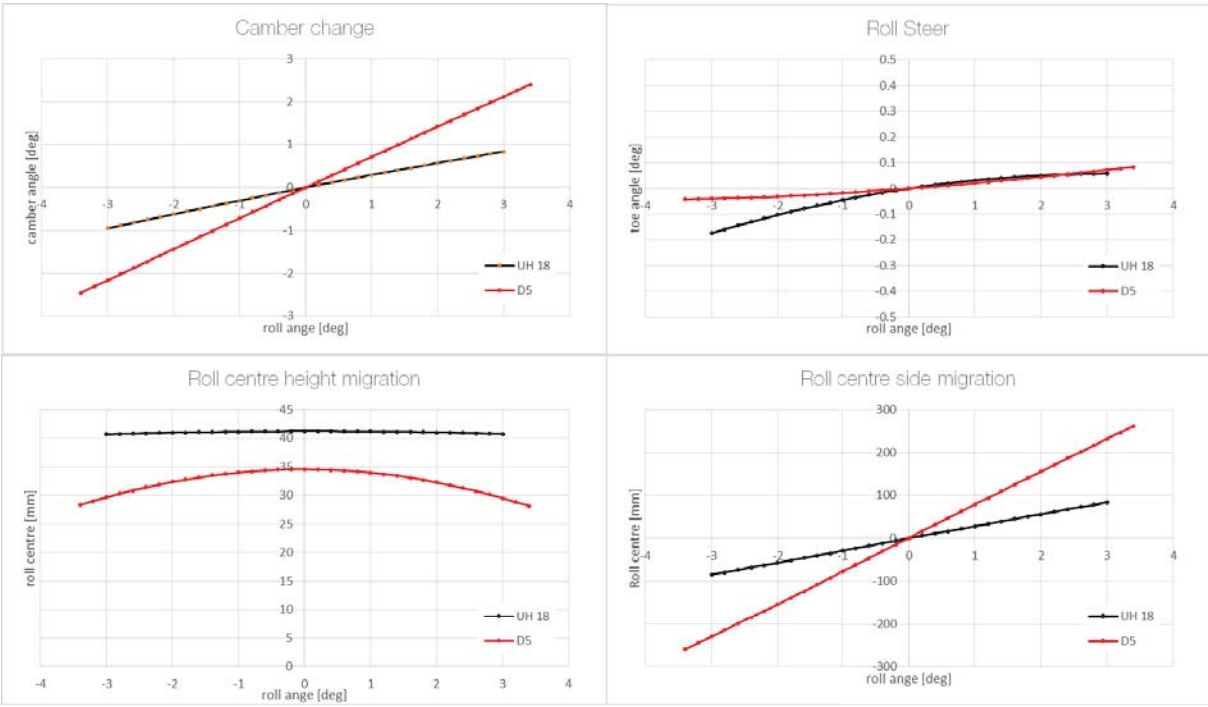


Figure 4 99 UH 18 rear suspension roll steer is improved a lot. Dragon 5 has better camber change in respect of tyre contact patch. Roll centre height migration of Dragon 5 could be better, however, the whole packaging was difficult in respect of engine space and chassis.

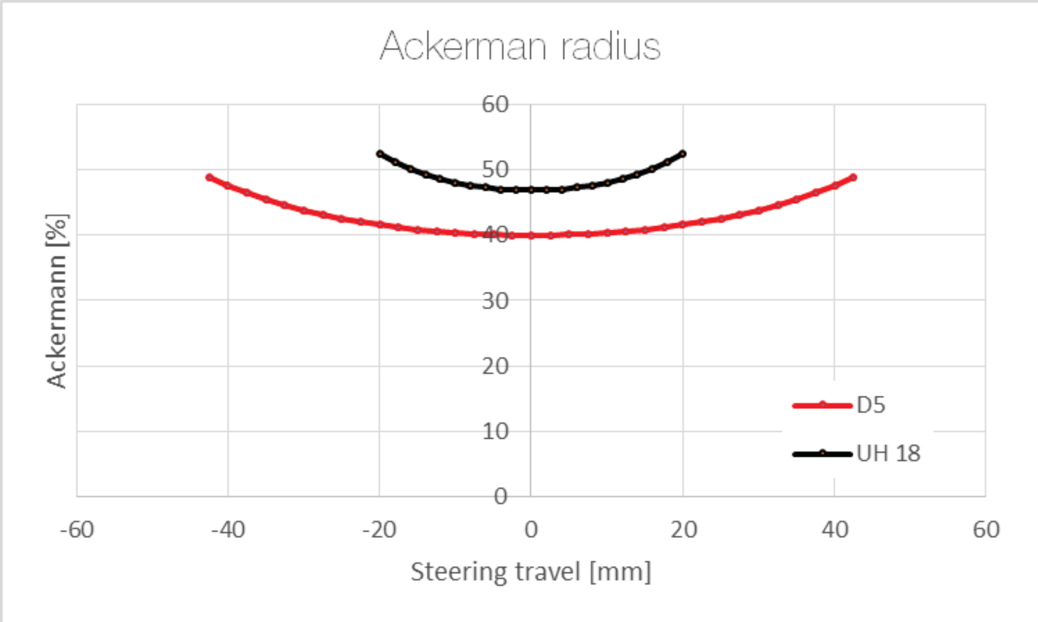


Figure 4 102 Steering characteristic of UH 18 and Dragon 5 is very dissimilar. The tyre diameter lead to different Ackermann radius. The UH 18 solution could deliver lower toe – out angles.

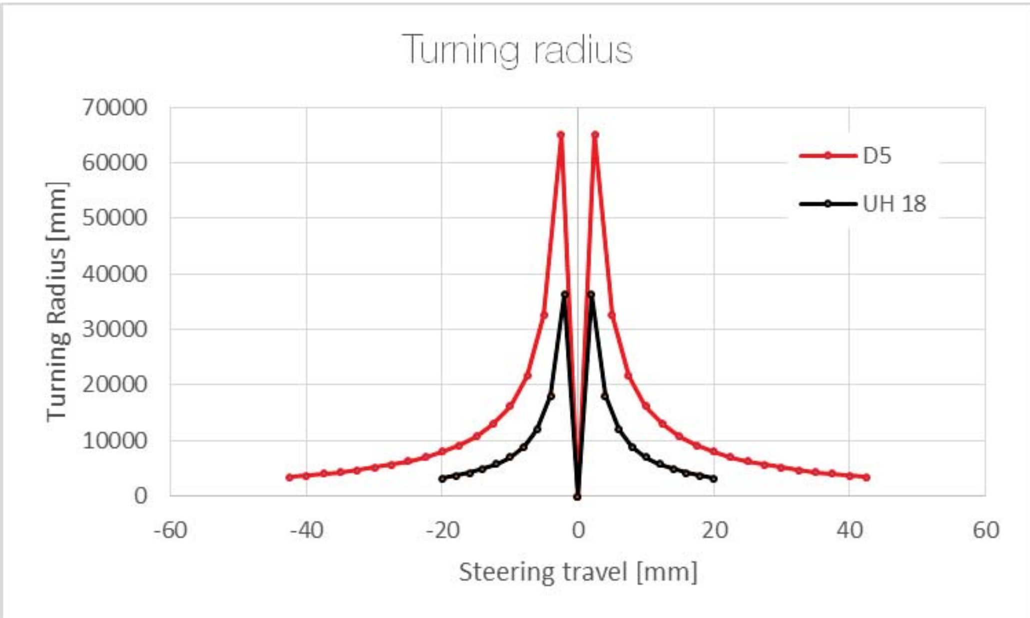


Figure 4 101 Turning radius comparison of UH 18 and Dragon 5

5 DESIGN

While the kinematics are designed the construction design can be started. Any vehicle is really complex system. It is desirable to be able to cooperate within the whole team to deliver the best possible package with high performance. The kinematics were designed to enable the designer's do the best part of their work.

As the kinematics were prepared in Lotus Shark it was necessary to forward the hard points to the CAD software. In TU Brno Racing the Creo 2.0 Parametric is in use. The same principle is common in every industrial company which brings any product to market.

Based on the hard points the skeleton model was prepared and hence the construction design can be easily attached to this points to ensure the kinematics intention. The author of this diploma thesis took part in designing the CAD models either what even confirms how complex the Formula Student project is.

In this chapter the CAD design and FEA analysis of some parts of suspension will be described. Namely, two generations of rockers, wishbones and anti-roll bars.

5.1 ROCKERS

Purpose of rockers was described previously. Transforming the force from the wheel through the push-rod or pull-rod to the damper via designed installation ratio. Another attachment point is to anti-roll-bar of the suspension.

The design of rockers were changed with the third generation of Dragon cars. The aim was to make it as simply as possible and try to reduce the weight either. Therefore the machined aluminium rockers were left in the past. The truth is that according to stress and strain the machined rockers could be better as they are able to forward this forces not only in single plane. On the other hand the simple design of rockers enables the reduction of cost and it is also very easy to change the geometry of the rocker during the testing.

Figure 5 1 machined rockers on formula type race car. (ultimatecarpage, 2015)

5.1.1 DRAGON 3

As was mentioned previously, the aim of rocker design was to be as simple as possible. Hence for the third generation of TU Brno Racing car the sheet metal layout was chosen. Main parts of the final assembly are: sheetmetal, plain bearings, pin and spacing (Figure 5.1). The rocker assembly is connected to the chassis via two welded sheet metals. Sheetmetal is easy to manufacture (laser cutting) or to replace. Therefore it was possible to prepare a few versions of geometry of installation ratio. The idea of using plain bearings (SKF) was to safe weight. Pin was manufactured on lathe as easy operation.

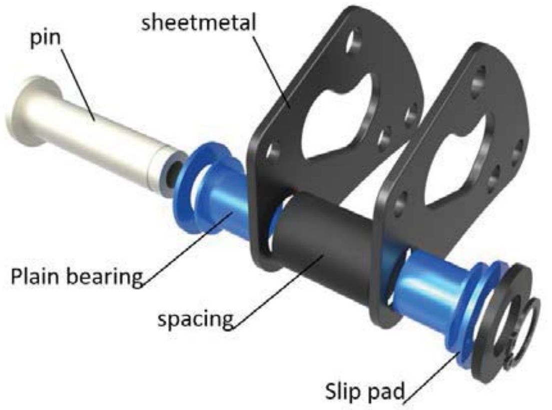


Figure 5 3 Rear Rocker Assembly. Exploded view.

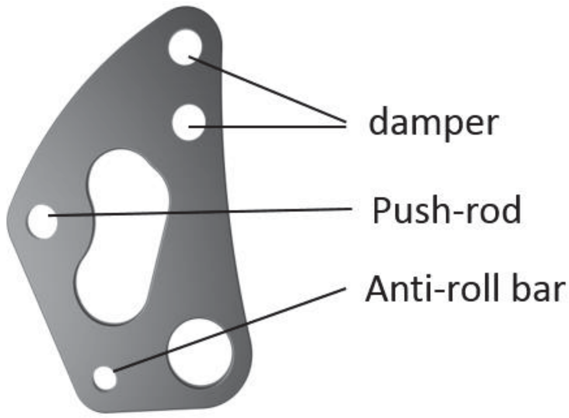


Figure 5 2 Rocker Sheetmetal attachment points

The most stressed element of the rocker assembly is the sheetmetal. It was tested in Ansys Workbench FEA software. The boundary conditions was previously simulated in Adams software. That enables to set the analysis the toughest condition. Two critical position was prepared. The bump-stop and full-rebound state.

The procedure of testing this sheetmetal in Ansys takes these steps. The sheetmetal CAD model is generated into the .STEP format in Creo 2.0 Parametric. It enables to import the model into the Ansys Workbench environment. In Ansys Workbench it is necessary to set the material properties in the Material Library. The Static Analysis is used to analyse the sheetmetal. Boundary conditions are set up. The mesh procedure takes a few steps to refine the critical places of the part. Once the analysis is finished, the most critical place is shown as the maximum stress. In this case the maximum stress is below the yield point of the steel material which is used.

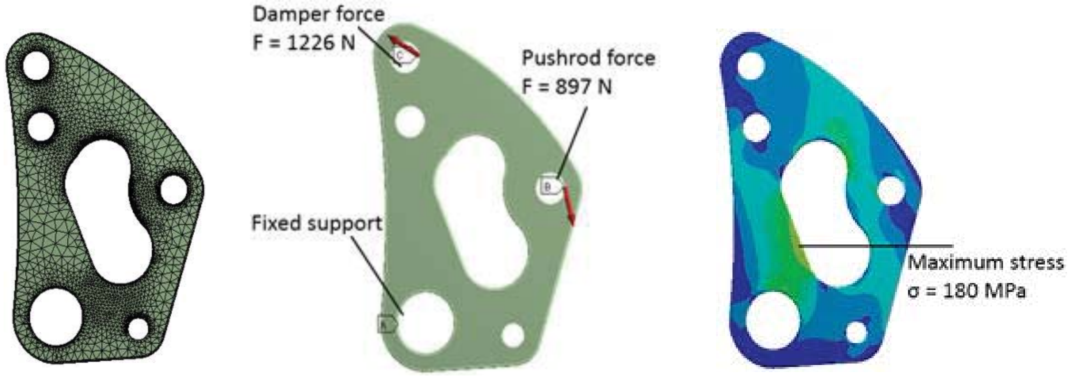


Figure 5 4 The FAE Analysis in Ansys Workbench software. Mesh, Boundary Conditions and final result of analysis

The rocker assembly was used at the Dragon 3 car during the whole season. There were only one issue which came. The plain bearings. The pin and the spacing were not manufactured properly which brought a lot of friction onto the plain bearings. It was not a stop problem of the car but obviously, it was a place to improve. Another space intended to improve was the weight. All these factors were thought and improved in design of new rockers for the next generation car – Dragon 4.

5.1.2 DRAGON 4

Dragon 4 had a great goal right from the beginning of new season in September 2013. The goal was to build up a far lighter car than its predecessor. The experience with previous car convinced the whole team that the weight reduction have to be delivered at every single part of the car. The idea was to save the weight at everything but not dramatically as it could bring the unreliability of the final product.

The rocker assembly is a great example. The decision for the fourth generation of TU Brno Racing car was to change the fasteners for the suspension. Therefore the shoulder bolts was used for every mounting point at suspension parts. It brought a massive reduction in contact press and prolonged every kind of bearings life. While the material of shoulder bolts was the 12.9 metric grade (compared to previous use of 8.8 metric grade) the change from M8 bolts to M5 shoulder bolts was done.

The plain bearings were changed for the ball bearings in direction to decrease the friction and increase reliability of this stressed part. That was the reason to change the layout of the assembly.

Still, the manufacturing process of low cost and easy to replace was wanted to sustain. The sheetmetal and spacing remained. Smaller dimension of bolts enabled to safe the weight on the whole assembly. Hence the final weight of new assembly was reduced almost twice a time from 380 grams to 190 grams although the light weight plain bearings was changed for ball bearings.

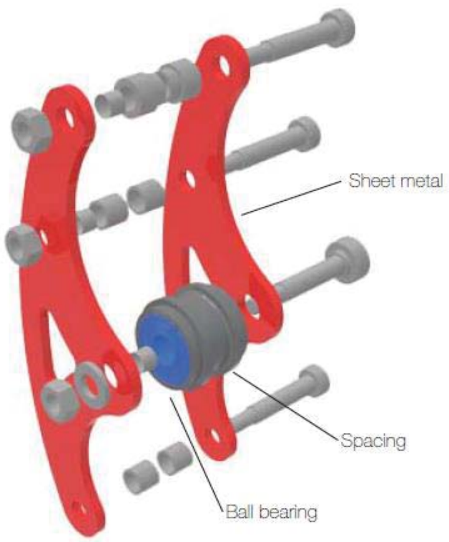


Figure 5 5 Front rocker assembly Dragon 4 exploded view.

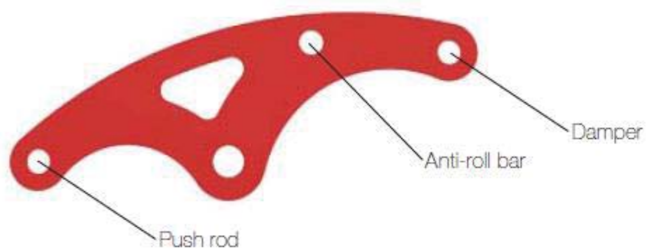


Figure 5 6 Front sheetmetal attachment points

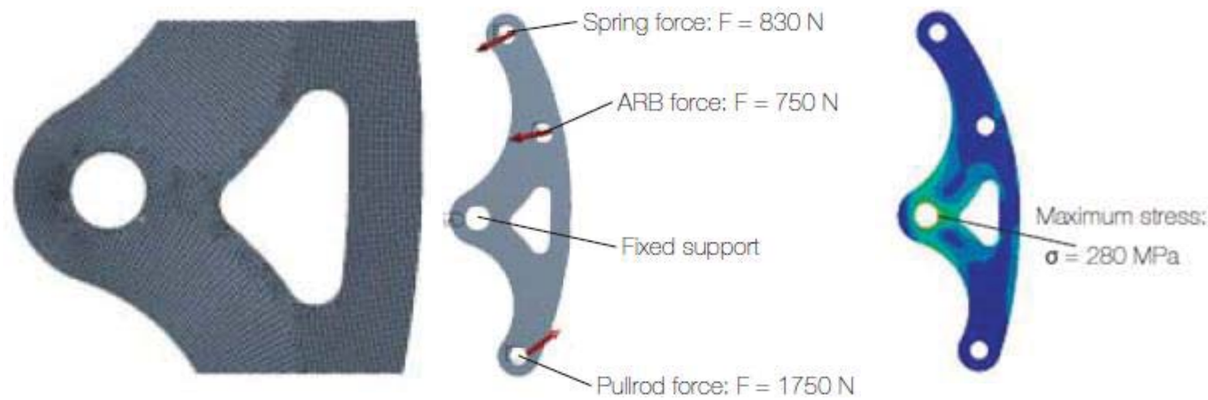


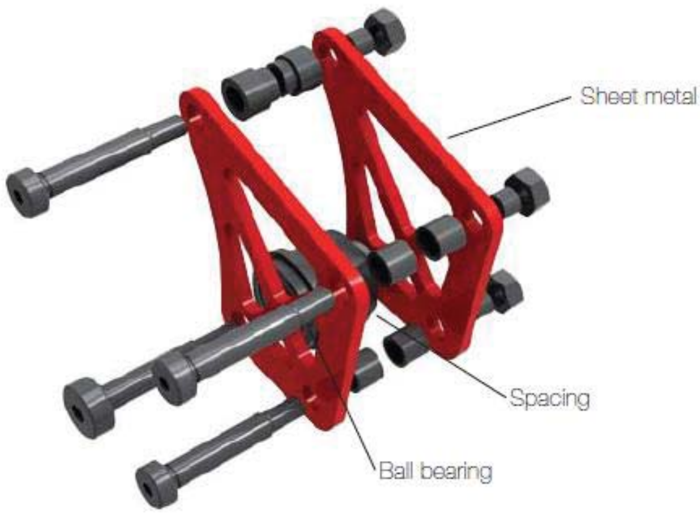
Figure 5 7 FAE Analysis of Dragon 4 front sheetmetal. Mesh refinement detailed, boundary conditions of critical state of rebound, Maximum stress close to the fixed support which is not relevant.

The same analysis of sheetmetal was used as for the previous version of the car. The procedure of analysis were described previously. The improvement shown in Figure 5.7 was in meshing. The tetragonal elements were changed for hexagonal. It should shorten the calculation time. But for such a small part it is not hugely important. On the other hand it is important from the educational point of view for any future analysis of larger assembly.

Important note about boundary condition is the forces act in the mounting points were calculated for the exact mounting points. That means the ultimate force acting in the sheetmetal plane will be much smaller. From the point of safety it was mentioned to be absolutely sure about the reliability of the rockers. Otherwise it could be the stop problem during races.

In Figure 5.7 is shown the maximum stress. The greatest number is 280 MPa which is still far away from the yield point of steel alloy used for manufacturing this rocker (440 MPa). The general theorem of FEA analysis states that the stresses in place where the boundary condition was set up should be overlooked as they are not relevant. In this case the maximum stress shown is close to the fixed support. Eventually the stress is approximately 200 MPa.

Figure 5 8 Rear Rocker assembly. The shoulder bolts were used for this car generation. The diameter was decreased from 8 mm to 6 mm. It brought a huge weight reduction as it influences the surroundings parts. For example the rod-ends bearings on Dragon 3 was 8 mm diameter. This one are 6 mm which saved 8 grams per each rod-end.



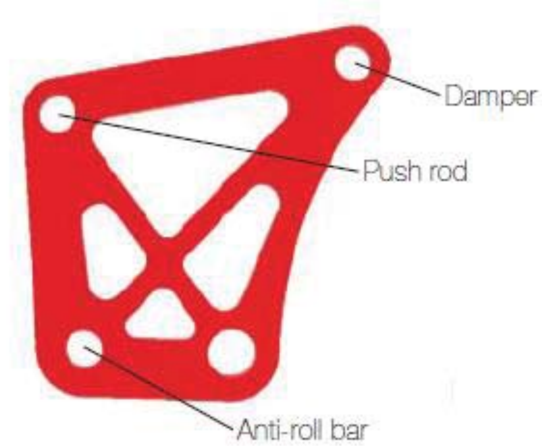


Figure 5 10 Rocker sheetmetal attachment points. The final geometry used for Dragon 4 installation ratio.

During the whole season the rocker assembly worked without problem. The only issue was the life of ball bearings. On the rear assembly it was changed only twice per the whole season which is absolutely good performance. Problem was with the front rocker assembly while the anti-roll-bar mounting point is single sheared and acts in different plane than the whole rocker assembly is. Furthermore the ball bearing chosen for this application was without any cover of balls. These two facts influenced the bearing life. It was necessary to change these bearings before every competition and a few times while testing. It was not a big problem but still place where to improve next generation of rockers.

Figure 5 9 Rear Rocker Dragon 4 FEA Analysis.

Also the rocker layout could be improved. The idea of easy to manufacture with low cost is very useful. The Dragon 4 rockers used the ball bearings in not definitely proper way. As the movement of sheetmetal was done only via shims pressed on the inner ring of bearing. The bearing was imposed into the housing. The housing was directly welded into the chassis. Next generation of rockers could accommodate the bearings right into the sheetmetal to guarantee the proper bearing conditions.

5.2 WISHBONES

Importance of wishbones is clearly visible. Their function is to attach the whole wheel assembly to the chassis. Therefore their position is generally discussed from the sprung mass point of view. Is that unsprung mass or is it still sprung mass? The rule of thumb says that the half of the wishbone weight is sprung mass and the other is unsprung mass part.

Nevertheless, the weight is truly important on the both sides of mass. That is the reason why Formula Student teams tend more and more toward the carbon fibre solution as seen in Figure 5.10.

Figure 5.10 Carbon fibre wishbones of Hawks Racing.

For the Dragon 4 design carbon fibre wishbones were not approved. This decision comes from the experience seen in other teams. It is quite often failure that the aluminium inserts fall off the carbon fibre wishbones. TU Brno Racing decided that the reliability is the crucial factor. Therefore the different way was chosen for Dragon 4 design.

5.2.1 DRAGON 3 ISSUES

Dragon 3 wishbones suffered with compliance in uniballs housings. It was problem of the bearing itself hand in hand with poor material characteristics of the housing. Furthermore the weight was satisfactory as well. These few problems result in design decision involved to Dragon 4 wishbones design.

Figure 5 11 Dragon 3 wishbone detail. Material properties were inappropriate and the bearing dimensions were unnecessary over dimensioned

5.2.2 DRAGON 4

Figure 5 12 Wishbone design layout

Experience is really important in the way of any development process. Thanks to experience from Dragon 3 season the big improvements could be involved.

Design aims were focused to deal with previous problems and at the same point the weight reduction was considered a lot. Material chosen for the uniball housing is high quality chrome - molybdenum steel. This improved a lot the product life while it prevent deformation. Therefore the compliance did not appear during the whole season.

The experience and research proved that bearings dimensions were unnecessary big. Dragon 3 design used 8 mm diameter uniball and rod – end bearings of a normal quality. For the Dragon 4 design 6 mm of diameter bearings were used. Difference of quality was high as the motorsport product line were used. Change of bearing dimensions reduced weight as it influenced other part of wishbone design. Housings are smaller and tube dimensions can be smaller.

The tube dimension was an element to focus on. The Formula Student Project is a great opportunity to meet the demands of industry communication. In this case this real life connection drove even the wishbone design. The aim was to reduce the weigh with different tube diameter. Unfortunately there was only 14x2 mm dimension available in the stock market. The aim was to use 14x1.5 mm dimension.

While the simulation proved we could use smaller dimensions the other solution were considered. The greatest forces on the wishbones is cumulated at the lower upright attachment points. Forces which are acting in top upright mounts are three times lower. That brought an idea of using event smaller tube diameter for the top wishbones. The 12x1 mm of cross section were decided to use for test set of top wishbones. That decision came from extensive FEA simulation shown in Figures 5.13 – 5.15

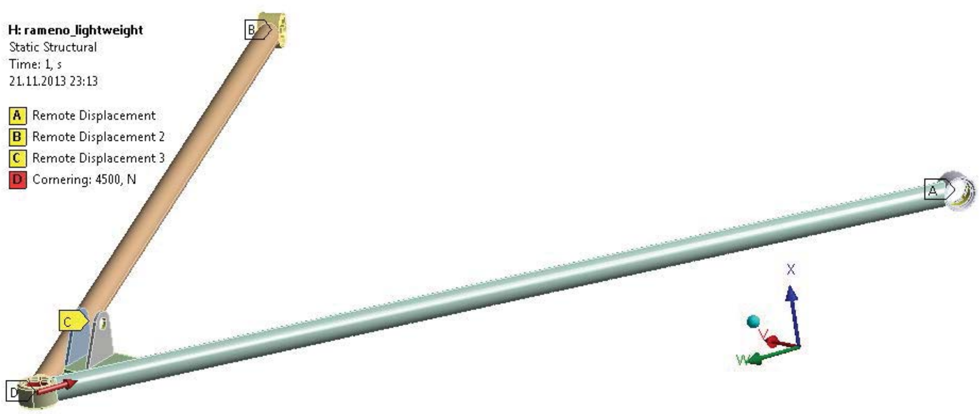


Figure 5 13 Lightweight version of top wishbones were tested with FEA. Tube cross section dimensions are 12 in diameter and 1.5 of thickness. Cornering force was used of 4500 N magnitude as it ensures a huge amount of safety factor

The FEA analysis provided comparison of Dragon 3 wishbone dimensions and the new lightweight version for Dragon 4 design. The analysis showed that the car could suffer from lower stiffness of suspension. The total deformation increased from 0.34 mm to 0.7. That means two times worse. However the decision was to test this version in real test on the car.

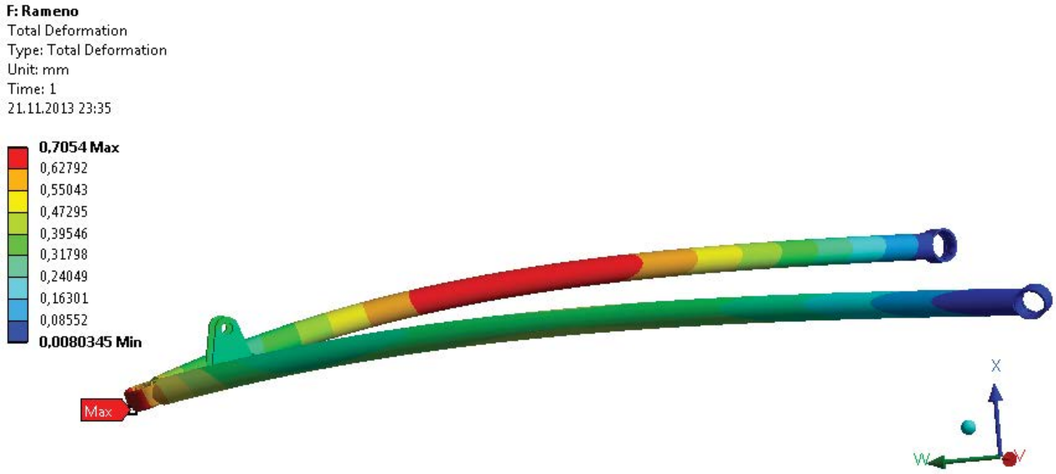


Figure 5 14 Total deformation of Dragon 4 lightweight top wishbone design is 0.7 mm under the steady state cornering conditions.

Eventually the test proved that the lightweight version works very well. At the end of the day the amount of weight which was saved were almost 900 grams! In contrast of the whole car this is considerable. The racing car is an ultimate machine which is driven by the driver. Drivers did not find any inconvenience of using this less stiff version of top wishbones. And this all matter. The comparison of weight is shown in Figures 5.16 – 5.20. Thanks to one of the main partners with manufacturing process we could test the welding quality under the x-rays – Figure 5.21.

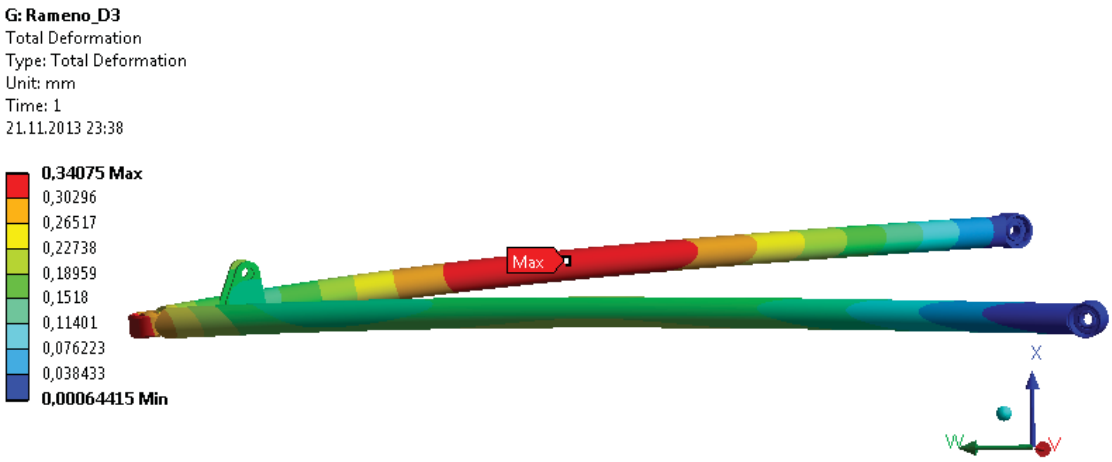


Figure 5 15 Dragon 3 wishbone design ensures higher stiffness, however, the lightweight version was used eventually with any problem.

Figure 5 17 Dragon 4 lightweight version of front upper wishbones. The pull rod attachment point is visible.

Figure 5 16 Difference of weight is 210 grams. This was considered as a big improvement as this is more than 40 % of weight reduction

Figure 5 20 Dragon 4 rear upper wishbone in configuration with bigger tubes cross section dimensions.

Figure 5 19 Dragon 4 rear upper wishbone is 45 % lighter.

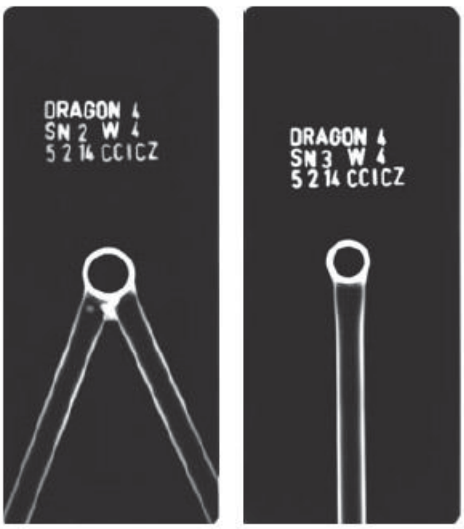


Figure 5 18 during the manufacturing the technology of x-rays were used to prove the welding quality. This is another great part of Formula Student project as students can be involved in the whole design process. Even the quality department.

5.3 REAR ANTI ROLL BARS

Since the very first prototype of Dragon cars the rear anti roll bar had been always a struggle a little bit. The biggest issue was that the boundary condition of lateral acceleration was set up at 1.6 G. After the Dragon’s 3 season when the data acquisition helped a lot with knowing the car better, the measured values of lateral acceleration was 2.1 G in peaks. That really helped to improve design for the fourth car.

Both solution – Dragon 3 and Dragon 4 went through the very similar process. The main difference is that at the Dragon 3 car the boundary condition was determined with kinematics software (1.6 G of lateral acceleration) whereas the Dragon 4 solution used MATLAB calculation which were previously developed for front anti-roll bar assembly.

5.3.1 DRAGON 3 ANTI-ROLL BAR SOLUTION

As was mentioned previous the Dragon 3 ARB system was developed with assumption of 1.6 G. The aim was to deliver as simple solution as posible. Therefore the torsion bar was fitted into a machined lever (arb arm) as is visible in Figure 5.21. The solution enables to change setup very easily and quickly.

As bushing the plastic bearings were manufactured and the whole assembly uses one of the chassis tubes under purpose of weight saving.

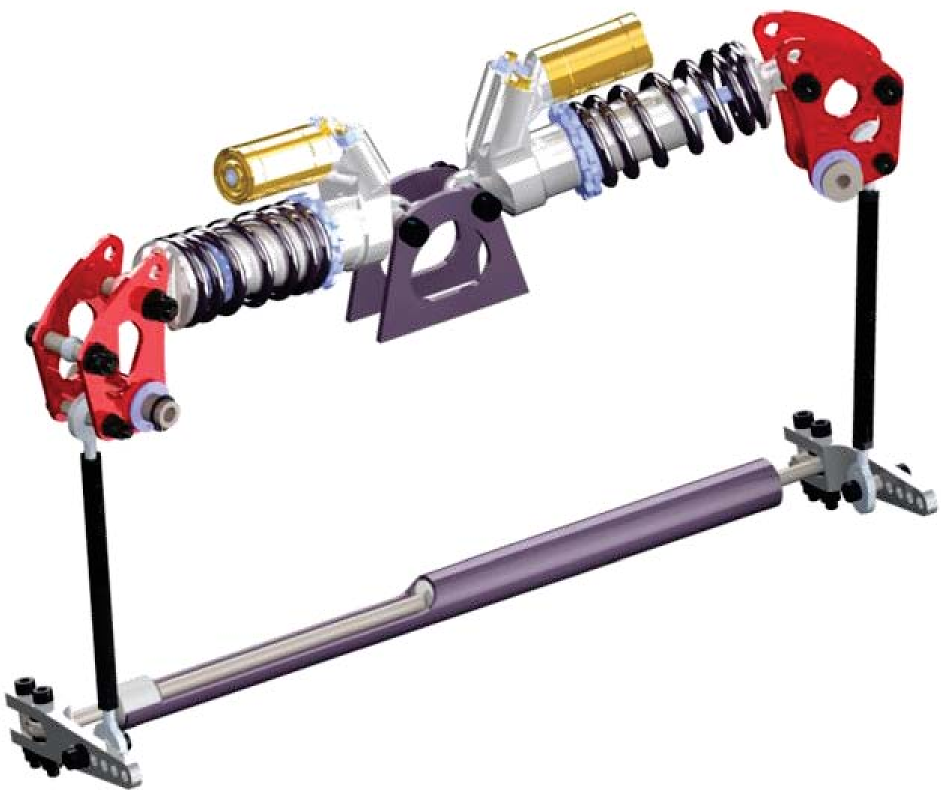


Figure 5 21 Dragon 3 Rear suspension assembly. Anti-roll bar was fitted into one of chassis tubes

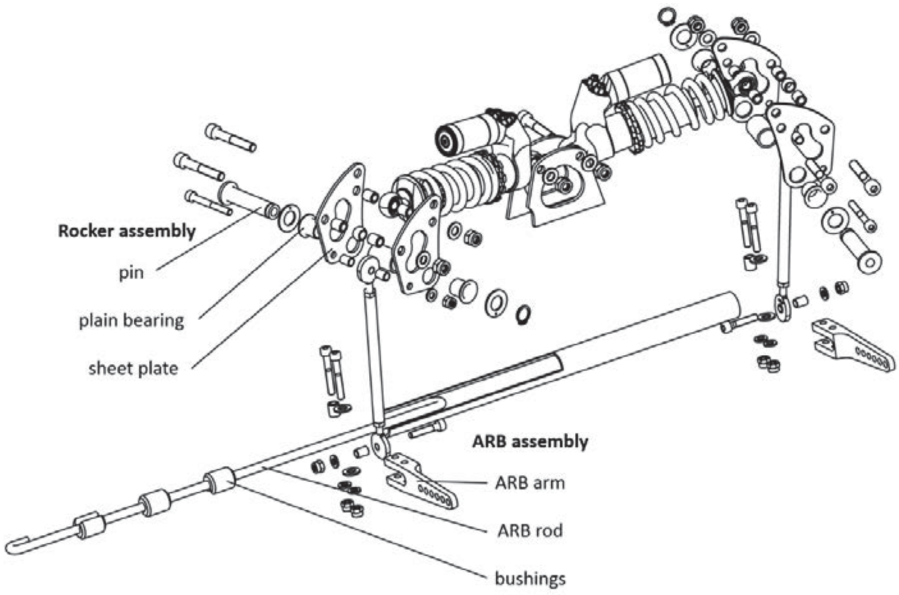


Figure 5 22 Dragon 3 Rear suspension assembly exploded view. Each part is described in detail

There were two main issues discovered during the testing and competition. The first problem which was already mentioned that the car reached much higher lateral acceleration than the anti-roll bar was actually calculated for. That means that the anti-roll bar did not work properly. The other issue which helped a lot with understanding the anti-roll bar design a lot were compliances. It was proved that what can work on computer screen may not work in real life. The biggest problem was to fit the torsion bar into arb arm. The idea was to use two bolts but it did not work.

5.3.2 DRAGON 4

These two issues was considered at the very beginning of development of the rear anti-roll bar for Dragon 4. Firstly, the boundaries condition was recalculated from the scratch. The MATLAB programme was used to analytically calculate inputs. Calculations were based on programme of previous development of front stabilizer (Sevcik Jan, 2012) while it was tailored to rear axle.

While the experience with type of front anti-roll bar has been positive, it was decided to use very similar type. The new model uses anti-roll bar blades instead of an arm. The range of setup is linear and still retains the simplicity of adjusting.

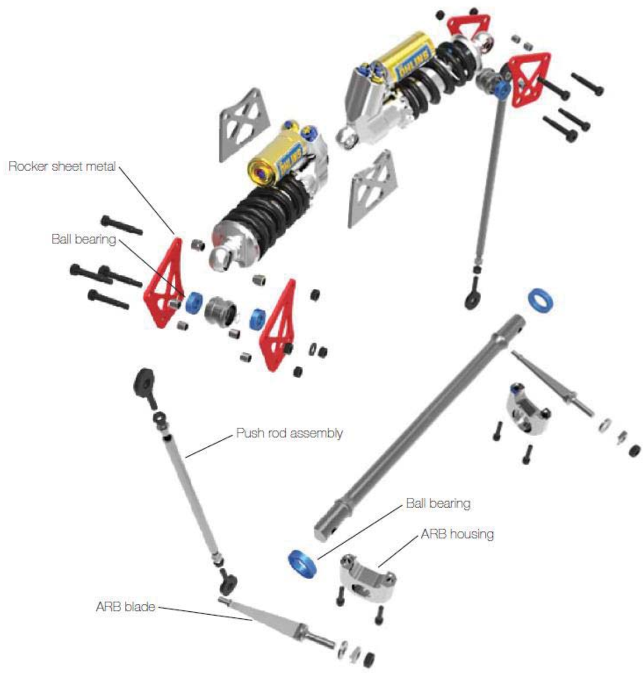
This design solution uses only the blades as a stress element. Therefore the torsion bar had to be calculated at least an order higher from stress point of view than the blades. Unfortunately there was limited space for mounting the torsion bar under the chassis. That requested a solution which uses housings for fitting of the whole assembly. The whole assembly is shown in Figure 5.23.

Figure 5 23 Dragon 4 rear suspension assembly with new generation anti-roll bar solution

In Figure 5.24 is visible the exploded view of the whole assembly. The other difference compare to Dragon 3 anti-roll bar is the ball bearing use. The reason of such an approach was to reduce the amount of friction as much as possible.

Dragon 4 solution brought satisfactory results during the whole season. Despite the fact of limited space the adjusting was very simple. The functionality was tested and measured during a test day where the understeer gradient was evaluated according to anti-roll bars stiffness changes. The whole results are described in chapter 6.

Figure 5 24 Rear anti-roll bar exposed view. The ball bearings use is visible. The whole solution tries to be as simple as possible. Setup change can be easily done with the M8 nut. The M8 nut lock the position of blade safely as it simply pretensions the whole assembly.



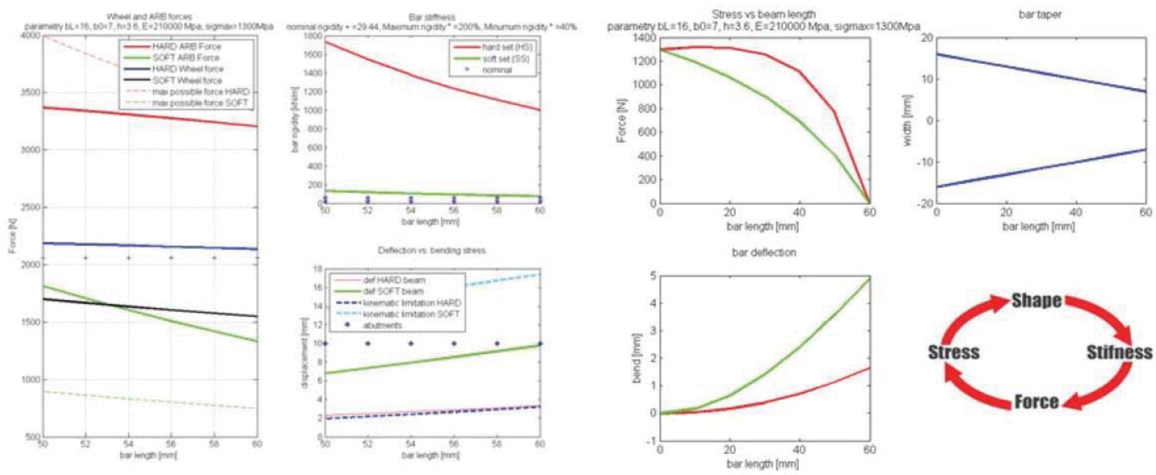


Figure 5 25MATLAB programme results based on previous diploma thesis. Programme was tailored towards the rear anti-roll bar solution. This really helped with the whole development cycle as the FEA just ensured the input gained in this programme.

BLADE FINITE ELEMENT METHOD ANALYSIS

Based on the calculation in MATLAB the dimensions of blade was used to design process involving the CAD software (Creo 2.0 Parametric) and the FEA software (Ansys Workbench). The MATLAB software helped a lot in this design phase as it really accelerated the development process.

Firstly the mesh was prepared. While the blade is a very simple element to analyse in FEA the mesh was fined well. In Figure 5. 27 it is visible that 3 rows of elements were prepared in mesh. The mesh was generated with taking in account that the blade is sheetmetal part. Therefore the mesh is hexagonal shape which accelerates the final solution.

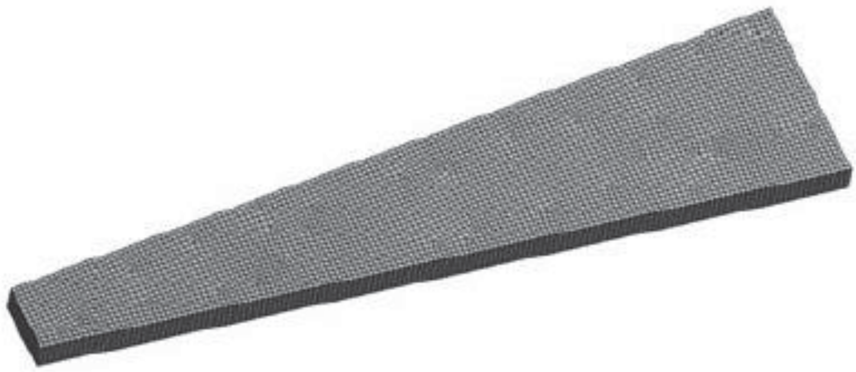


Figure 5 26 Blade basic shape tested in FEA. Meshing was refined for the best results

Two extreme boundary condition was analysed. The soft position and the hard position. The soft position is visible in Figure 5.28. The opposite solution (angled by 90 degrees) is in Figure 5.27.

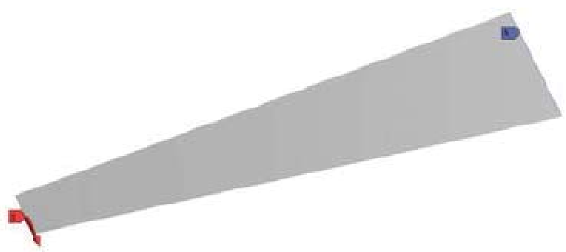


Figure 5 27 Boundary conditions for hard position. Force is acting in the blade plane

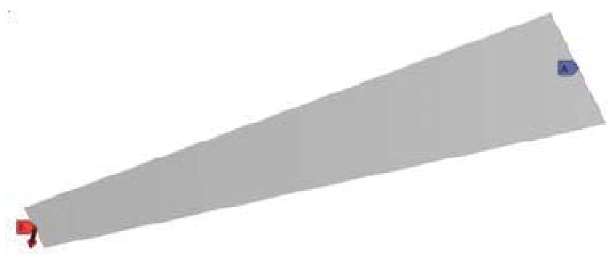


Figure 5 28 Boundary conditions for soft blade position. Force is acting perpendicularly to blade plane

The finite element analysis proved the MATLAB analytic approach right. The material used for blade manufacturing is CSN 19 083.8 (DIN C45W, 1.1730) which is heat treated by hardening on 800 degrees of centigrade. Therefore the material characteristics are really high. The yield stress has value of 1300 MPa.

Both condition which were tested (soft and hard) were under the maximum yield stress of this material. Blades were tested statically. Fatigue was not analysed. On the other hand, only single blade broke down while testing (after 500 km). The reason was that the heat treatment process were not done well. The test of hardness proved that the material characteristics were much lower. The second version were manufactured perfectly. Since then the performance were absolutely perfect.

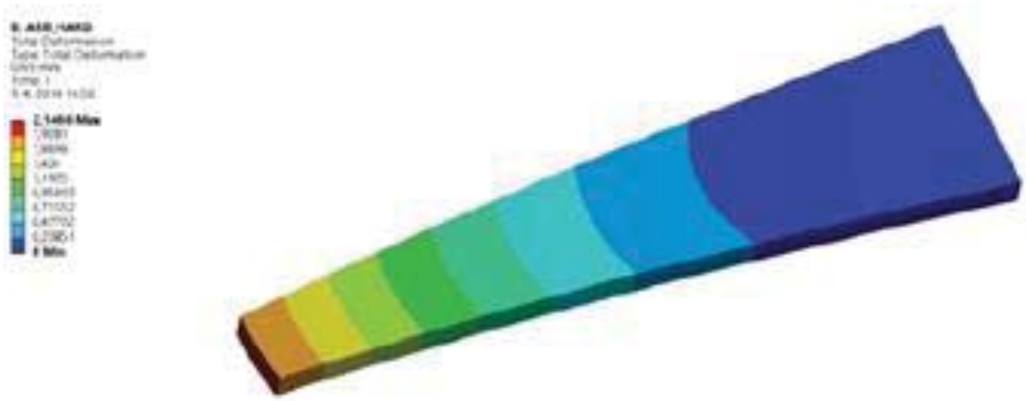


Figure 5 30 Maximum displacement of the blade under the maximum of static force is 2.1 mm in the hard configuration

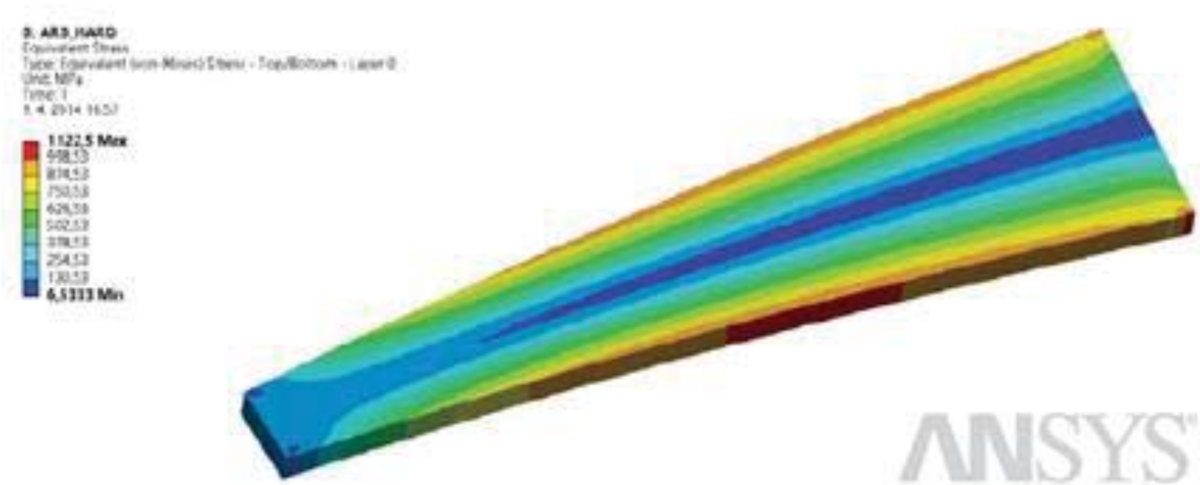


Figure 5 29 Maximum stress (Equivalent Von-Misses) is 1122 MPa. Which is under the maximum of Yield stress of used material 19 083.8. The force which were used for this analysis used safety factor of 1.5. Therefore the whole safety factor is around 1.3

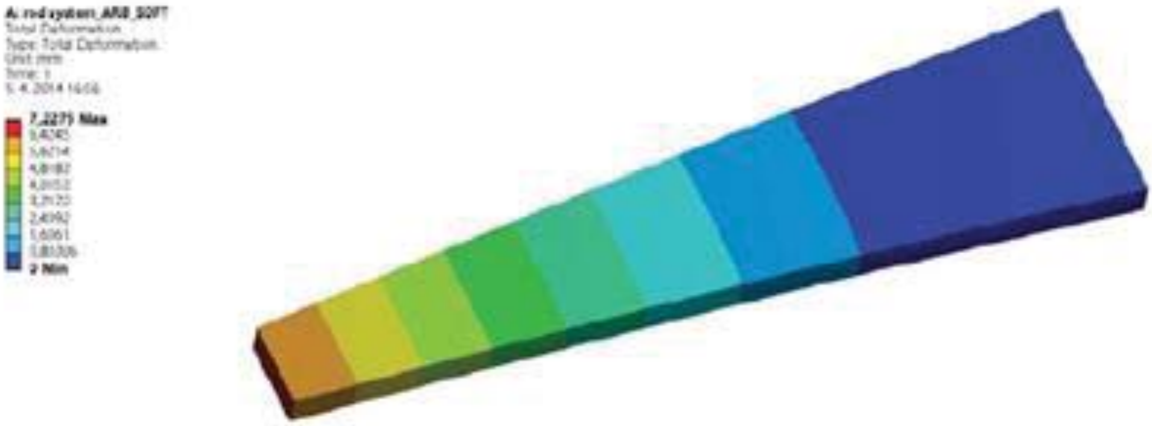


Figure 5 31 the soft setup of blade. The displacement is 7.2 mm

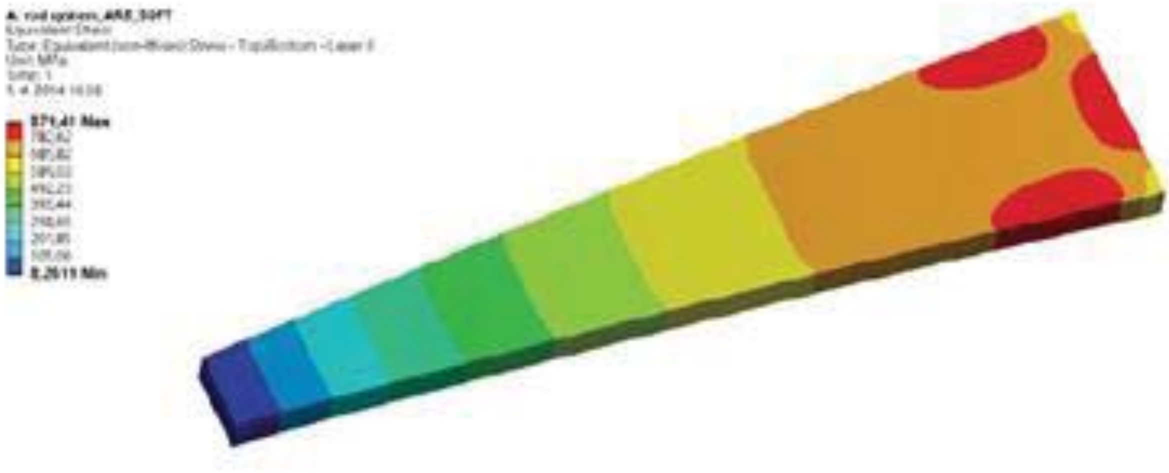


Figure 5 32 maximum stress which is produced in soft configuration is considerably lower. The magnitude is under 900 MPa. This still ensures that the usage of 19 083.8 material is the right variant.

Assembly Finite Element Analysis

Based on the calculation from previous years, the much higher attention was focused for whole assembly simulation. The whole assembly can really show how the design works, furthermore, it helps to predict the real functionality.

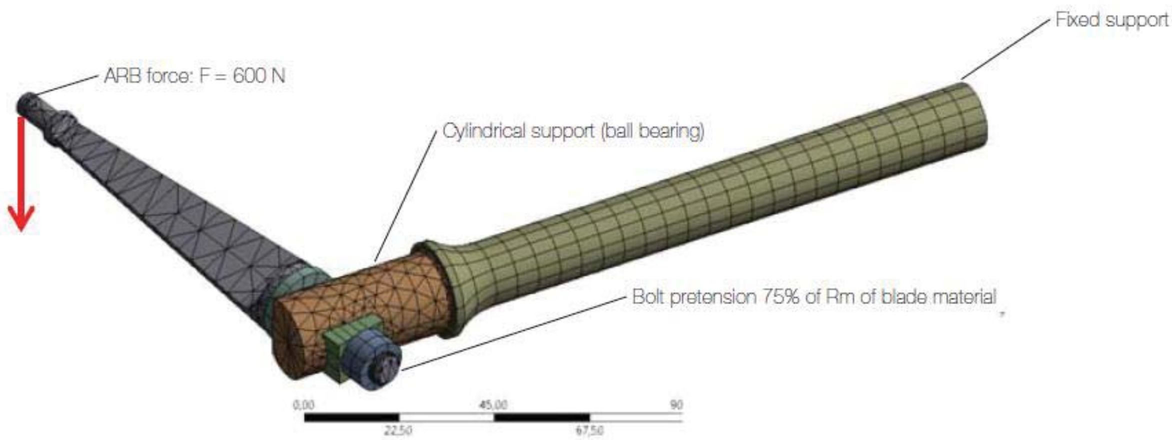
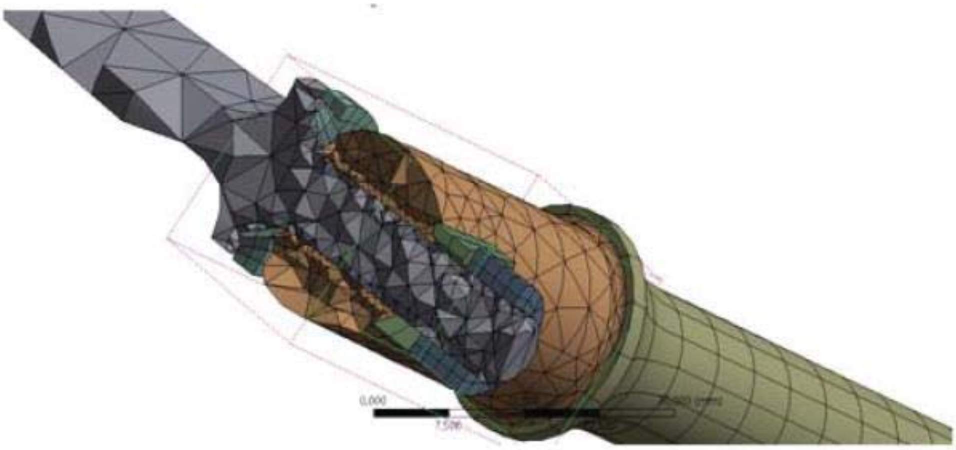


Figure 5 33 only the half of the model was used to FEA as it accelerate the simulation time. Different meshing engines were also decreasing time needed for simulating.

In Figure 5.33 is shown how the approach for testing was. The aim was to deliver high quality mesh which enables short amount of simulation time. Therefore each part of the assembly was deeply considered.

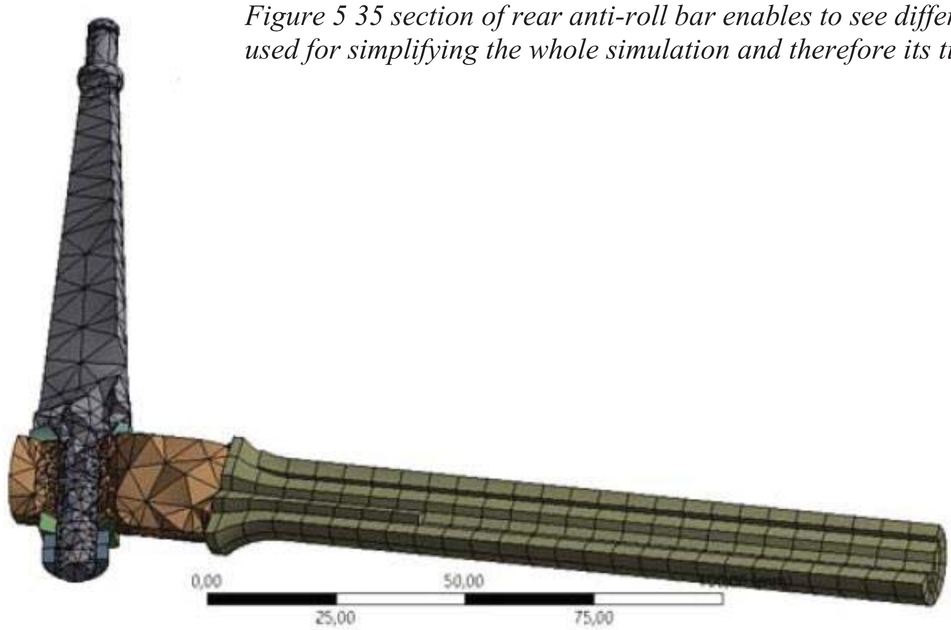
Torsion bar is supposed to be stressed constantly in its part behind the bearing. Hence the bar was divided into two bonded parts. The hexagonal sweep method was used for the straight middle part (green part in Figure 5.33). Tetrahedral mesh with refinement around the surface of the hole as is visible in Figure 5.34. Hexagonal mesh was also used for the spacers used under the blade fitting face and under the nut. As the blade was tested analytically and then finite element method proved this calculation, main concern was about the strength of the stem. Finite Element Analysis do not work with overlaying parts as there would appear local maximums of stress reaching infinity. Therefore the nut and stem have to be simplified.

Figure 5 34 shows mesh detail in section. The refinement was widely used in places with highest stress to ensure that results are as close as possible to reality.



Another issue with this kind of simulation is phenomena called bolt pretension. Setting the bolt pretension is crucial to deliver good results. This procedure has to be done in two steps of iteration. First step applies the pretension force and the second one starts with applying of force on blade. The force applied on blade is in in place and direction of rod end bearing.

Figure 5 35 section of rear anti-roll bar enables to see different types of mesh used for simplifying the whole simulation and therefore its time.



Thanks to this quick possibility of simulating the whole assembly the final version could have been delivered really fast. The whole assembly simulation enables to use the results for calculations of cornering behaviour of car as well.

First design solution of the anti-roll bar used stem 6 mm of diameter. It had to be changed to 8 mm as the maximum of stress exceeded the Yield stress of the material. After that two different diameters of torsional bar were simulated. The intention was to reduce the weight of the whole assembly. The results show absolute small amount of difference (Figure 5.37).

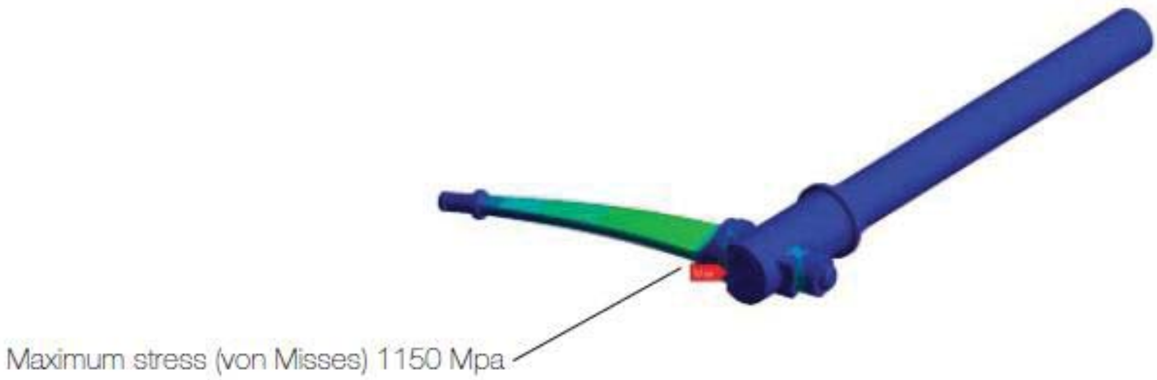


Figure 5 36 local maximum of stress reaches 1150 MPa which is below the Yield stress of the material used for manufacturing. The whole assembly worked well during the whole season. Dragon 4 run more than 700 racing km.

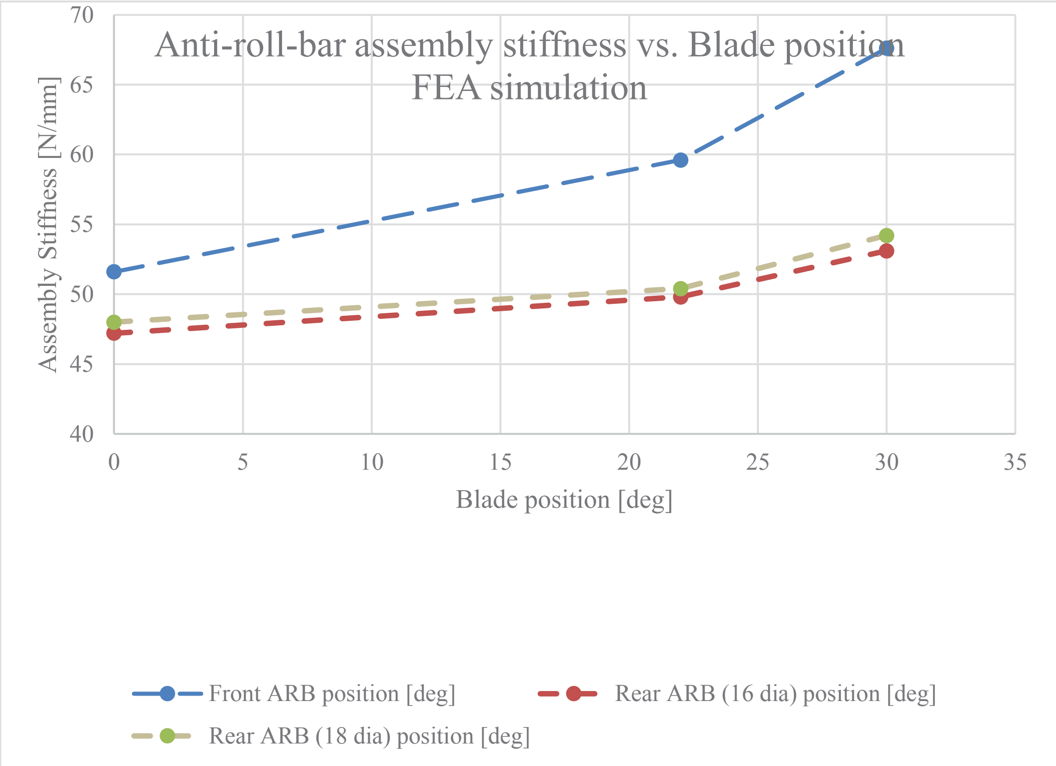


Figure 5 38 the whole assembly stiffness was tested with different blade positions. The trend is not linear as the assembly is most sensitive with higher amount of degree. 0 degrees mean soft position of blade, 90 degrees mean hardest configuration. The car was tested in whole range of the anti-roll bar conditions. The results are shown in Chapter 6

As was mentioned above, the results were used for calculating the car cornering behaviour. Based on Milliken & Milliken approach (Milliken & Milliken, 1995) the understeer gradient was calculated. The results were correlated during test season of the car. In the Figure 5.37 the whole car was analysed in term of the understeer gradient. That help us to understand how the car will behave in range of 0.5 – 3 G of lateral acceleration. This calculation shows understeer behaviour of the car. The real car differs just little bit as the natural behaviour of Dragon 4 was slight understeer.

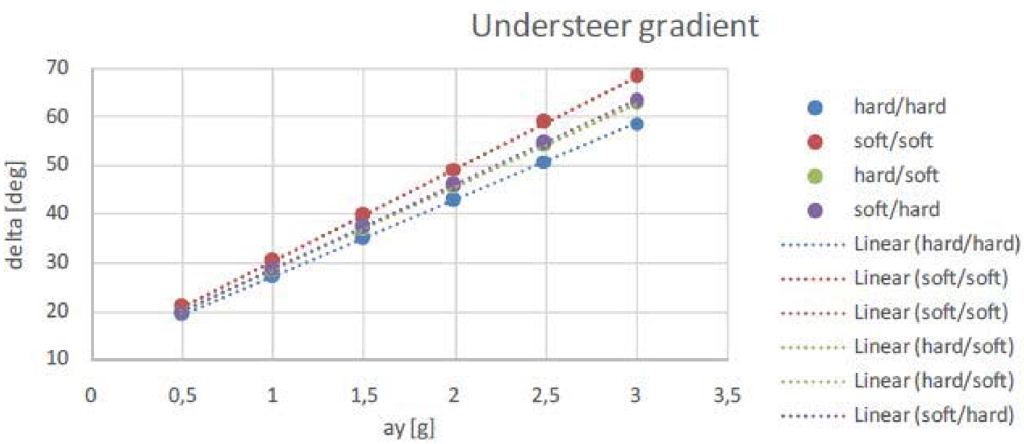


Figure 5 37 calculated understeer gradient. Understeer could have been expected from the car. The data were correlated during testing. Results are shown in Chapter 6.

6 DATA ACQUISITION

Measuring and evaluating a process is something what humans have been doing since the time they needed to improve. In general every kind of human activity could be measured. It does not need to be an engineering approach in motorsport or any kind of research. Nowadays almost every company in the world measuring (logging) some kind of data which control grow and performance.

> *If you cannot measure an activity, you cannot control it. If you cannot control it, you cannot manage it. When performance is measured, performance improves. When performance is measured and reported back, the rate of improvement accelerates. (KPI, 2015)*

While Motorsport has been always used as a laboratory of automotive companies, the aim of developing new technologies was crucial. In development of an engineering solution the only way how to prepare a reasonable result which can control design decision is to measure the functionality, reliability or performance of a component. Therefore Formula 1 teams in early years were logging some kind of data.

During last two decades the data acquisition systems have developed a lot. Where is demand, offer comes immediately. This rule is applicable even in this industry. Today there is a lot of companies in the market. The main difference is probably in software which has been developed by each of these companies. The data units themselves are very similar. They vary in number of analog or digital inputs, some of them have GPS module or accelerometers inside etc. Data logging systems would be nothing without a sensors which measure behaviour of a component. Example can be wheel speed sensor, engine RPM or damper position sensors. All these sensors have to be connected into the unit (directly or via CAN).

One example is shown in Figure 6.1. The product Motec i2 is data analysing software developed by Australian company MoTeC. The layout of software is fully personal and it depends on engineer's demand. In the same figure there are different traces to analyse driver's style.

Figure 6 1 MoTeC i2 pro software with example data. Speed trace, throttle position pedal trace, engine RPM, lateral acceleration, brake pressures or coasting calculation is shown driver to improve his or her time.

6.1 DRAGON SOLUTION

TU Brno Racing have been using Race Technology data logging system with a whole ecosystem of sensors. All of the sensors are visible in Figure 6.2. Data logger itself contains accelerometers and gyroscopes. Data logger should be at the vehicle centre of gravity as there would be the best position for measuring accelerations and yaw movement of the car. In single-seater car it is difficult as the centre of gravity is located in driver's hips. Therefore the unit is mounted beneath driver's knees.

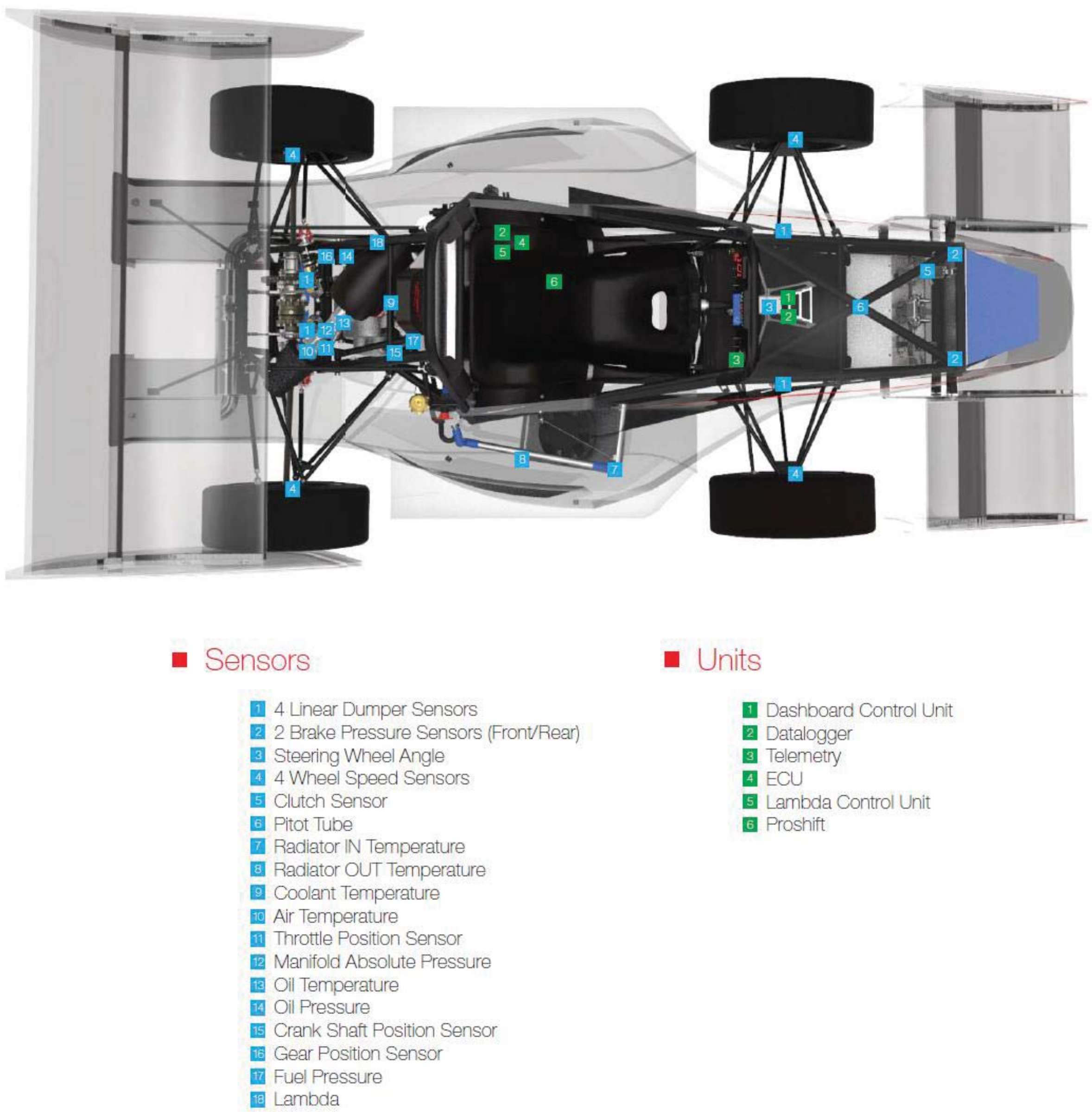


Figure 6 2 List of sensors and units used on Dragon 4 monopost.

Race Technology data analysing software Analysis v8.5 is used for analysing data logged on Dragon cars. The software layout was been tailored to team's demands. In general there are simple rules which should be undertaken every single time when the car data are downloaded into computer. This also drives the software layout itself. Car vital signs – the most important to the whole team (at least it should be). The solution of TU Brno Racing layout is visible in Figure 6.3. If the car is in good condition the driver and vehicle analysis can be started. Driver's behaviour is analysed based on his inputs to the car. In reality driver can control the car with steering wheel, throttle pedal, brake pedal (clutch) and gear shifter. Data engineer can help driver to find space to improve driver's smoothness and consistency lap by lap.

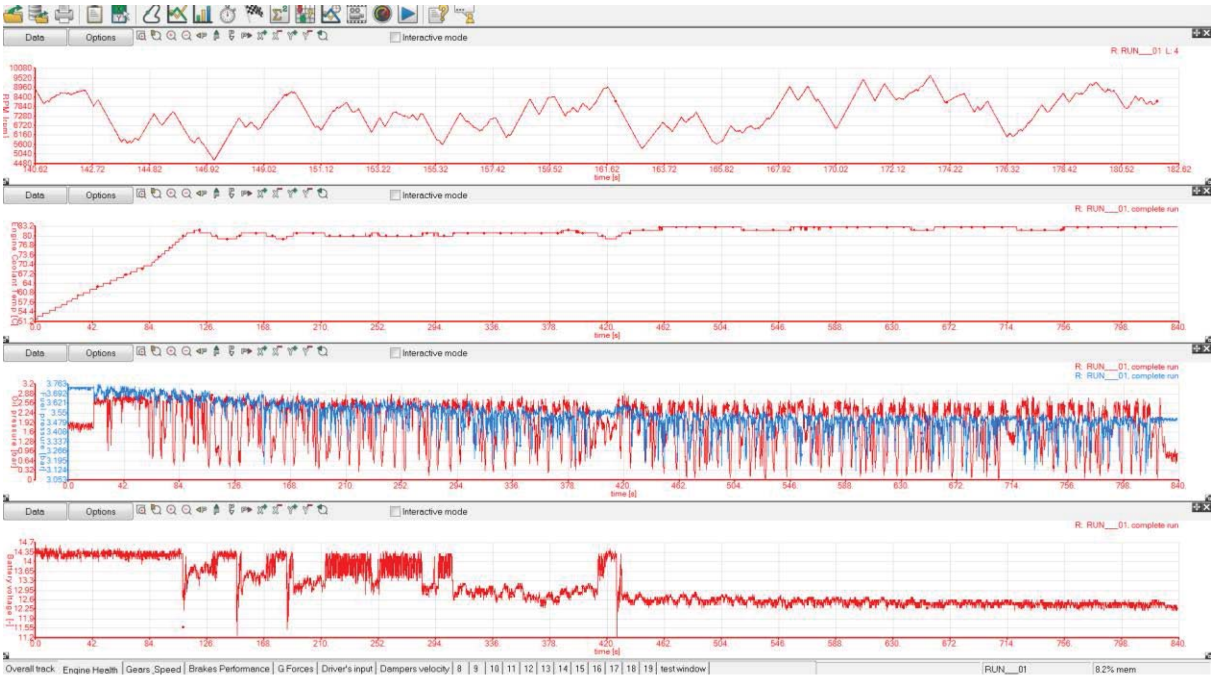


Figure 6 3 Engine health screen layout in Race Technology Analysis v8.5 software. In this situation it is reasonable to show data on time (not on distance). This helps to control engine vitality. Engine RPM, Engine oil pressure, oil temperature, water temperature, battery voltage and many more sensors can be shown on such a screen.

In 2014 season data acquisition system was used a lot in TU Brno Racing team to evaluate vehicle and drivers' data. In Formula Student project are non-professional drivers. This brings demand of driver training. On the other hand the car is prototype with unknown behaviour. For example Dragon 4 was the first car of Brno which had aerodynamics package. This new feature needed to evaluate in real testing to find best possible solution of suspension setup.

In next part of this capture vehicle analysis and drivers' behaviour will be shown as was analysed during test season. All these data was used as a document Setup Book at competitions during the season in Design presentation. The biggest influence it had at Formula Student Germany 2014 where it was one of the main element which brought 11th place in Design Presentation. It proves how important is to track the vehicle and drivers performance in time (in distance). Because without logging data and analysing them the whole solution of any problem is driven only by opinion of a few persons.

6.2 TIME SCHEDULE DRAGON 4

At the beginning of test season it was important to set up time schedule of these days. The very important factor which helped a lot with this planning was the day when the car was fully prepared for testing. TU Brno Racing managed to run the car at 31st of May which ensured 2 months of testing before first competition Formula Student Germany.

It was decided to follow Formula Student competition program in the test season. At the very beginning there were 3 days of reliability. These 3 days were all about primary check of all systems and about calibration of each sensor. Immediately after this calibration the aerodynamics test were prepared. As was mentioned before Dragon 4 was the first monopost with aerodynamic package. Due to impossibility of testing in a wind tunnel it was important to correlate the CFD data and tailored the suspension setup according to downforce. Right after the aerodynamic tests team focused on skid pad discipline. This discipline is very important to undertake as soon as possible as it enables to setup the suspension as well as possible. Moreover drivers need to be well prepared and have this ritual under their skin. It sad to see failed attempts to run through skid pad at competition every year. During skid pad season the understeer gradient was measured depending on different anti-roll bar setup.

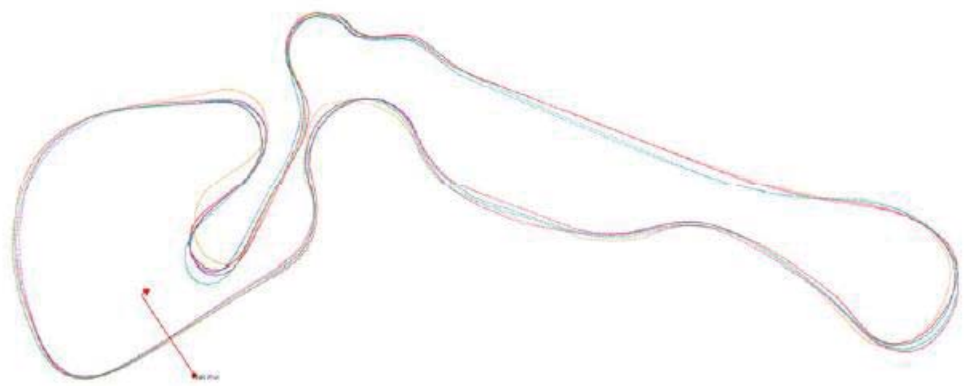


Figure 6 4 TU Brno Racing test circuit at Brno exhibition centre. Track conditions simulate the real track at competitions based on FSAE rules (SAE, 2015). The only difference is wide of the track. It is one meter narrower to deliver tough conditions for driver. To train the driver not to hit cones is important as there is always penalization for such an incident. Basic data of the track provides 70 m straight, 13 m to 9 m slalom, slow and fast corners, skid pad corner, typical FSG chicane. Width of track is 2.5 m in average (compare to 3.5 m as is stipulated in rules).

The skid pad testing provided decent setup for rest of disciplines. Autocross and Endurance tests was fairly identical at the beginning. Measuring tyres temperature after first and second fast lap enables to understand tyres behaviour. Long distant stints tried to simulate whole endurance and hence the reliability of the car. Last discipline which had to been tested is acceleration. On local agricultural airport (same where the aerodynamics were correlated) the best time with our single cylinder engine car were improved a lot.

In Figure 6.4 is shown the testing track. It is important to prepare track which simulates real conditions at competition as close as possible. Another aspect of having consistent track is the opportunity to compare performance during the whole test season or even to analyse improvement (hopefully) of the new car in the next season. Because at the end of the day time is everything. Everything should be compared to lap time.

6.2.1 TEST SEASON OVERVIEW

Before the team left university facilities to compete at Formula Student Germany these numbers were analysed after test season. Between 31st May and 26th of June there were 26 test days with 500 test km. The car run 10 full Endurance simulations, around 350 skid pads (100 of them was wet pads as at Formula Student Germany the skid pad is run in wet conditions) and around 300 accelerations.

In these test the maximum of longitudinal acceleration was 1.6 G, minimum of this acceleration was 2.1 G. Maximum of lateral acceleration was 2.4 G. At the end of Endurance tests the maximum of tyre temperature was 70 degrees of centigrade. New design of brakes ensures that the brakes were working in right range of temperatures – 250 degrees of centigrade on front and 150 on the rear axle.

All these information are provided in Figure 6.5 for easy orientation.

Total # of racing km	500
Total # of test days	26
# of Endurance simulations	10
# of Skid pads	350 (100 wet skid pad)
# of Accelerations	300
Maximum of long. G	1.6
Minimum of long. G	2.1
Maximum of lat. G	2.4
Maximum of tires temperature	70 deg
maximum of brakes temperature	250 front/150 rear

Figure 6 5 Preseason tests overview

6.2.2 CALIBRATION

The first 3 test were used to get used to new car from the mechanical point of view. The test track was just a simple oval (Figure 6.6) at the university parking place. In Formula Student team it is important to set the team roles for the test sessions. This “simple” test days were used to prepare team for team work.

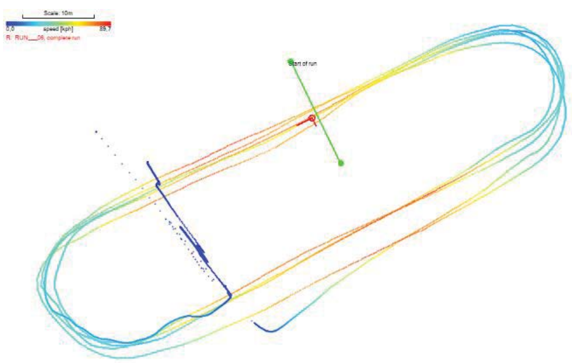


Figure 6 6 First tests were done at university facility. Safely closed parking place at weekends can be great place where to start with testing without going far away to bigger test places.

Beside the reliability testing the sensor calibration and sensor control was undertaken. In Figure 6.8 are the brake pressure traces shown. This enable the team to understand brake bias (distribution) and also it helps to control if the brakes are bleed well. In racing regime this traces are used a lot to evaluate driver’s style, consistency and smoothness for example.

There were also damper position sensor calibration provided, accelerometers check, and engine management control for example. In Figure 6.9 are acceleration traces provided. This traces help to analyse tyre capacity and drivers ability to make the most of them. From statistical point of view it is useful to track the tyre performance in time. Different ambient temperatures, different camber and toe settings provide different tyre temperatures. Understanding the tyres is ultimately the most important element in racing world.

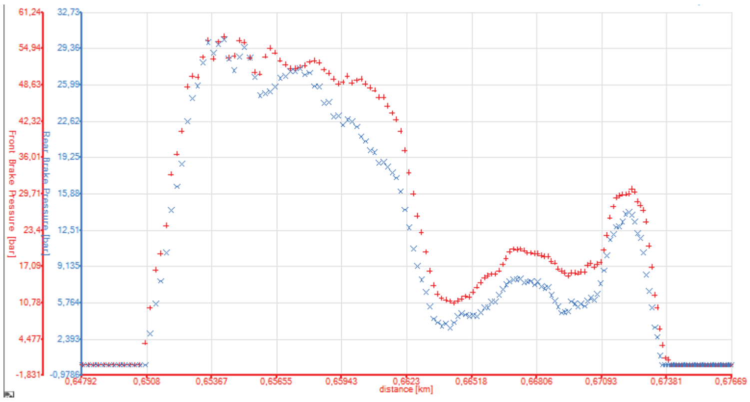


Figure 6 8 Brakes traces (red is the front, blue the rear loom) are very important in data analysis. It is enabling to understand brakes a lot from the vehicle point of view. Moreover drivers can learn a lot of information out of this traces as well. Consistency, smoothness, speed and aggressiveness are important factors.

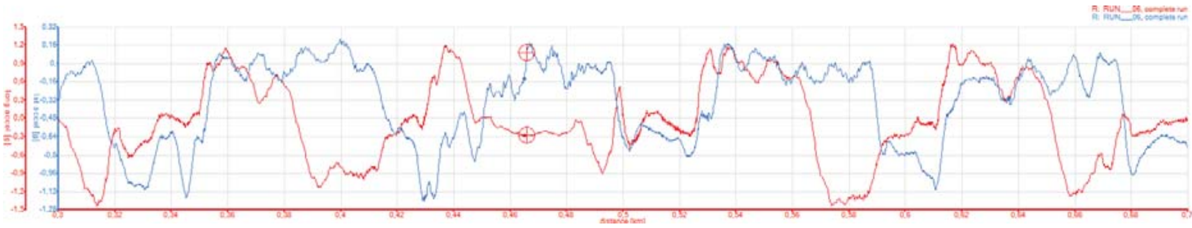


Figure 6 7 longitudinal and lateral traces show the capability of tyres and drivers' ability to use them right on the edge of their performance.

6.2.3 Skid Pad & Wet Pad

Skid pad discipline is widely used not only in Formula Student testing. Cornering ability is very important element even for passenger cars. Therefore this test of steady-state cornering is very popular. Based on FSAE rules the skid pad was tested extensively in pre-season tests. There were 5 all days of testing used for this discipline. It was important to teach drivers to be consistent, different setup of suspension was tested as well. Different springs were used based on aerodynamic downforce influence. Before Formula Student Germany extensive testing of wet skid pad were planned to teach driver and set up the car accordingly to wet conditions.

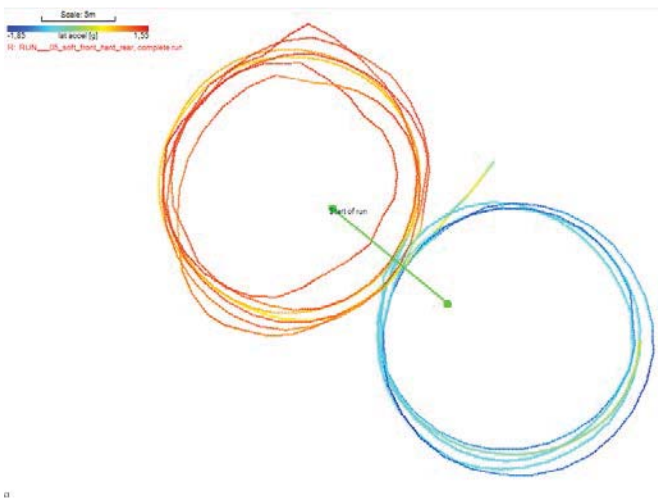


Figure 6 9 GPS map of skid pad. Consistency is important in this discipline. The test procedure was driven by rules as the car has to run two right circles (blue trace) and two left circles (red trace).

UNDERSTEER GRADIENT EVALUATION

To understand the car at the beginning of season the understeer gradient measurement was done at the first skid pad tests. This characteristic shows how the car is sensible to different anti-roll bars setup. This tests helped the team to understand the setup and eventually find the way how to deliver mechanically well-balanced car.

Different anti – roll bar setup at test:

a) Front ARB soft / Rear ARB dismantled

b) Front ARB soft / Rear ARB soft

c) Front ARB soft / Rear ARB half hard

d) Front ARB soft / Rear ARB hard

e) Front ARB half hard / Rear ARB hard

f) Front ARB hard / Rear ARB hard

In figures 6.10 to 6.15 the different characteristics which were analysed are shown and explained. At the end of the test day understeer gradient were evaluated. The surprise was that the rear wing influenced the car a lot even at this speed level (less 45 kph in average). As the results of this downforce effect different springs were used for the car at the rear axle. Stiffer springs provided significant difference of understeer behaviour of the car. This difference is shown in Figure 6.14 and 6.15.

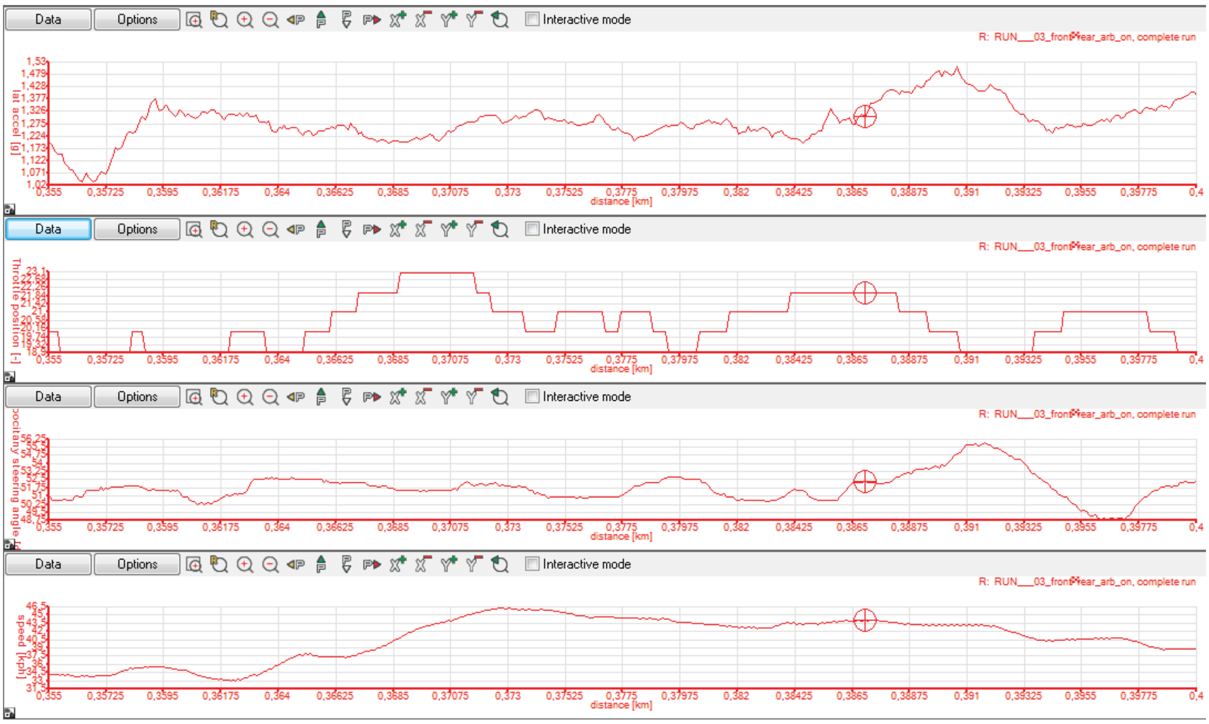


Figure 6 10 Single circle of skid pad is shown in these traces. The target of this discipline is to be smooth and consistent. Steady-state cornering - the name of the act is clear enough. Therefore the constant lateral acceleration, throttle position, steering angle and speed traces should be consistent.

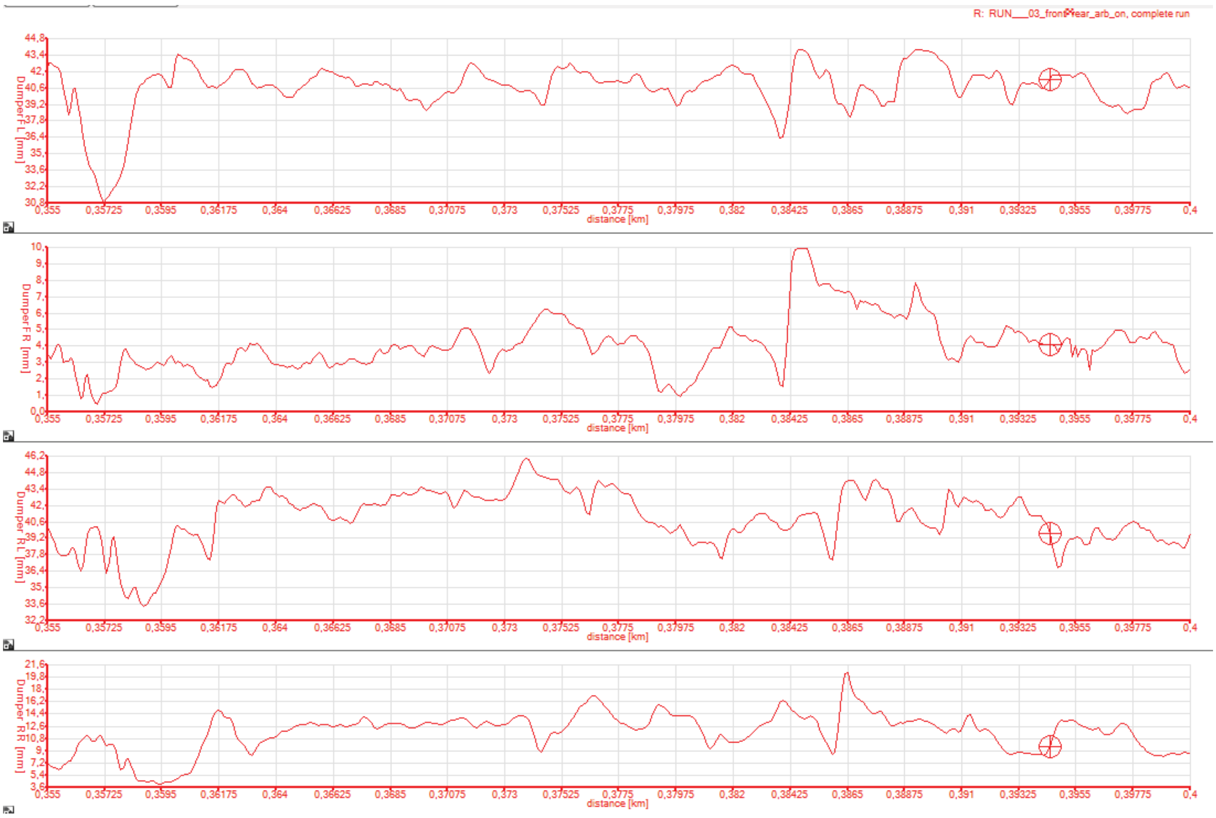


Figure 6 12 dampers sensor position enable to see the track profile. It is important to find ideal track condition. These set of data were collected at a local agricultural airport. One of the design aims of such an airport is the angled profile (compare to roof) to enable water to go off the surface naturally. This drop is seen in the data at 0.38 m of distance axis.

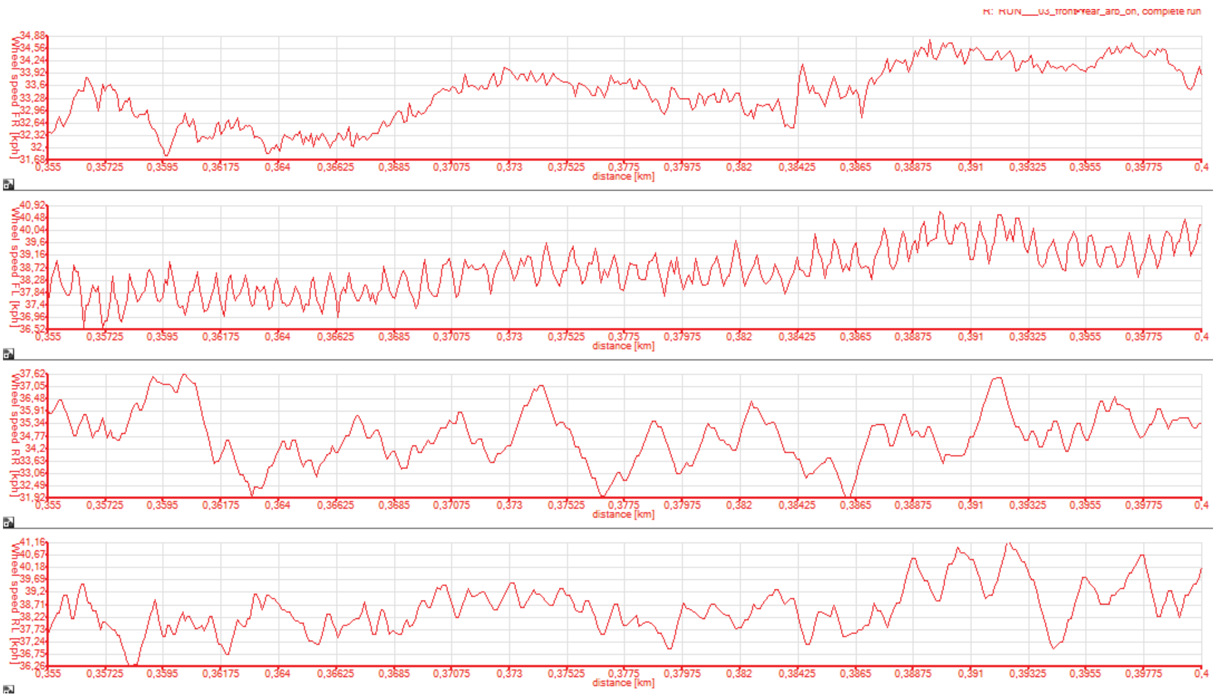


Figure 6 11 having all wheel speed sensors at each wheel provides a huge advantage. In these traces is clearly visible how the rear right wheel is unstable. The contact between the tyre and track surface is insufficient as the wheel slides on the track. Wheel is unloaded. This fact was improved with different anti-roll bar setup. Another option is to change differential setup. This is one of the fact which drove the team to design new kinematics for Dragon 5 generation.

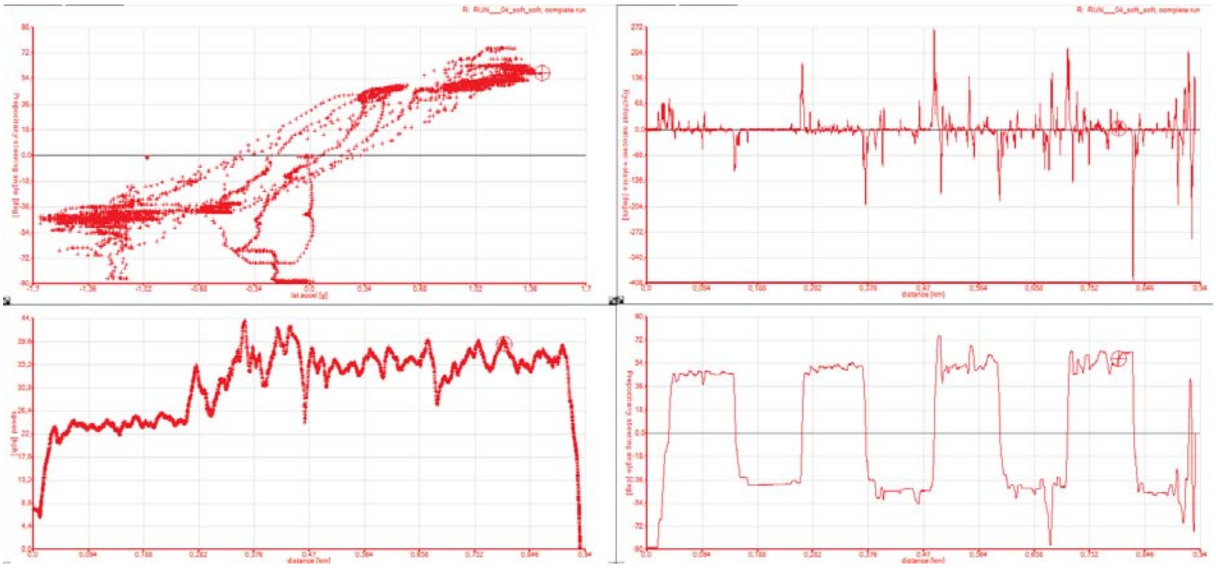


Figure 6 14 four different graphs analyses different aspects at skid pad. Left upper graph shows one possible view of understeer gradient. Lateral acceleration as x axis and steering angle as y axis. The progression is very similar to data measured and evaluated in Figure 6.14 and 6.15. Right upper and right down graphs control the driver smoothness and consistency. On the steering angle trace are visible a few drops. This was due to the track profile as was mentioned previously (roof shape). Unloading of the front axle had to be controlled by driver.

Figure 6 13 Understeer gradient evaluated with exported data to excel. This could be used as a comparison between different setups. The absolute numbers could be provided with measuring of slip angle of the car. Unfortunately the TU Brno Racing was not able to test this characteristics.

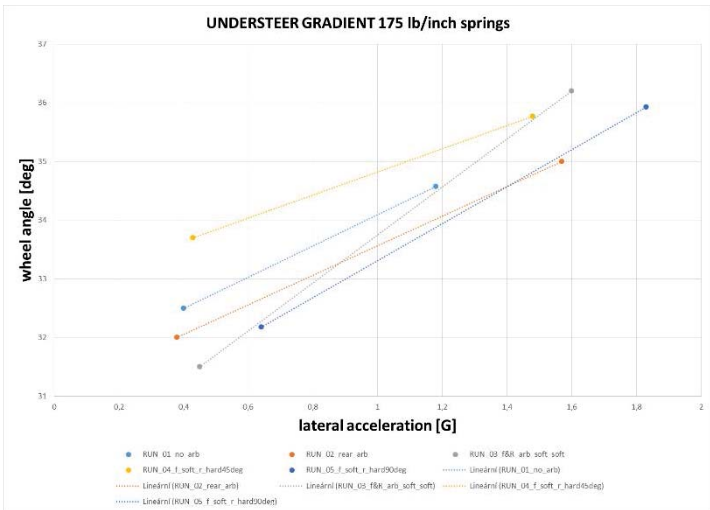
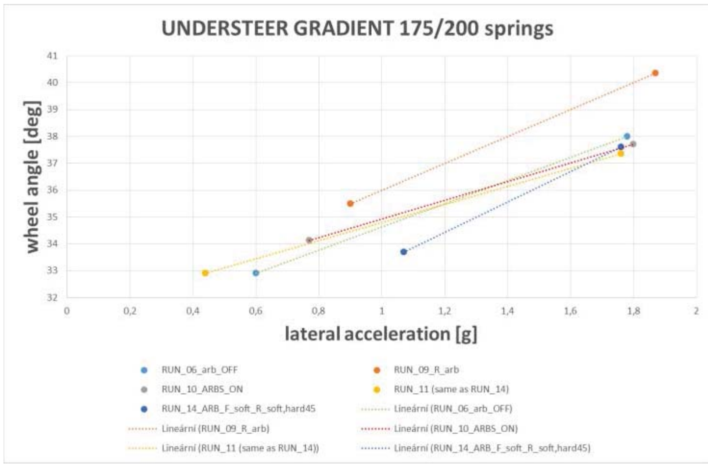


Figure 6 15 due to the downforce which is acting on the car even at this speed it was necessary to change the rear springs stiffness. This spring layout was used for the whole season. In aerodynamic data it is shown how efficient the rear wing was. Therefore the load transfer in speed progression was quite significant. Stiffer rear springs helped to solve this effect significantly.



DRIVER AND VEHICLE ANALYSIS AT SKID PAD

After the basic setup was found the team could proceed to another stage of skid pad testing. That was the final vehicle setup and mainly drivers' training. The consistency is the main factor. That was the reason for the approach which is visible in figure 6.16. Every driver had to undertake the skid pad procedure as he would done at competition.

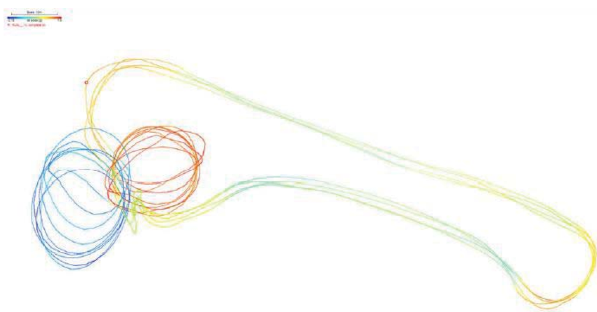


Figure 6 16 consistency is important. The process is described in text. The vehicle racing line is influenced with the damaged cable of gps module. This problem could be sorted in the winter after the season.

That means start procedure, two right circles, two left circles and long slow drive around the site. This is really important habit. Driver would be stressed a lot at the competition and there is no place to make an unforced mistake. The stop/start procedure is important even from the psychological point of view. Driver needs to be calm and fully concentrated to each attempt as it is the real one. This approach helped the team to succeed for example at Formula Student Germany afterwards.

In this part of skid pad testing the vehicle behaviour was studied a lot. Formula Student project is a learning process. Therefore the car behaviour is something what was explored from the scratch. In Figures 6.17 – 6.21 is explained what was studied deeply.

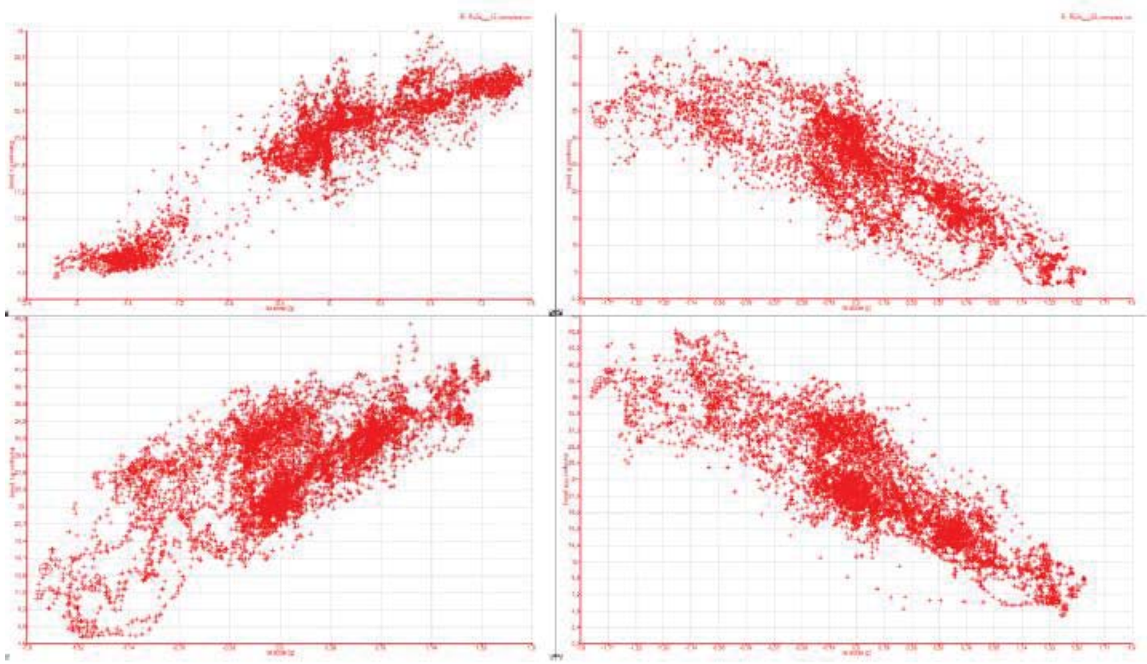
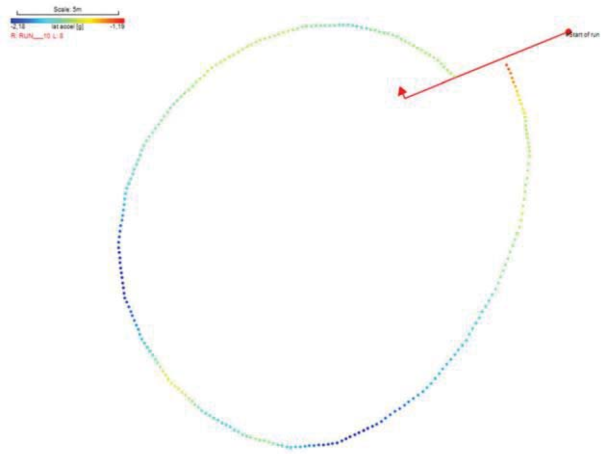
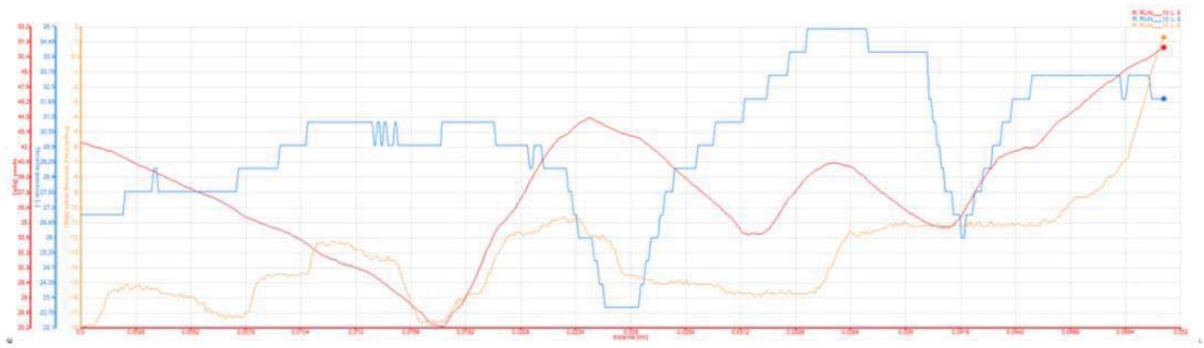


Figure 6 17 Vehicle load transfer. The lateral acceleration on x axis and damper position on y axis help to analyse this phenomena. Each graph represents different wheel of the car. It is top view on the car. For easier understanding this could be differ with different colours for each corner of the car. At the beginning of the test season this graphs helped team understand the lateral weight transfers. Basically it can show if the damper works in the whole range of travel or if there is any bump stop problem. During the season this graphs helped to analyse different suspension setup. The example is provided in Autocross and Endurance chapter. Different mounting points (therefore different kinematics) of rear wishbones were tested extensively.

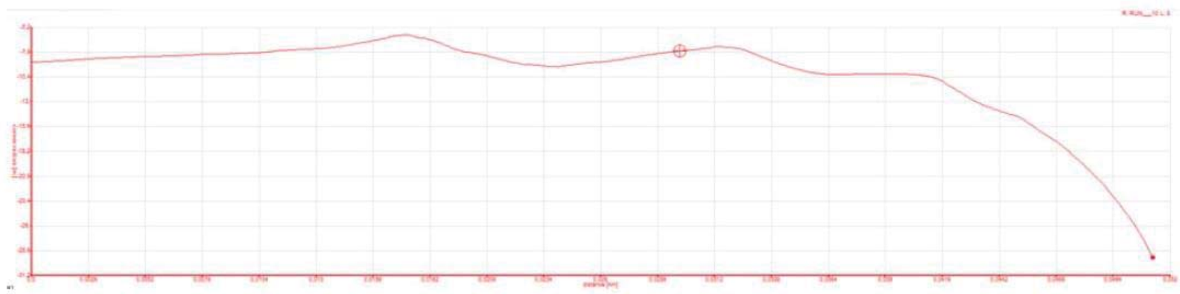
Figure 6 20 Lateral acceleration on this track map helps to show driver his inconsistence. Colour of the map should remain the same throughout the whole circle. This map analysis can inform about the driver or car behaviour at the first sight. Deeper analysis are shown in next Figures.





Handling ability - throttle pos, speed, wheel angle

Figure 6 19 Oversteer problem of the car is visible in these traces. Significant steering wheel reaction and pulling of the throttle influence the speed of the car. The final time is not sufficient. This problem was done due to lack of driver's experience. It is necessary to handle the car as smooth as possible. Only the steady-state handling could deliver steady-state car behaviour. Once the driver is experienced and knows the car enough the car setup can be tailored to his or her demands.



Corner radius, opening at the end

Figure 6 18 corner radius of the last skid pad circle was tested as well. There are two different approaches. First - in the graph - is to open the steering wheel and chase the throttle a lot. The other is to stay consistent till the end of the skid pad. These two different approaches were used for different occasions. The wet pad needs to be driven as smooth and consistent as possible. However dry conditions enable driver to use the tyre mechanical grip much more and the high slip angle should be delivered.

WET PAD DRIVERS TRAINING AND VEHICLE FINAL SETUP

One of the last test days before Formula Student Germany competition was only about wet skid pad testing. Drivers' confidence was really important. Once again the real racing conditions were delivered. The procedure of the skid pad was done one by one. At the end of the test days the best time at time gate was slightly above 5.5 seconds. That would be first place at Formula Student Germany 2013. This results were very encouraging. Eventually the seventh place was a little bit of disappointment. However Formula Student is about learning and experience.

Figure 6 21 Wed pad map with lateral acceleration trace used as a colour. The approach remains still the same. Stop/start procedure, full focus and concentration, two right circles, two left circles. In the map is visible the consistency of the driver as the circles are single coloured.

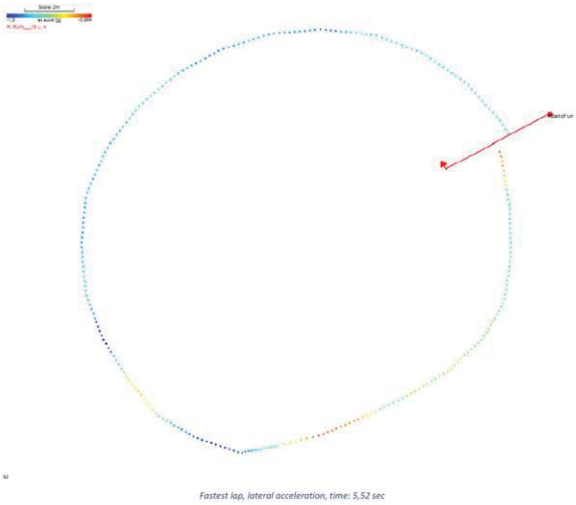


Figure 6 23 Map coloured with lateral acceleration trace. The driver is on the edge of the car's performance. The slight oversteer is visible in the next Figure. The time 5.52 is the best time of the Dragon 4 while test season.

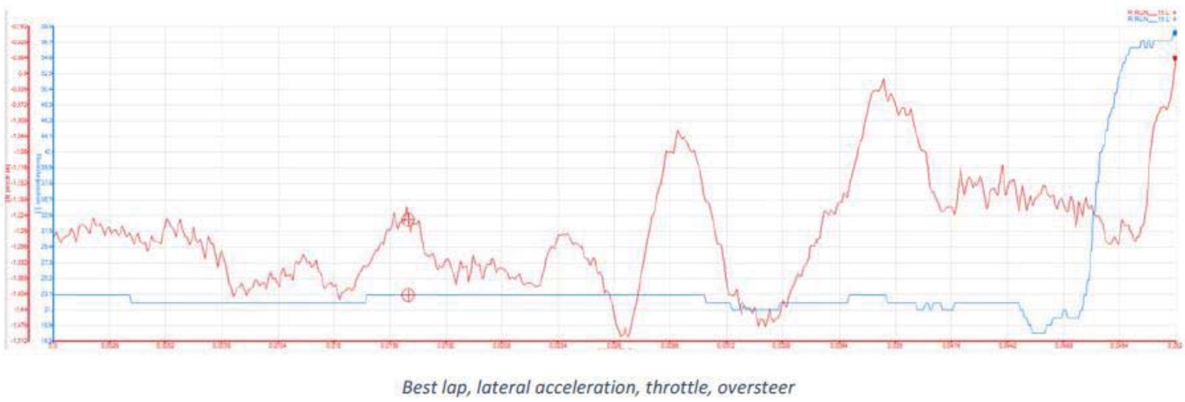
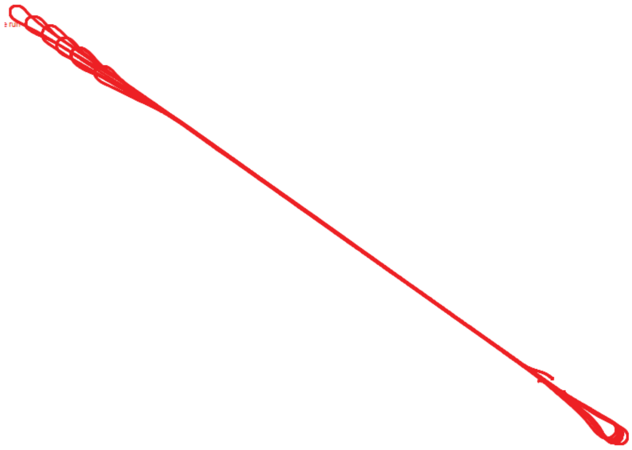


Figure 6 22 in the best lap it is visible how consistent the driver is on the throttle. The lateral acceleration shows the edge of the car performance. Driver chased the throttle a lot at the end of the circle which is not sufficient at wet pad.

6.2.4 AERODYNAMICS



One of the most important test at the beginning of test season was aerodynamics correlation test. Due to lack of experience with driving the aerodynamic car, team needed to understand this new feature as soon as possible. Therefore right on the start of this phase the aerodynamic test were undertaken. Two days of testing brought new insights into the aerodynamic knowledge of the whole team. While the team was interested mostly in downforce at each speed level the tests of constant speed were analysed. In future it would be useful to test even the drag of the car deeply. The only test which was done to deliver an understanding of vehicle drag was the maximum speed test with and without wings. The difference of the top speed was around 30 kph. Without wings the car was able to reach 145 kph. With the wings under the same condition on the same day it was 110 kph. This speed is still more than enough for a formula student track.
The main test of aerodynamics were the constant speed level test. The downforce was calculated with knowledge of static damper position and dynamic damper position at each speed level. Due to the spring stiffness it is possible to calculate downforce. Difference between static and dynamic damper position provides the change of downforce acting on the vehicle. In Figure 6.24 are these speed traces described.

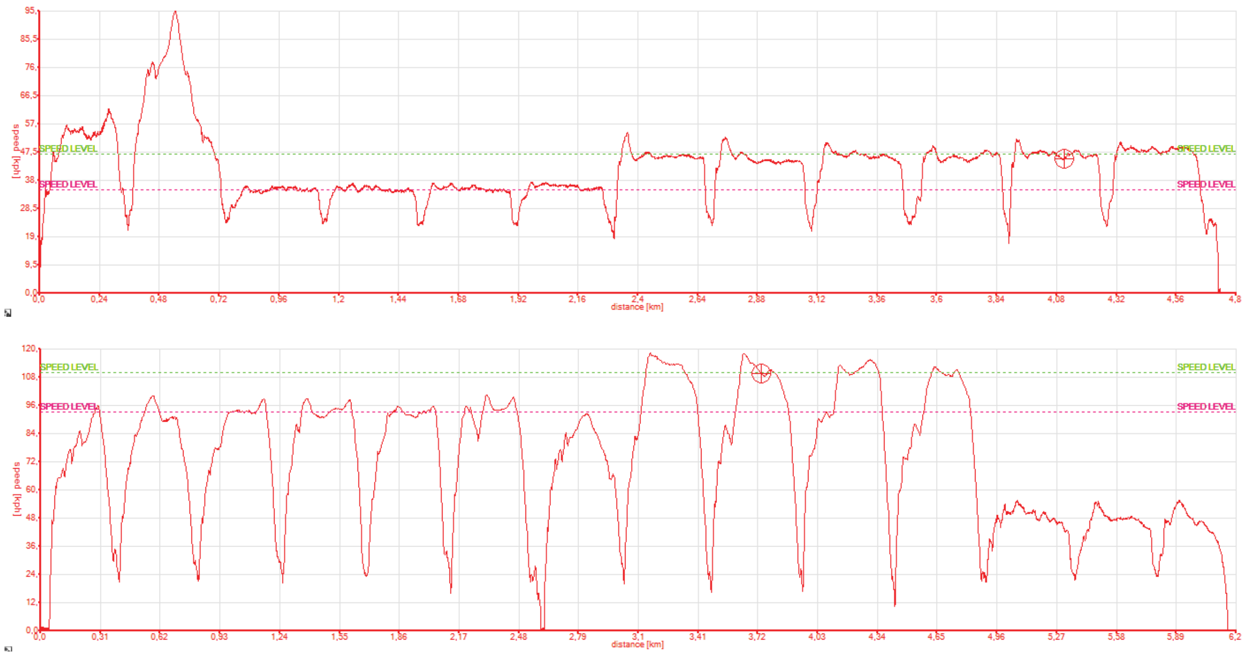


Figure 6 24 these graphs show data which were logged during the constant speed level test. A few speed levels were chosen to evaluate these data. Formula Student average speed track is around 50 kph. Therefore the test started with very slow speed - 30 kph. Then the crucial 50 kph level was measured. To ensure as precise results as possible the 90 kph and 115 kph speed level was measured.

The Figure 6.25 shows influence of the wind. On the damper position is shown how much the head wind can change the final results. This issue could solved Pitot tube, unfortunately budget of the team did not enable to buy one. The solution was to measure more data in both directions to provide some average of the data.

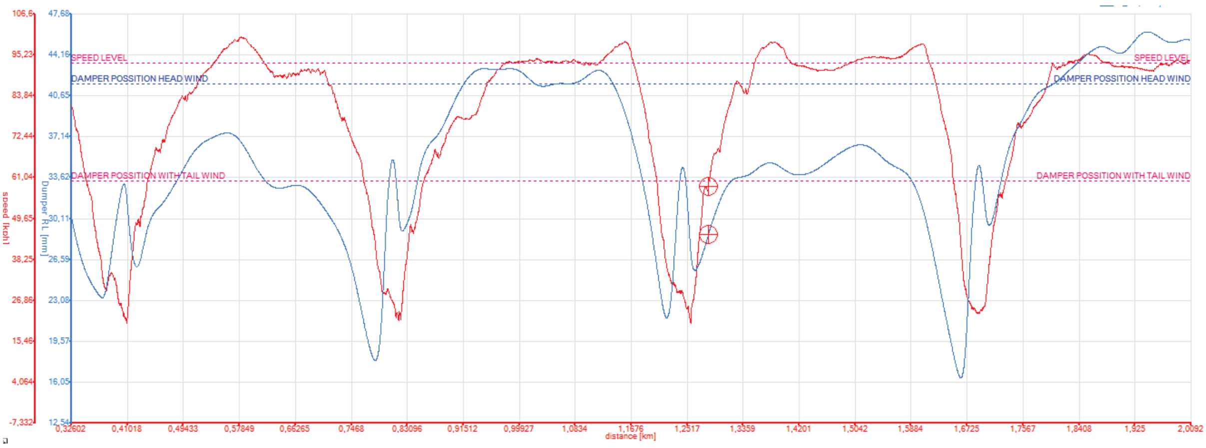


Figure 6 25 Head wind and tail wind clearly influence the measured data. With the same speed level (red trace) there is significant difference in damper position (blue trace - rear left damper). This problem could be solved with Pitot tube. However in this case the results were averaged. The huge amount of data delivered quite sufficient results.

The set of damper position data were filtered in Race Technology Analysis v8.5 software. Afterwards the data was exported to excel for further calculations. As was mentioned before with knowledge of spring stiffness it was possible to evaluate the downforce of the car at each speed level. In Figure 6.26 and 6.27 the final data are shown. Two different wings setup are provided. The “high lift” – in the other words the high downforce configuration and “low drag”. Low drag configuration is used for acceleration discipline at the competition.

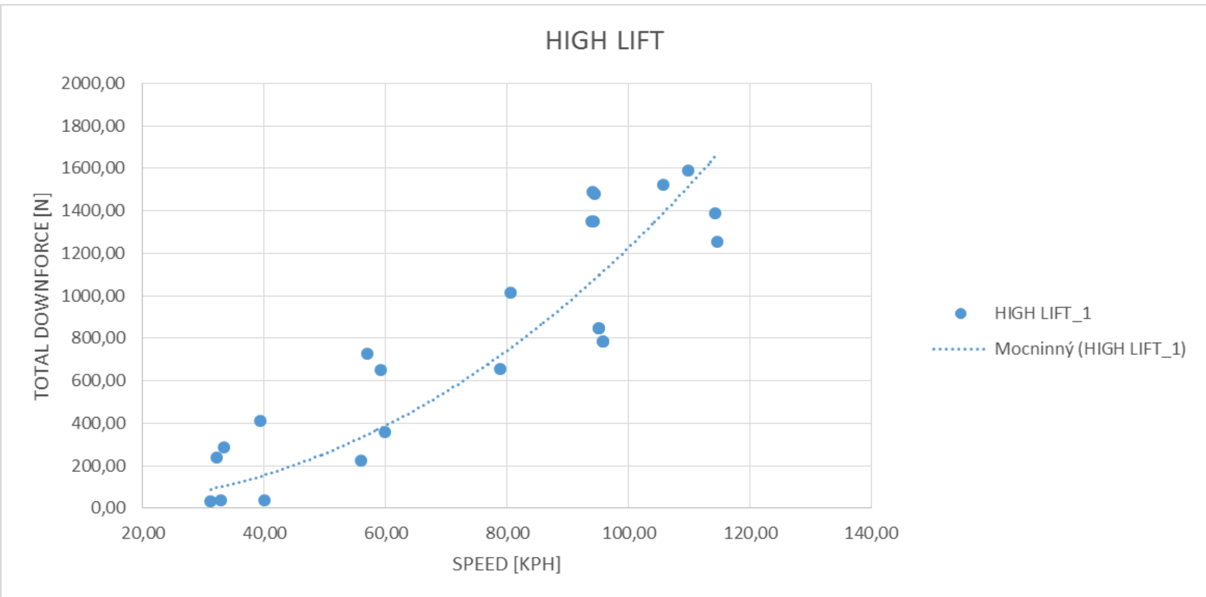


Figure 6 26 the high lift configuration of wings delivers around 1000 N at 100 kph. The set of data in excel were averaged with polynomial trend line of second order. The aerodynamic force is depends on speed with the second order.

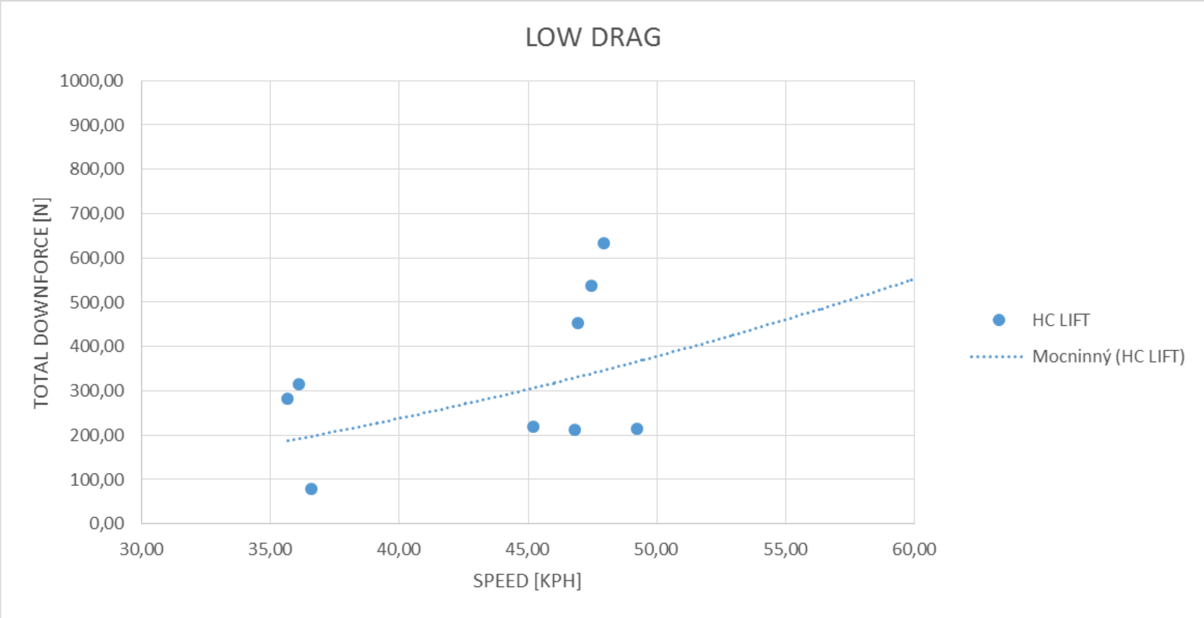


Figure 6 28 the low drag configuration is used solely for acceleration discipline at competition. The target is to decrease drag as much as possible.

This set of data enabled to evaluate the aerodynamic load transfer (Figure 6.28). This effect was eliminate with using stiffer springs at the rear axle. The rear wing of Dragon 4 is much more efficient than the front one. This was another important test to provide such a data set which enables to improve aerodynamic knowledge of the whole team. The aerodynamic load transfer influenced the car even at skid pad tests a lot as was described earlier.

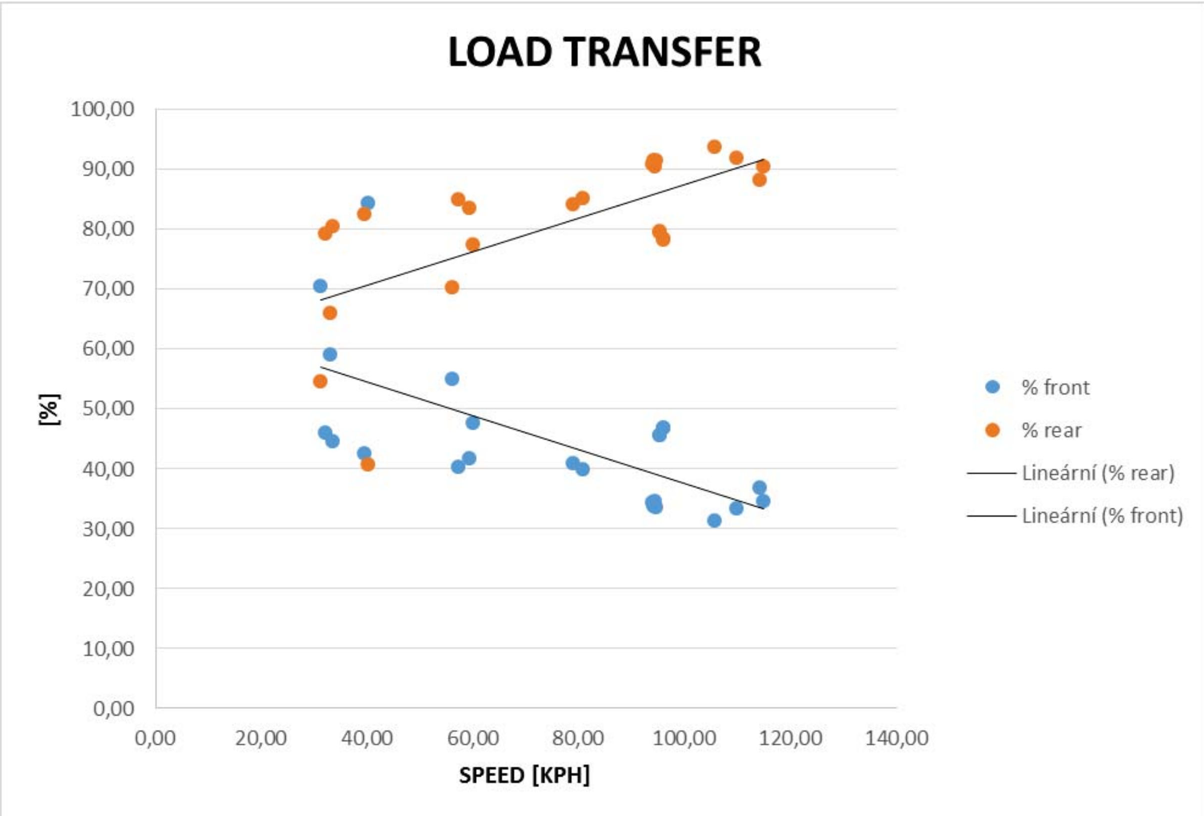


Figure 6 27 aerodynamic load transfer of Dragon 4. At higher speed corners the car would suffer from understeer a lot as the majority of downforce acts at the rear axle. With stiffer springs on the rear axle the car behaviour has been improved significantly.

Figure 6 30 visual control is important as well. This test cannot be seen in data which are logged in data logger, however, taking photos and videos is another way how to collect very useful data.

Figure 6 29 Go Pro camera mounted on rear wing end plate provides really important set of data as well. Boundary layer of this wing is really good. Cotton strings were stable and straight during every speed level.

6.2.5 AUTOCROSS & ENDURANCE

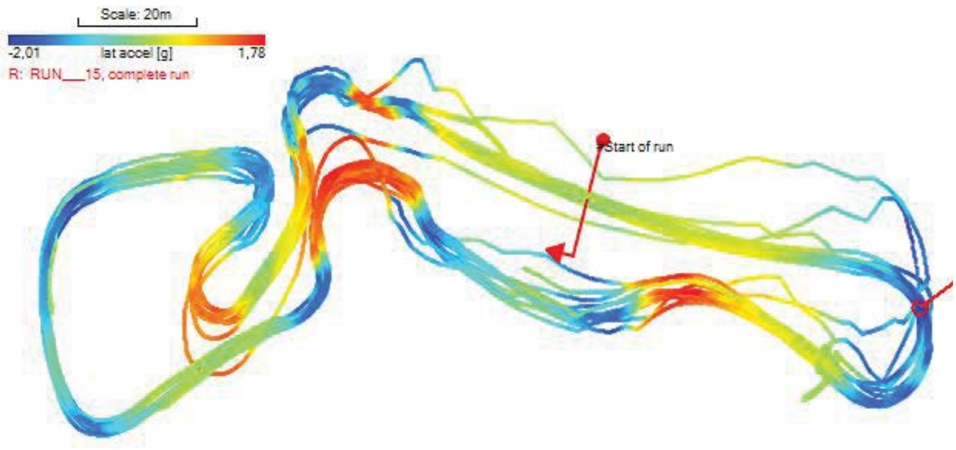


Figure 6 31 the map is based on lateral acceleration. The data set used is from the first tests on an old set of tyres. It was important to put driver into the car and let him know the new car properly. The track which is in this Figure is TU Brno Racing test track at Brno Exhibition Centre prepared according to FSAE rules. More about the track data is written at the beginning of chapter 6.

Big portion of test kilometres took autocross and endurance. The reason is clear. These disciplines are the most important. Especially the endurance with the amount of available points makes almost half of the competition. Reliability is the most important element in racing industry in general. In the Formula Student world it is the only way how to really succeed. Finish means win. Maybe not in overall classification but definitely the emotions in team after the whole year of developing, manufacturing and testing it are really crucial as it could motivate (or not) for future competitions. To finish means to win for most of the teams.

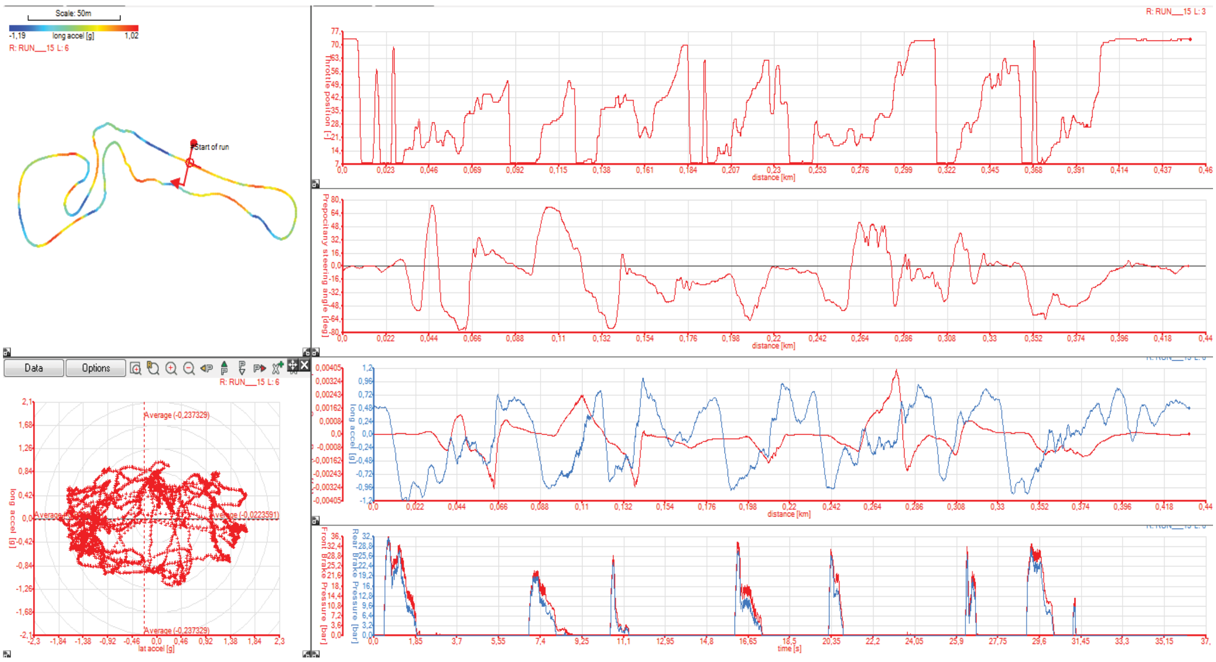


Figure 6 32 one of the very first laps on the track with the new car. The driver's hesitation is clearly visible in this set of data. Throttle position trace shows that the driver does not know the car and the tyres. Formula Student is a learning process. Later graphs of this chapter provides the big improvement of driving style. Traction circle provided shows the hesitation as well.

The first tests of autocross and endurance are always about the driver and reliability. In Figure 6.32 is shown how the driver used the car. Check all the systems and slowly graduate in speed. This is the point where the driver and data (race) engineer can start to learn a lot of information from the data.

Information about the car – controlling the vital signs of the all package and vehicle & driver analysis furthermore. In the Figure 6.33 the damper position sensors are shown. Upper half of traces are distance depended, lower half is lateral acceleration depended. The load transfer is one of the basic elements in race car analysis. In this case the range of damper travel was checked. Basically the intent was to allow the damper to travel in the whole range without going to full bump or full rebound.

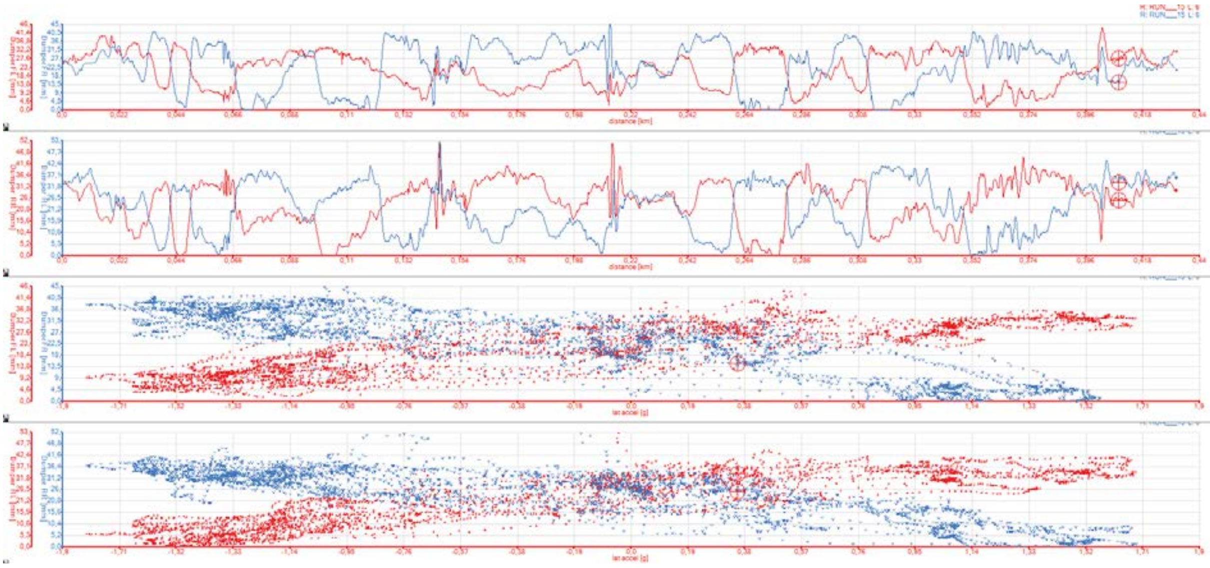


Figure 6 34 controlling the damper position sensors. Damper position visualised in lower half of the graph is lateral acceleration depended. The load transfer in corners can be therefore analysed. In this part of the test season it was one of the basic focus of enabling dampers to travel in their all range.

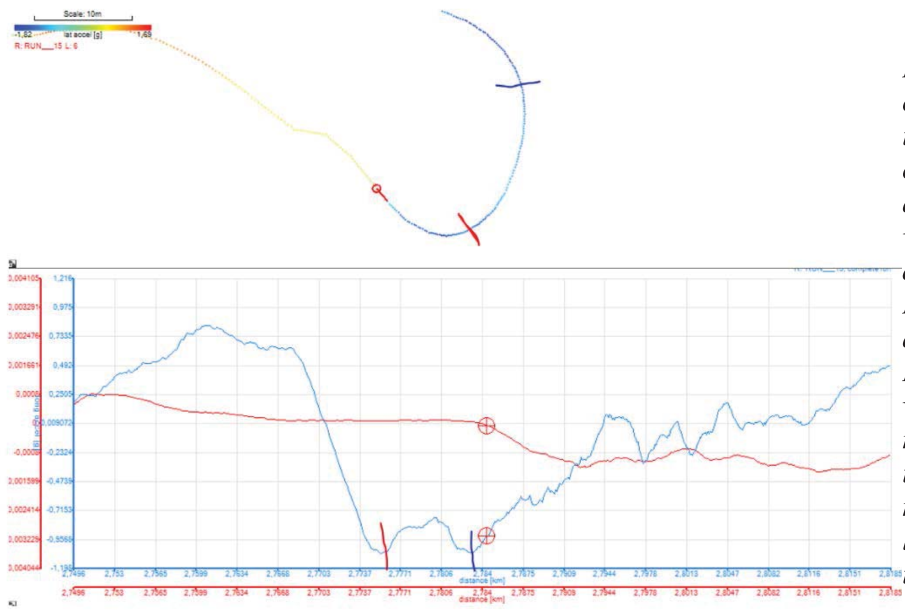


Figure 6 33 inverse corner radius is one of the important math channels used in data analysis. This enables to visualize racing line driver used in a corner. In this case the double apex corner is shown. Every apex is highlighted with a line (blue and red). According to tyre theory the inverse corner radius should be smooth line as the driver is using tyre in predictable way.

INVERSE CORNER RADIUS

In Figure 6.33 the inverse corner radius math channel is presented. One of the basic channel how to visualize racing line (or simply the curvature of taken path). This math channel enables to understand driving style and it is possible to explain driver what to improve. With this function the corner analysis can be undertaken with easier imagination. In the Figure 6.33 is shown typical double apex corner. Sometimes it is necessary to compromise speed in the first apex to be able to chase the throttle pedal in the second one.

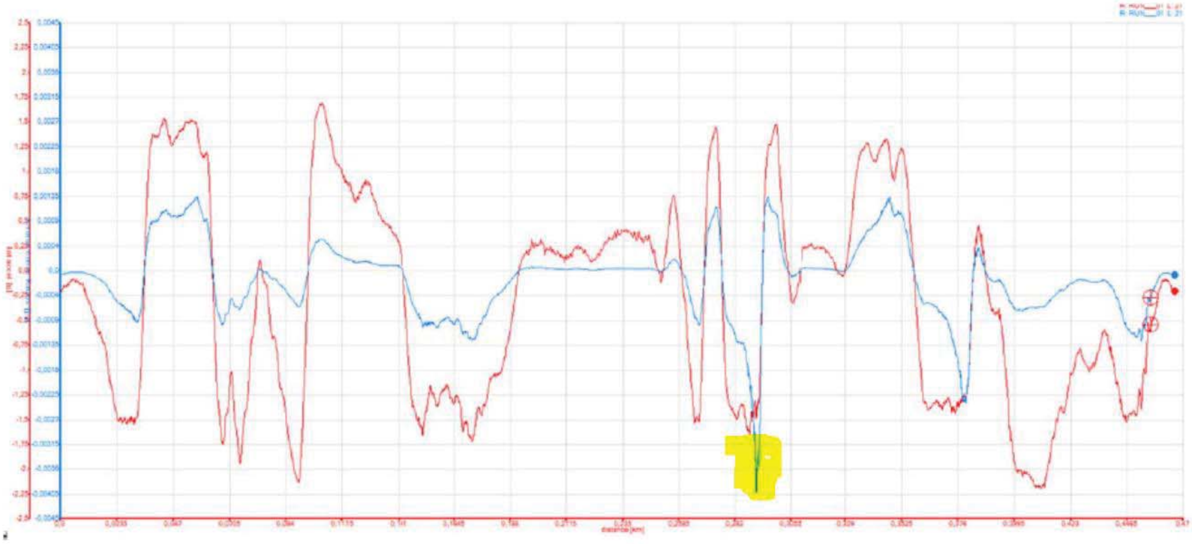
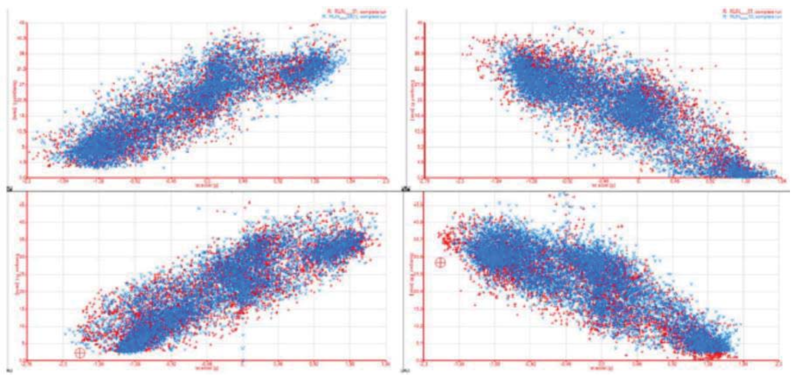


Figure 6 35 inverse corner radius (blue trace) and lateral acceleration (red trace). In the whole lap distance it is possible to use these to traces together to analyse driver and car behaviour. The highlighted part of graph shows huge peak of inverse corner radius. Driver took that corner really sharp. It is a place to be concerned with. As was mentioned before – it is crucial to be smooth to deliver highest possible grip of the tyres and hence the best time. In next part of this chapter the understeer and oversteer characteristics are explained with the lateral acceleration.

During this part of test season the car struggled with rear inside wheel lifting. Therefore the different mounting points of wishbones were tested for the first time in TU Brno Racing history. The improvement came with lowering roll centre of the rear axle. This is one of the reason which lead to new kinematics design for Dragon 5 monopost.

Figure 6 36 Dragon 1 – 4 concept had possibility of different mounting points of wishbones. That enables to change kinematic characteristic according deliberate behaviour of the car. In this graph the rear right suspension was an issue (due to track characteristic this particular wheel struggled with lifting, in other words the damper position sensor indicates full rebound position – red colour). After the change of setup (lowering the roll centre of the car this issue was improved).



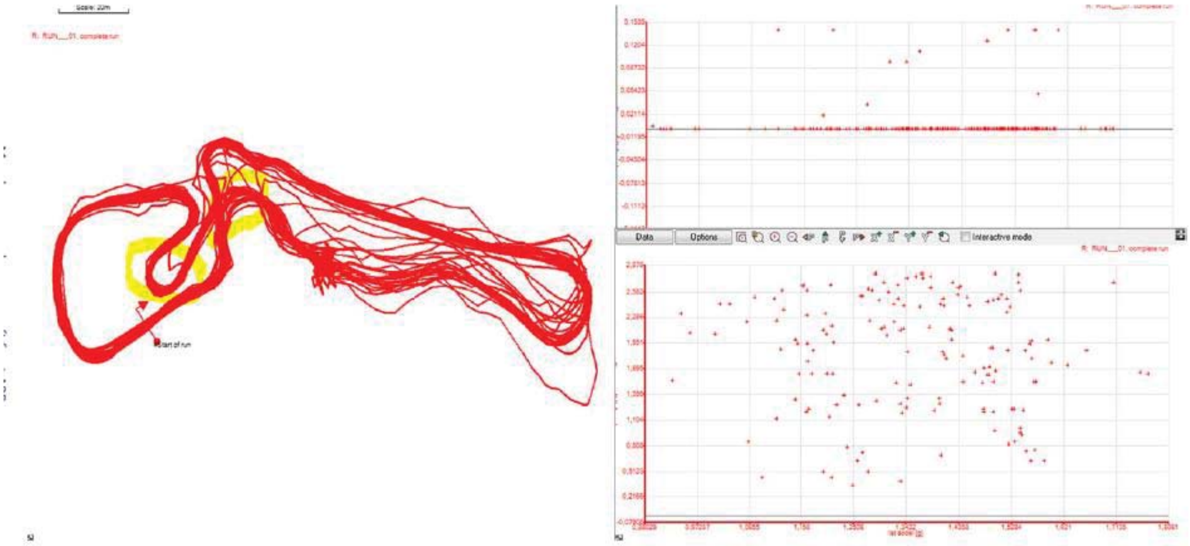
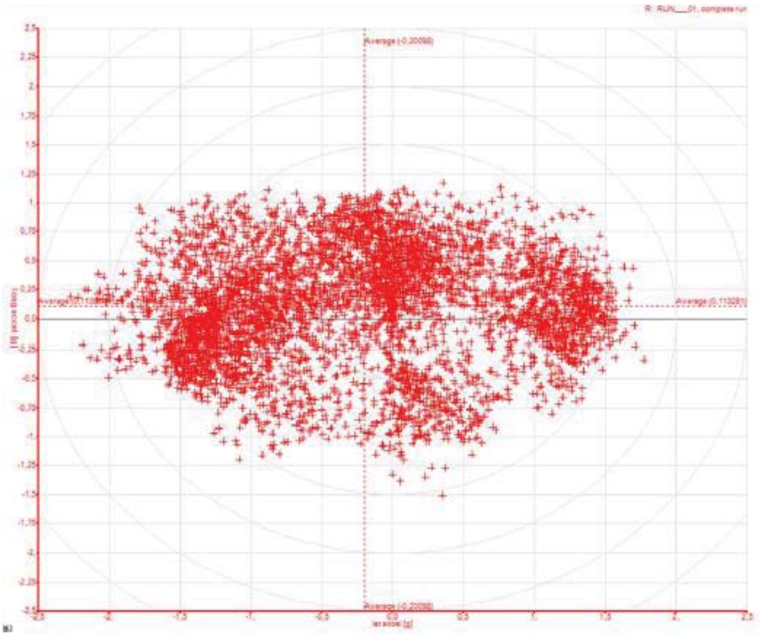


Figure 6 37 visualisation of the most problematic corners where the car struggled with rear inner wheel lift. One of the corners is skid pad turning circle. Data points on the right side show the two different zoom steps of damper position. It is visible that the damper is on its rebound stop. That means that particular wheel is lifting in the air. This is unintended.

As was mentioned before. Wheel lifting was one of the Dragon 4 issues. The differential struggled a lot with this problem during season. With different car setting – front anti – roll bar and kinematics points of the car the team were able to improve this behaviour. However the jacking force at Formula Student Hungary motivated the team to change the kinematics of the car rapidly for the first time in team history.

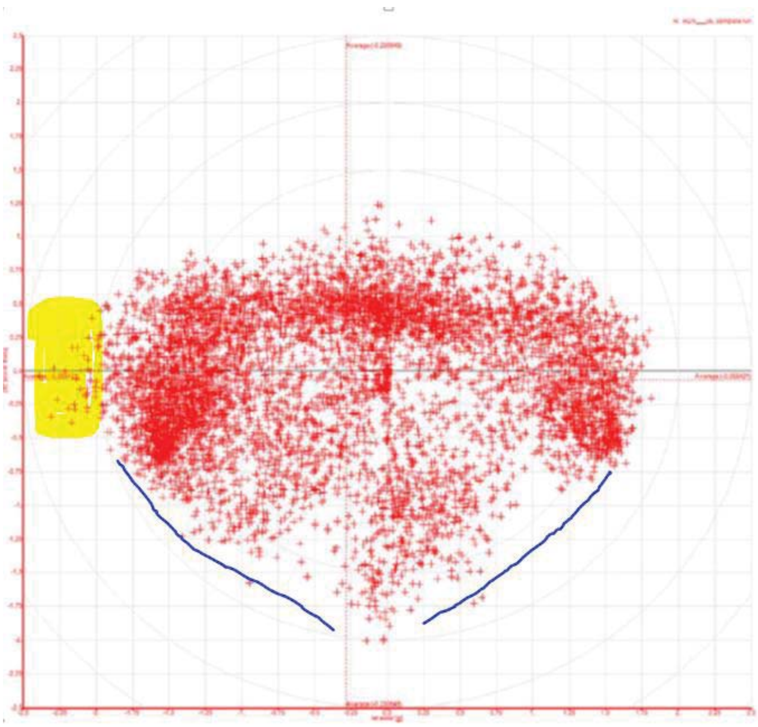
TRACTION CIRCLE

Another graph which is very useful in data analysing is traction circle. It is shown in Figure 6.39. This graph enables to evaluate how well the car is driven. In Chapter 3 (Tyre theory) was explained the maximum forces which the tyre is capable to transform on the road surface. Based on the data it is possible to determine where the traction limits should be. Ideally, the driver uses the tyre only on its edge. That would mean the traction circle is only ring not the whole circle. In real the traction circles are influenced by many factors. For instance weather conditions, driver skills, tyres condition and temperatures.



G-circle

Figure 6 39 traction circle at the beginning of the test season. It is visible that driver does not using the car at the edge. It is due to driver inexperience with the car. Peaks of lateral acceleration show where the potential is. In high speed corners this car has no problem to achieve more than 2 G. Later on of the 2014 season the maximum reached 2.7 G.



G-circle

Figure 6 38 to show the possible difference in traction circles the data set from late part of test season is shown in this figure. Cornering ability of the car remains very similar. The biggest improvement is in tyre using. The braking zone reaches its maximum at -2 G and even the acceleration is harder than in the G circle in figure 6 39.

Still, the space for improvement is visible. Transition from hard braking to cornering especially. In left hand and in right hand corners. Data set should follow the "ideal" curve which is drawn in the graph.

As was mentioned in Figure 6.39 – potential of maximum lateral acceleration is in high speed corners –highlighted left hand corner.

In data analysing it is important to read data with understanding of the whole car and in respect of track conditions. In the traction circles the maximum lateral acceleration shows the ability of the car to reach 2.3 G. Thanks to the aerodynamics it is possible. But the aerodynamic forces are depend on the vehicle speed. Therefore in the high speed corners the effect of downforce is much higher. Not only is the mechanical grip acting in the contact patch of tyres. The downforce is the reason in such an improvement.

With this knowledge race and data engineers can help driver find the possible performance edge of the car in particular corner. This can be very complex discipline as every corner of each particular track has different properties. Different corner radius, surface roughness, banking, bumps etc.

While discussing the traction circle the importance of tyre knowledge should be stressed once again. The driver can be on the edge of the car performance. At the same point the car performance can be still improved furthermore. Achieving the best position of tyre contact patch in every corner can improve the lap time. This is predestined with the quality of suspension kinematics but can still be improved with camber settings. The great way how to find great setup is to log tyre temperatures. Unfortunately TU Brno Racing Dragon 4 car did not have this feature. But according to Jorge Segers seminar and his book (Segers, 2014) this can lead to find the ideal camber value for each corner and hence to set up the car in the best way. With tyre temperatures the possibility of understanding the car can go really further. With combination of tyre pressure sensor this could be winning combination of any endurance race. Even author realizes the complexity of the sport. Fuel consumption, mechanical issues or driver fitness level are just another elements of the success. These ideas are beyond the range of this diploma thesis as these sensors were not mounted on Dragon 4 monopost due to budget limitation.

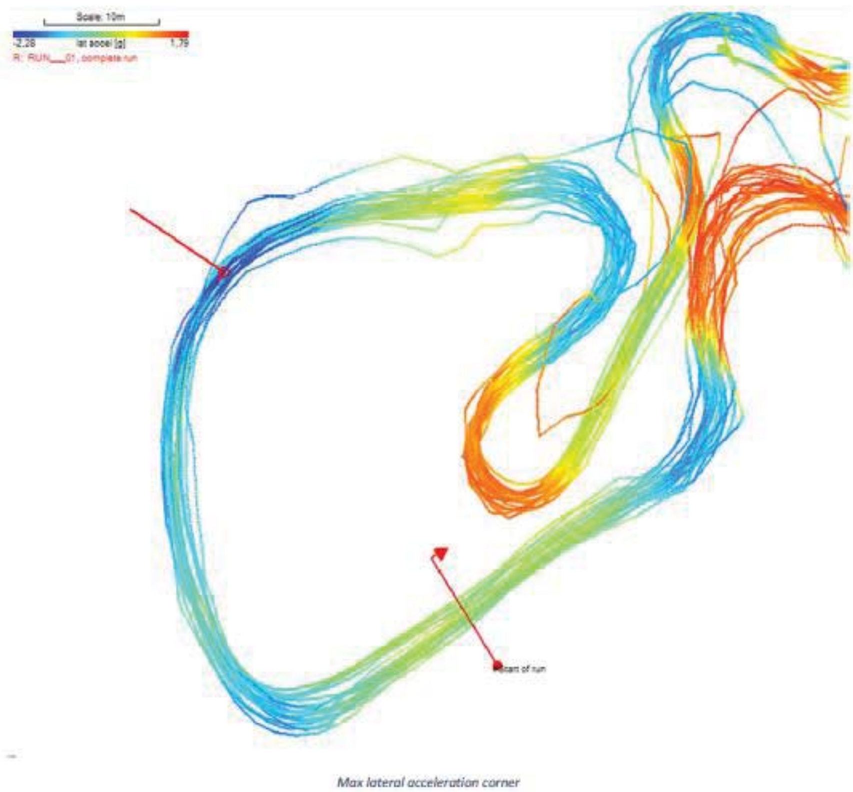


Figure 6 40 left hand corner at TU Brno Racing test track at Brno Exhibition centre shows the highest lateral acceleration values.

SHIFTING TIME AND POINTS

Straight acceleration. Another key of success. While the car is great in corners it enables driver to chase the throttle pedal much earlier. With Dragon 4 TU Brno Racing wanted to solve the historical issue with shifting. Electro-magnetic system was changed to pneumatically controlled one.

Once the new system was set up properly (there were issues at the beginning which are shown in data in Figure 6.40) the best shifting points can be evaluated. In Figure 6.41 not only the shifting problem is shown. Another thing which was controlled was shifting time. This information is important for engine engineers while they are trying to set the shifting in the best possible way. In ECU this information is also provided as this can be controlled even with RPM sensor or shift request sensor for example. The correlation of various source of data is useful. For example if there is a problem one source can provide information that everything seems alright. The other source of different information can reveal the real issue. Once the issue is found it is time to find the right solution.

The experience with this engine gearbox enabled TU Brno Racing to develop bespoke gears for next generation of car (Dragon 5). This step can improve the car performance once again as the gear forks are different and the gears have been reduced to number of four. It is believed that this save another lap time as a driver will have less work to do.

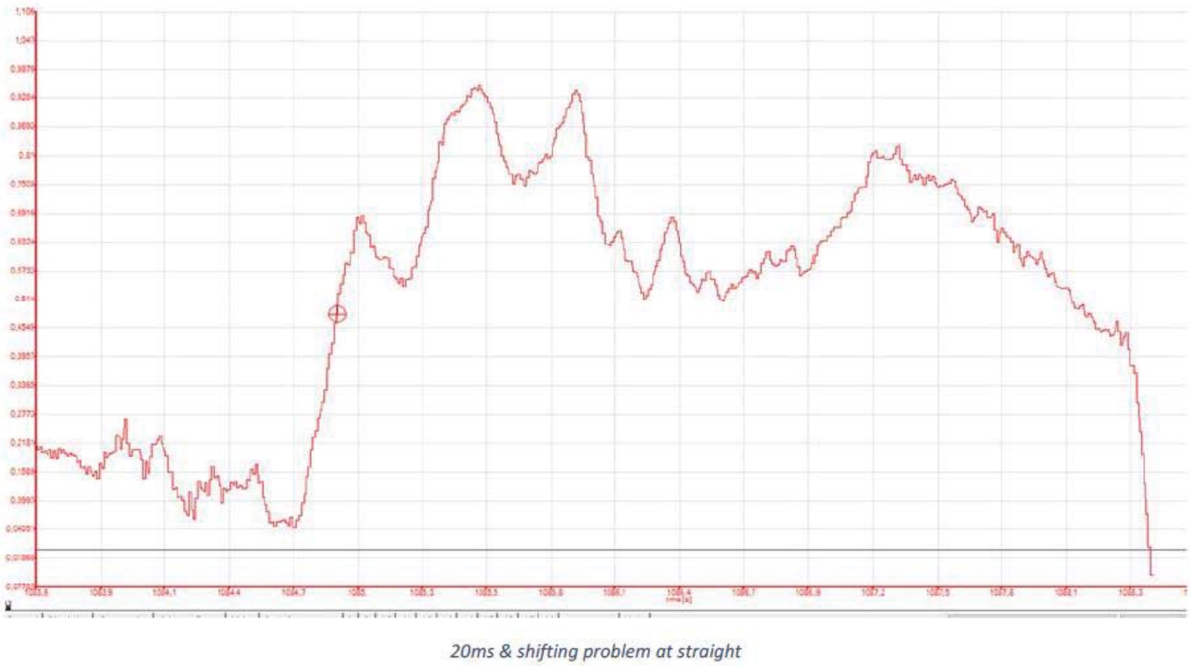
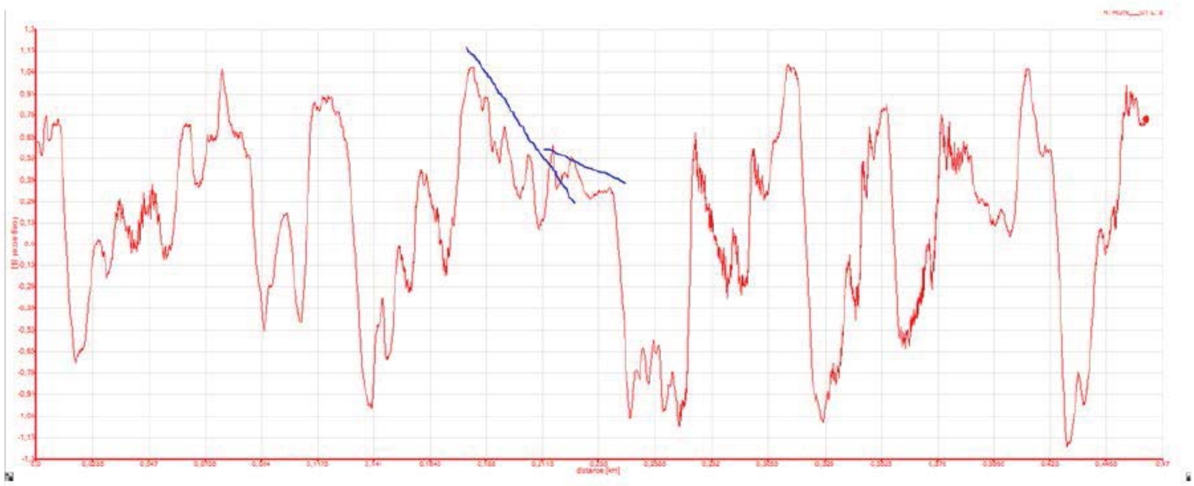


Figure 6 41 lateral acceleration is shown on time x-axis. Dips between the peaks of local maximum and local minimum determines the shifting time. In the case of successful shift the time is around 20 ms based on data. The huge hole is visible after the attempt to change the 3rd to 4th gear. This problem was solved later in the test season.

TU Brno Racing test track has only one long straight. This is based on FSAE rules (SAE, 2015) and on space limitation. Therefore the only place where the shifting analysis can be visibly shown is that particular straight. Shifting points are very important in cars and in racing cars especially. Passengers' cars have aim to reduce fuel consumption. Racing cars try to find the highest performance. Although in modern way of racing the fuel consumption is more and more important.

The shifting points have been defined on engine dyno tests. However, in the real conditions the whole car behaves differently as the engine is not only at full load conditions. Even the driver does not need to be precise since the very beginning. That is the reason to help this situation with data analysing.



Early upshift

Figure 6 42 with different shifting solution of Dragon 4 the shifting has improved. Therefore the team could analyse even such driver behaviour. In this graph the early upshifts are shown.

Shifting points were analysed with longitudinal acceleration sensor. In Figure 6.41 this technique is shown at the only straight of TU Brno Racing test track. Based on theory – everything should be smooth to deliver highest performance. The slope of the whole straight in longitudinal acceleration should be constant. That ensures the maximum possible traction force were used for acceleration.

If the trend of such a curve is not constant – there is any step in this trace data engineer should ask driver why he is shifting in this way. In discussion with engine engineers this problem can be solved. In the case shown in Figure 6.41 the reason was that driver did not concentrate on the shift light diode. Therefore he changed the gears earlier that he had to. This lead to inappropriate using of engine power hence to loose lap time.

THROTTLE PEDAL POSITION

One of the very few inputs driver can use in the car is throttle pedal. The amount of power he asks the engine to transform on rear wheels. Once the engine was developed on the dyno and it was developed to be used at maximum power, engine engineers want driver to use it in the right performance range.

Engine engineers do not like to see hesitation in throttle pedal position. There are a few typical bad habits of drivers in general. Hesitation in corner phase, not using full throttle at straights, slow chasing of throttle pedal at the straight beginning and early lifting off before corners. All these vices are shown in Figure

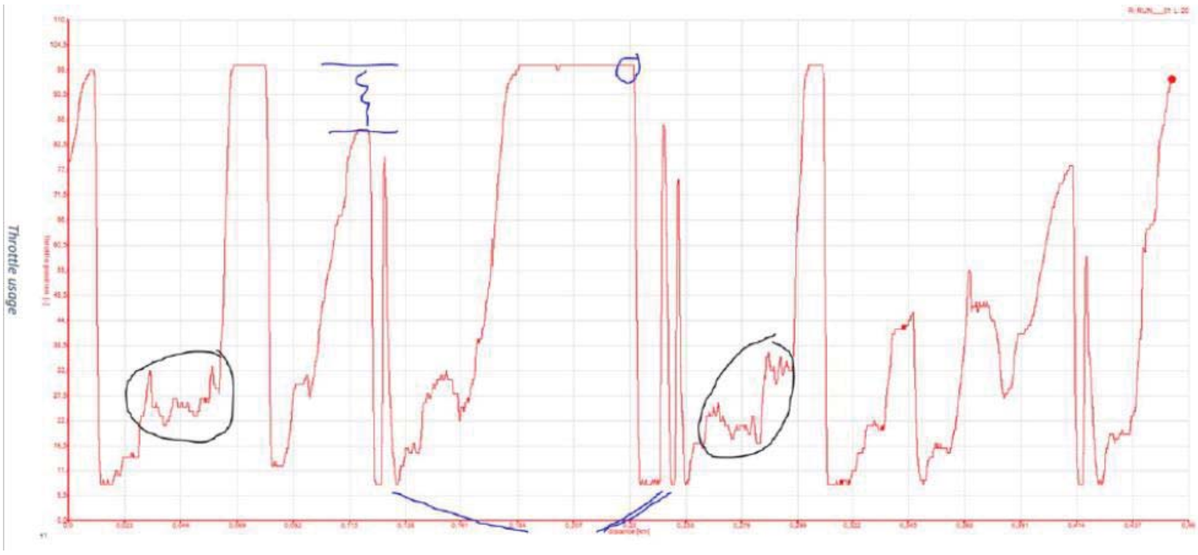


Figure 6 44 driver's habits with using of throttle pedal. Black circles show hesitation in corner phase. The final part of the circuit is even worse. The car struggled there with understeering therefore driver had to use the throttle very cautiously. The third straight shows the inappropriate using of throttle (not full load). On the other hand the small blue circle shows good lift off at the end of that particular straight. Lines at the bottom of the graph show places where driver blips to help the gearbox with downshifting.

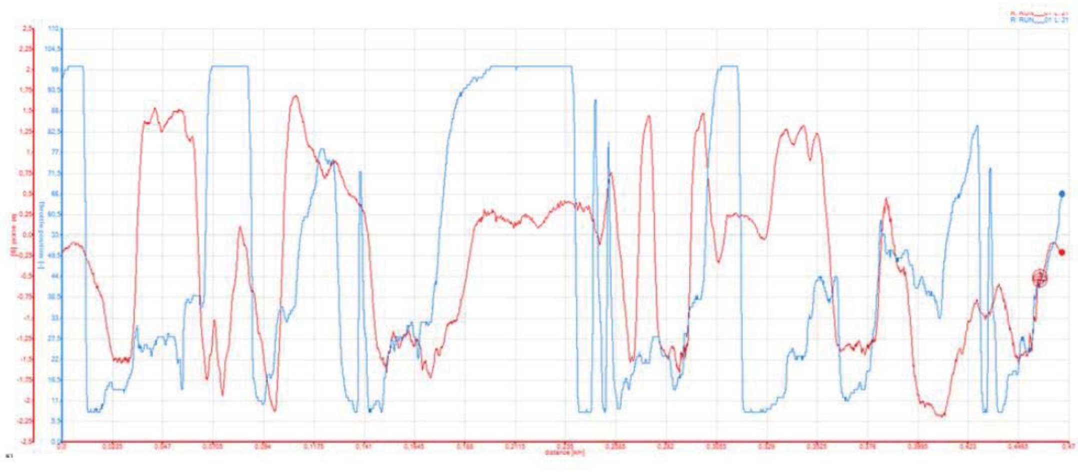


Figure 6 43 lateral acceleration and throttle pedal position trace can evaluate under or oversteering issues of the car.

CAR BALANCE

Alpha and omega. That is car balance in Motorsport. If the car understeers majority of drivers do not like it. If the car oversteers majority of drivers struggle to get to the top of the lap time board. Each driver in the world has different style of driving. Therefore two different drivers in the exactly same car can experience various amount of understeer or oversteer behaviour.

There are many possibilities how to evaluate this phenomena with logged data. In the 2014 season TU Brno Racing team started with very basics. Lateral acceleration, steering wheel position and throttle pedal position can really help to understand how to determine car balance. Besides this basic channels the yaw sensor and tyre temperature sensors are big advantage in respect of analysing the car cornering behaviour.

These data can be use subsequently in math channels. Therefore the understeer or oversteer channel can be prepared to show the car behaviour in a nice graph. This can be compared with another driver later. This is very useful in a few different ways. Immediately performance chase or in long-term tracking. For example the number of average understeer per each lap can reveal a trend of some behaviour. It could be influenced by driver stamina, tyre wear, brakes balance bar changes or any other difference in setup.

In Figure 6.45 the data of one fast lap at TU Brno Racing test track are presented. At this part of season focus was on lateral acceleration and throttle pedal position. In data a few moments are highlighted. In lateral acceleration trace understeer can be seen as flat part in the cornering phase. On the other side of car balance - oversteer behaviour is shown as small dips.

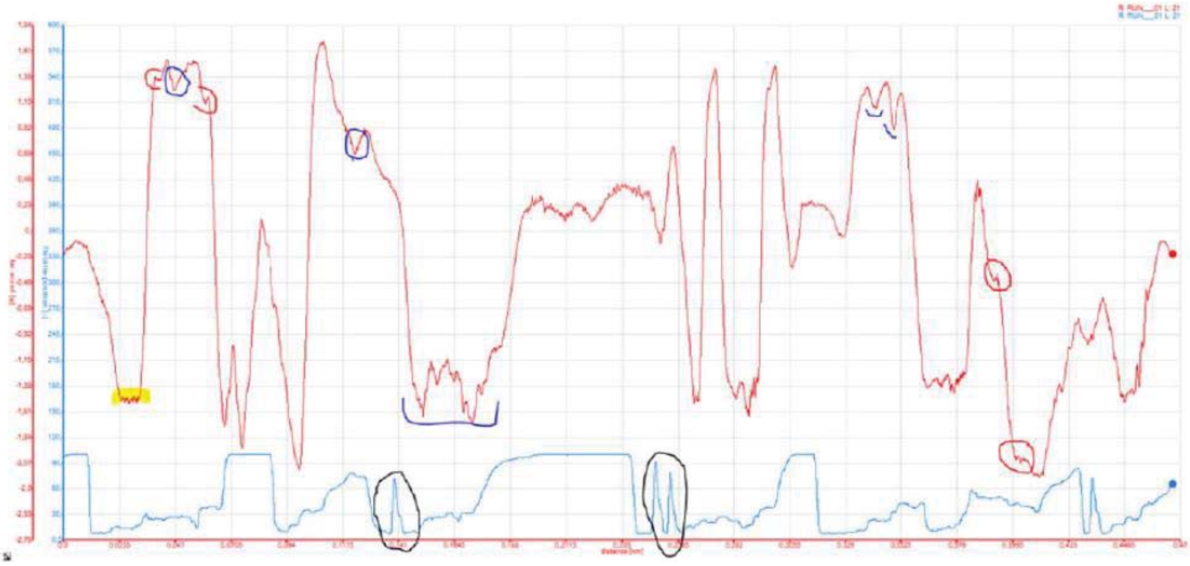


Figure 6 45 lateral acceleration and throttle pedal position. This is one of a few other ways how to evaluate car behaviour. Flat part of the lateral acceleration trace in cornering phase are understeer behaviour (highlighted with red circles) and oversteer is highlighted with blue colour. Double apex corner (before long straight) was discussed previously in this Chapter.

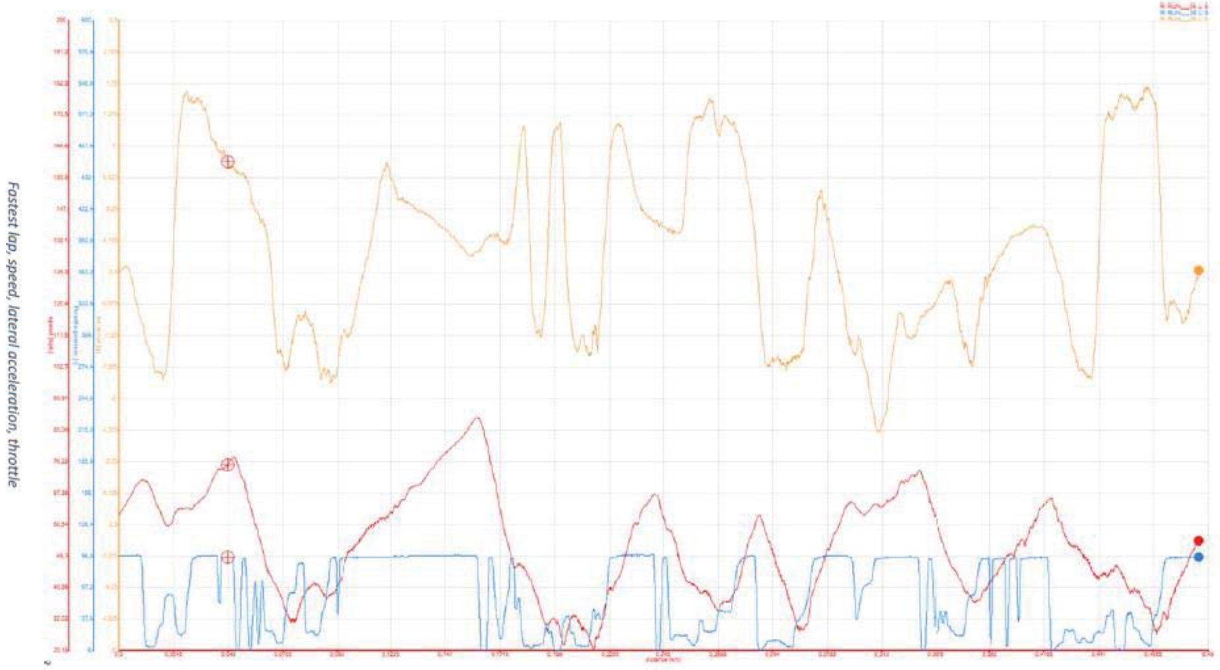


Figure 6 46 performance can be found by many different ways. How to visualise data is everyone's preference. In this graph the best lap at TU Brno Racing circuit is shown. In comparison with very first laps shown in this chapter the driver improvement is clearly visible. Throttle pedal position is better. Throttle chasing in the corner exits, full throttle time, lift offs and blips are using the car better. Although there is still lot of space to improve.

LAP AND SECTOR TIMES

At the end of the day the only thing which is truly important is achieved lap time. Data analysis software packages enable engineers to show this data. In overall it is very similar in each software. The track has to be separated in a few sectors. It is done automatically or manually. Every software solves this problem in its own way.

Thanks to table such as shown in Figure 6.47 team can see the consistency of the driver, improvement or not after setup change, fuel consumption (less fuel = less weight = lower time), tyre wear (worse time), change of weather condition etc.

An attention should be in understanding of best lap interpretation. Every software can provide you with best theoretical lap and with best continuous lap. The difference can be confusing. While the theoretical best lap is put together as best sector times, the best continuous lap (or rolling lap in other software) is the best time from point to point. Therefore best continuous lap can start at the end of sector 2.

Best	Sector 1	Sector 2	Sector 3
Theoretical, 35.43	23.54	5.56	6.33
Continuous, 35.66	23.59	5.61	6.46
Simulated, 30.76	19.60	5.44	5.72
Sim delta, 4.67	3.94	0.12	0.61

Lap times	Sector 1	Sector 2	Sector 3
Run "Patrik (1)" (7:44.55)			
Lap 1, N/a	N/a	5.98	6.96
Lap 2, 37.90	24.96	6.12	6.82
Lap 3, 36.53	24.06	5.78	6.69
Lap 4, 36.58	24.07	5.77	6.74
Lap 5, 36.49	23.71	6.13	6.65
Lap 6, 36.82	**23.54 F**	6.37	6.91
Lap 7, 36.02	23.98	**5.56 F**	6.48
Lap 8, 36.28	24.21	5.61 C	6.46 C
Lap 9, 36.63	23.59 C	6.25	6.79
Lap 10, 35.84 F	23.75	5.76	**6.33 F**
Lap 11, 36.62	23.95	6.01	6.66
Lap 12, 36.25	24.12	5.67	6.46
Lap 13, 36.23	23.81	5.68	6.74
Lap 14, N/a	24.09	N/a	N/a

Figure 6 47 example of lap time board. TU Brno Racing test track was separated into 3 sectors. Difference in Theoretical and continuous lap times can be confusing at the beginning. But it is important to understand that the continuous lap time can be influences with late braking in one sector – achieving best time in the sector, however, in subsequent sector is the time much worse. Therefore this continuous lap time could be just motivation but probably not the real target.

6.2.6 ACCELERATION

Last dynamic event which have not been discussed so far is acceleration. This discipline was trained at the local airport same as the aerodynamic tests. Very same technique as was described in previous part of Chapter were used to analyse gear shifting. Another feature of Dragon 4 is launch control. Therefore two days of the test season was dedicated only to acceleration training.

In the Figure 6.48 the map shows how the acceleration test was undertaken. The map is coloured with longitudinal acceleration. The start position can be seen as red colour, end of acceleration is blue colour trace as the driver was braking into a slalom. It is important to keep driver focus to driving. That was reason to prepare at least few corners to achieve this. This procedure lead to good results as the driver was enjoying the whole day of accelerating.

Figure 6 48 acceleration training map. The procedure was prepared to train acceleration and slalom skills. At the beginning of every lap the driver hat to stop, calm down, focus for the best possible start.

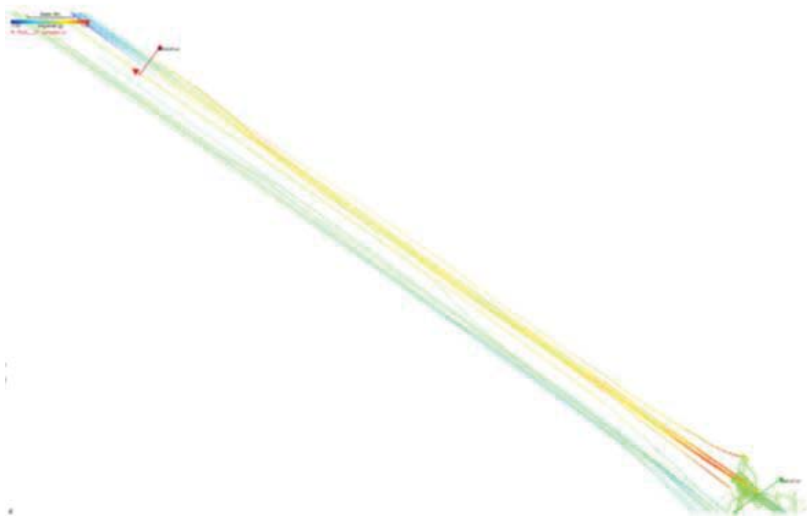


Figure 6 49 zoomed in view of acceleration test. The accuracy of GPS module is sufficient.

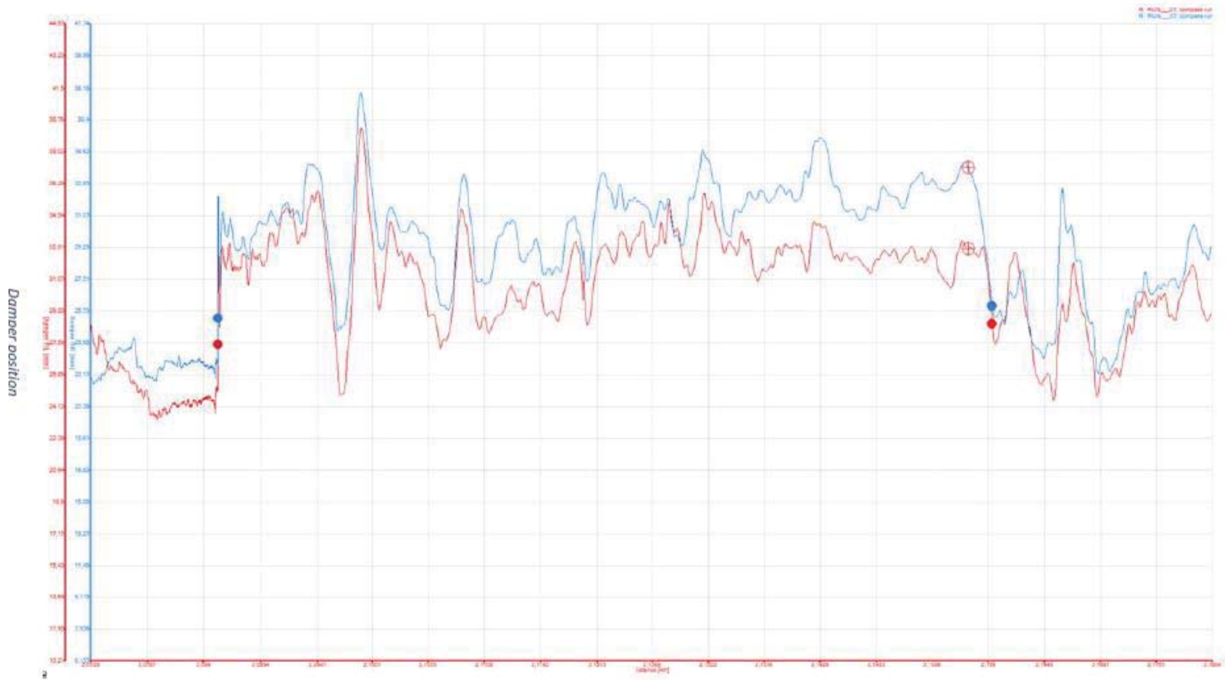


Figure 6 51 rear damper position sensors while acceleration. One of the ideas was to test different kinematic setup - changing the anti - squat characteristic. Unfortunately, sometimes the plans do not work as it was planned. This test was interrupted with engine issue.

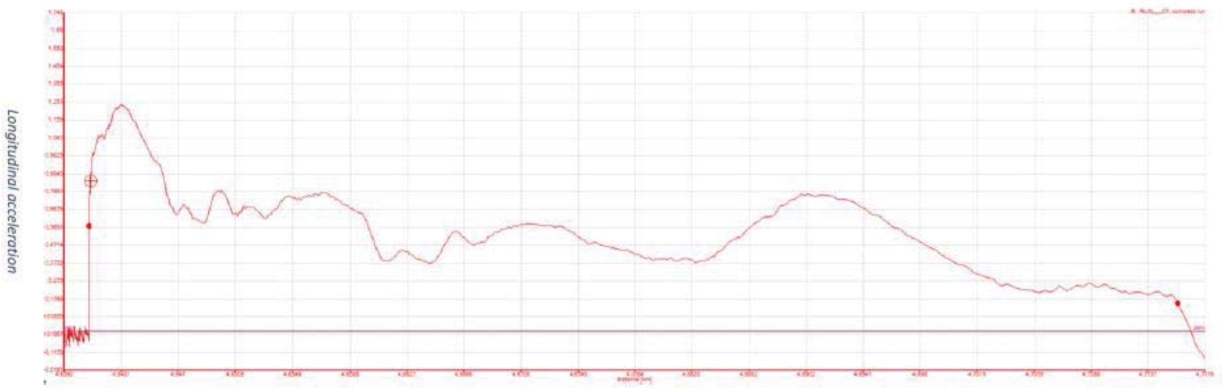


Figure 6 50 Longitudinal acceleration vs. distance while acceleration. The car is accelerating at the whole distance. Digs are explained as gear changing.

CONCLUSION

Formula Student project has been the right place to expand the product development knowledge. Real world of industry requires lot more than just finalized CAD model. Team work, communication, design, development, simulation or understanding the rules with huge responsibility. These ideas together with description of particular Formula Student disciplines were purpose of the first part of this diploma thesis.

The whole racing car is a truly complex piece of machine. Such a car requires knowledge from each sector. However, the ultimate part of racing car is a tyre. Tyres provide the only interaction between the vehicle and the road surface. Therefore, understanding the tyre theory is crucial for the whole race car development process. Particularly important for suspension kinematics. With tyre theory knowledge and with tyre data the kinematics development phase could be undertaken with great advantage. Redesigning of TU Brno Racing and UH Racing cars are described in chapter four of this diploma thesis.

Dragon 4 car uses the same kinematics as its predecessors. While this car was first which run more than 700 km during the whole season 2014, decision to redesign kinematics for the new generation of TU Brno Racing car – Dragon 5 has come itself. There were a few ideas which have driven this redesign. Dragon 4 struggled with jacking force in corners especially at the rear axle and while the initial turn-in understeer was improved with 10 mm of toe-out at front we have decided to make a lot of changes. With new tyre data knowledge the Ackermann value of steering is modified. In aim of reducing the jacking force, whole approach has been changed. Centre of gravity as the most important feature of racing car was one of the whole-team motivation. This drove every decision on the car. No exception is the suspension layout. Rear axle has been completely redesigned. Suspension layout is newly as a pull – rod. Therefore dampers, rockers and the whole attachment to the chassis has been moved down. Rear axle centre of gravity is reduced from 64 mm to 34.6 mm. Rear uprights points has been designed from the scratch to provide high stiffness, right tyre usage and manufacturability.

Participation on UH 18 development has been a great experience as the UH 18 car runs 10 inch tyres. Front axle remains very similar to previous car – UH 17, however, rear axle has been completely redesigned. Once the aim of TU Brno Racing – reducing the centre of gravity has been decided, almost the same solution is visible at UH 18. Push-rod configuration was changed to pull-rod in respect of centre of gravity. With 10 inch tyres the space limitation was a challenge. To deliver tight packaging of rocker and damper and at the same time the intended motion ratio characteristic required precision in development process. After the design process UH18 rear axle is very similar to the Dragon 5 solution. There are two different solution. Anti-roll bar position and Toe-link position. Anti-roll bar position was driven by space limitation of each car and toe-link is influenced by different approach. Dragon 5 has toe-link in the middle of upright due to upright stiffness, manufacturability and to provide different setups of bump steer. UH18 does not have different mounting points of wishbones as Dragon 5.

Kinematics of the car have to be scrupulously prepared in respect with engineering design. Once the kinematics are developed the whole suspension and chassis has to be designed according to it. Racing car aims to be as light as possible with the low possible height of centre of gravity. This enable driver to be fast on the straights and in corners as well. To deliver lightest possible solutions which still ensure the reliability, FEA methods have been developed to help engineers. FEA was used to develop every single part in this diploma thesis. Rockers, wishbones and rear anti-roll bar. All these components were designed to be lighter, however, their functionality was proved during the whole 2014 season. Design aim of rockers and wishbones was to deliver as light as possible solution. Weight of the rockers has been lowered by a half of the original weight (Dragon 3 to Dragon 4 step). Wishbones undertook extensive development. Issue of Dragon 3 were the uniball housings. Material of wishbones of Dragon 4 was therefore changed to chrome-molybdenum (25CrMo4-QT). Hand in hand with new housing solution the weight reduction came as well. With analysis of suspension forces, different uniballs and different tubes dimensions were chosen for wishbones. Upper wishbones run just 12x1 tube diameter (compared to 14x2 mm of lower wishbones). Uprights' uniballs are motorsport specification with shoulder bolts (M5). Uniballs of the chassis attachment are for the same shoulder bolts, however, they are not motorsport specification as the forces there are much lower. This solution delivered large weight reduction of wishbones by half compare to previous design with no compliances.

One of the biggest challenge of Dragon 1 – Dragon 3 cars was rear anti-roll bar. There were no solution which provided intended functionality. Therefore Dragon 4 has completely new solution. It was decided to manufacture more expensive solution but functional. Extensive FEA simulation, MATLAB analytical approach and vehicle dynamics calculation ensured the functionality. Dragon 4 anti-roll bar uses blades and torsional bar. This solution was working well all the 2014 season. Understeer gradient measurement at Skid Pad tests (based on different ARB setup) showed the range of the possible weight balance. With fully functional front and rear anti-roll bars the car could be balanced in the way the drivers wanted. Hence, for the Dragon 5 generation the only aim is to reduce the weight.

To close the design and development circle there should be some measurement which allows engineers to judge their job. Of course, the most important aspect are points gathered at the end of the season. However, to track the performance lap by lap, understand the car properly, and train drivers to drive the car on its edge or to obtain important data for future research and development – the data acquisition systems have been developed. With data analysing the possibility to improve the car and the whole team significantly raises.

Dragon 4 team had more than two months of testing before first competition in Germany. These two months the car did more than 500 km of testing. It was very important to deliver schedule of these days. In this very short time it was important to find the reliability, performance and train the drivers for particular disciplines. First tests were dedicated to sensors calibration, reliability control and the whole team was learning how to work with the new car. This is very important from managers' point of view. To ensure that everyone in the team knows what is his or her job, to motivate the team to maintain the car after tests and prepare the car for next tests. This was one of the biggest challenge for author of this diploma thesis.

Along with the testing season the whole team was improving with the car. After reliability tests every discipline of Formula Student competition was prepared. This part of test season was the most interesting one. Skid Pad test days were dedicated to understeer gradient measurement where the different anti-roll bars setups were tested. Dragon 4 did almost 400 skid pads attempts. The aim was to fight for the best positions at competitions as the car and drivers improved since last year almost by a second at Skid Pad. Acceleration test days were divided into aerodynamics and shifting tests. Aerodynamics measurement were absolutely crucial as we could correlate CFD simulation with reality. Thanks to the damper position sensors we were able to calculate downforce at particular speeds. Results showed that the rear wing of Dragon 4 is significantly more efficient than the front wing. This influenced balance of the car in high speed corners and surprisingly even at Skid Pad where the velocity of the car is around 45 kph. We changed spring stiffness on the rear axle to balance the car. New pneumatic gear shifter solution was tested at acceleration. Before the first event in Germany reliability was found with this system. An average time of upshifts was below 30 ms.

Endurance and Autocross test days had a few aims. Reliability, drivers' training and engineers training. To finish Endurance event is absolutely crucial. In the other way there is no chance to be successful at any competition. Dragon 4 was a big improvement. Car was faster, much more reliable with better cornering behaviour. While the drivers in Formula Student are not professionals we wanted to let them know the car perfectly. Author of this diploma thesis is one of the drivers. This was absolutely great way how to study the data. Once something was found in data it was great to try different setup or different driving style according to that.

In overall the new car was almost by 4 seconds per lap faster on TU Brno Racing test track than its predecessor. Aerodynamics improved the cornering ability as the maximum of lateral acceleration increased from 2.1 to 2.45 G (at Formula Student Hungary which is on concrete surface the lateral acceleration peaks were up to 2.7 G). As the car is lighter by 15 % even the longitudinal acceleration increased from 1.1 to 1.45 G. Braking ability of the car is over 2.1 G.

Formula Student Germany has one speciality. Skid Pad event is run in wet conditions. This should equal chances for every team. Before this competition TU Brno Racing prepared even for this so-called Wet Pad event. After more than hundred Wet Pads Dragon 4 and its drivers were able to go through the track in 5 seconds. This would have been first place overall in 2013 season at Formula Student Germany. However, at the 2014 competition things did not go so well. Car had small technical issue in first run and drivers under pressure did not perform their best. 7th place in overall is still a huge success. The 2014 was the most successful season of TU Brno Racing so far. With these experience, another knowledge and motivation Dragon 5 can improve the historical records once again.

Following this diploma thesis there are some recommendations which author would like to offer. In next generation of Formula Student monopost 10 inch wheels should be taken into consideration. Experience with UH 18 car showed that the only difficulty from kinematics point of view is installation ratio for pull rod solution. However, recommendation is to omit pull or push rods. Formula Student car should be as light as possible. This simplification should deliver another weight reduction if there would be a right replacement of very light magnesium rims. Space limitation of smaller wheel should not be a huge hurdle as lot of other top Formula Student teams have solved this with success.

Regardless of any design approach or solution – the most important recommendation are rules knowledge and understanding (SAE, 2015). Formula Student is a learning process. The way which the particular team member decides to approach this project is crucial. Probably in any aspect of human life the motivation is truly important. With passion and motivation throughout the whole team the design steps and decision with real scientific approach can secure that the educational purpose of Formula Student project is achieved.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

a	[G]	Vehicle acceleration
C_D	[-]	Aerodynamic drag coefficient
C_L	[-]	Aerodynamic lift coefficient
C_p	[-]	Tyre specific heat
F_x	[N]	Longitudinal Traction Force
F_x	[N]	Lateral Force
LFC	[-]	Lateral force coefficient
M	[kg]	Vehicle mass
r	[m]	Corner radius
R	[m^{-1}]	Corner curvature
SR	[%]	Slip Ratio
T	[deg]	temperature
v	[$m.s^{-1}$]	Vehicle speed
α	[°]	Slip angle
K	[-]	Thermal conductivity
ρ_T	[$kg.m^3$]	Tyre
Ω	[rad]	Angular velocity