The Racetrack Dynamics approach to Engineering Design in FSAE

RD Racetrack Dynamics

About your speaker today

I have done many mistakes designing. Many.

My First Formula Car UPCT, 2014

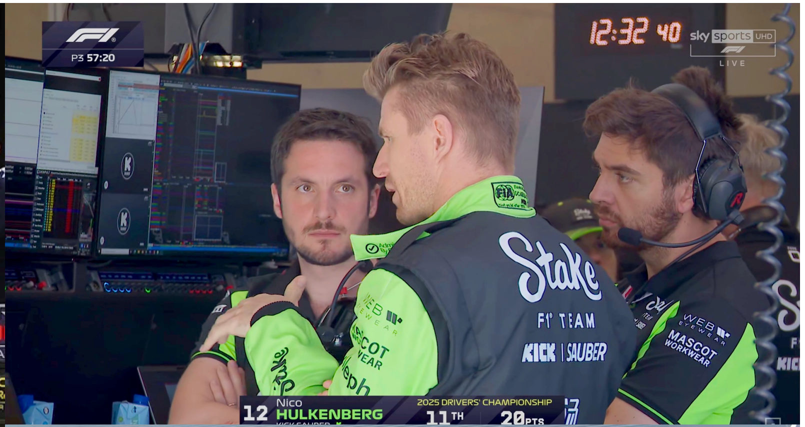
- Didn't manage to compete in FSS
- Was almost 2x the intended design weight
- Felt embarrassed comparing to other cars

Which didn't stop me from succeeding

RB19, 2023

- Won 22/23 F1 races in a single season
- Most dominant car of F1 history
- Constructors and Drivers Championship
- Broke every single record

About your speaker today



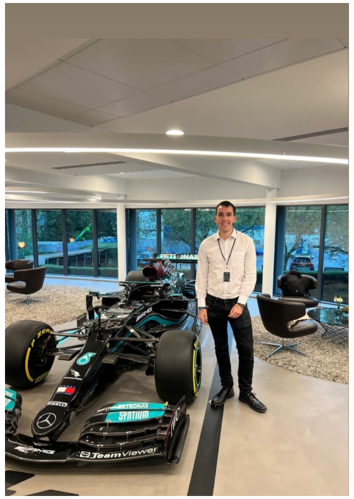
- Tire Modelling and Vehicle Dynamics Engineer
  Bridgestone
- Vehicle Simulation Engineer
  Prema Racing
- Vehicle Dynamics Engineer
  IDIADA
- Vehicle Dynamics & Analysis Engineer
  Oracle Red Bull Racing
- Race Performance Engineer
  Audi F1 Team
- Founder and technical lead
  Racetrack Dynamics

About RD


DEWESoft
KARMA COMPOSITES
AGEMASPARK
AQUAJET
UNI OF SHEF
RD Racetrack Dynamics
S.FRIGOLET
MOZA RACING
RD Racetrack Dynamics


UFV Universidad Francisco de Vitoria
1. MY JOURNEY TO F1
CAREER

About your speaker today



1. Plan your season

A successful FSAE season starts with planning

Define the Foundations Early

- Set realistic objectives and performance targets
- Establish the season timeline and key milestones
- Identify critical bottlenecks and high-risk areas
- Create and monitor the team budget
- Define team structure, responsibilities, and communication channels
- Plan manufacturing, testing, and competition preparation

2. Allocate your resources

Not every FSAE team is the same.

Large & Structured Teams

- Specialized roles and departments
- Clear separation between technical and management responsibilities
- Dedicated people, project, and knowledge management

Small & Emerging Teams

- Cross-functional and interdisciplinary roles
- Greater flexibility and collaboration across areas
- Team members often contribute to multiple functions

2. Allocate your resources

Not every FSAE team has the same budget

Well-Funded Teams

- Strong sponsor support and larger budgets
- Ability to invest in advanced manufacturing, testing, and development
- Greater freedom to pursue bespoke designs and optimized solutions
- Technical excellence can be fully expressed through engineering refinement

Budget-Constrained Teams

- Limited resources require careful prioritization
- Greater reliance on creativity, ingenuity, and smart trade-offs
- Focus on extracting maximum performance from affordable solutions
- Innovation often comes from doing more with less

2. Allocate your resources

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

Not Every FSAE Team Has the Same Know-How

Experienced Teams

- Ability to develop advanced models, simulations, and design studies
- More ambitious performance targets and optimization efforts
- Focus on refining and pushing the limits of existing systems

Developing Teams

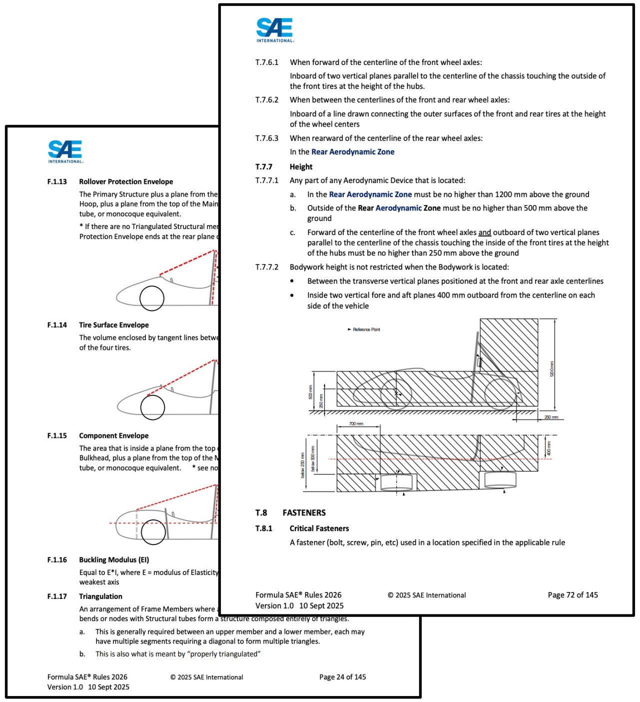
- Focus on mastering the basics. Build knowledge, processes, and tools step by step
- Simpler methods can still provide valuable engineering insights
- Progress comes from establishing solid foundations before increasing complexity

The Key Principle

- For one team, success may mean fighting for a podium finish. For another, success may mean completing all dynamic events.

3. Learn The Rules & Scoring System

- Studying the rules can be about as exciting as watching paint dry, but unfortunately, it's non-negotiable.
- Treat this as an opportunity to actively learn, find hidden areas for performance gains and staying ahead of the game.
- Great F1 designers have the ability to read beyond the rulebook and find performance in tiny loopholes.


SAE INTERNATIONAL

T.7.6.1 When forward of the centerline of the front wheel axles:
Inboard of two vertical planes parallel to the centerline of the chassis touching the outside of the front tires at the height of the hubs.

T.7.6.2 When between the centerlines of the front and rear wheel axles:
Inboard of a line drawn connecting the outer surfaces of the front and rear tires at the height of the wheel centers

T.7.6.3 When rearward of the centerline of the rear wheel axles:
In the Rear Aerodynamic Zone

T.7.7 Height

T.7.7.1 Any part of any Aerodynamic Device that is located:
a. In the Rear Aerodynamic Zone must be no higher than 1200 mm above the ground
b. Outside of the Rear Aerodynamic Zone must be no higher than 500 mm above the ground
c. Forward of the centerline of the front wheel axles and outboard of two vertical planes parallel to the centerline of the chassis touching the inside of the front tires at the height of the hubs must be no higher than 250 mm above the ground

T.7.7.2 Bodywork height is not restricted when the Bodywork is located:
- Between the transverse vertical planes positioned at the front and rear axle centerlines
- Inside two vertical fore and aft planes 400 mm outboard from the centerline on each side of the vehicle

T.8 FASTENERS

T.8.1 Critical Fasteners
A fastener (bolt, screw, pin, etc) used in a location specified in the applicable rule

Formula SAE® Rules 2026 © 2025 SAE International Page 72 of 145
Version 1.0 10 Sept 2025

F.1.13 Rollover Protection Envelope
The Primary Structure plus a plane from the ... Hoop, plus a plane from the top of the Main ... tube, or monocoque equivalent.
* If there are no Triangulated Structural me... Protection Envelope ends at the rear plane ...

F.1.14 Tire Surface Envelope
The volume enclosed by tangent lines betw... of the four tires.

F.1.15 Component Envelope
The area that is inside a plane from the top ... Bulkhead, plus a plane from the top of the M... tube, or monocoque equivalent. * see no...

F.1.16 Buckling Modulus (EI)
Equal to E*I, where E = modulus of Elasticity ... weakest axis

F.1.17 Triangulation
An arrangement of Frame Members where ... bends or nodes with Structural tubes form a structure composed entirely of triangles.
a. This is generally required between an upper member and a lower member, each may have multiple segments requiring a diagonal to form multiple triangles.
b. This is also what is meant by "properly triangulated"

Formula SAE® Rules 2026 © 2025 SAE International Page 24 of 145
Version 1.0 10 Sept 2025

3. Learn The Rules & Scoring System

- The **Endurance** event is by far the most valuable, worth **250 points,** nearly one-third of the total competition score.
- Reliability often delivers more points than chasing maximum performance.
- A car that consistently finishes all events usually outperforms a faster but unreliable car.
- **Autocross** is "cool" but it is only worth **as much** as a "less exciting" **Cost & Manufacturing.**
- Your **optimization variable** in the competition problem becomes **points**, not speed. Remember that FSAE is still an engineering competition, not a race.
- This can affect design priorities from the beginning.

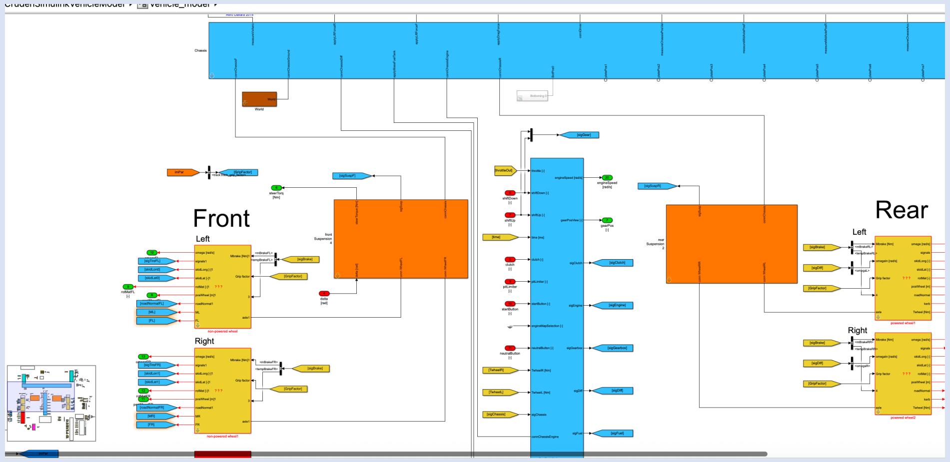
Static Events (EV)	Points
Engineering Design	150
Cost & Manufacturing	100
Business Presentation	75
Total	**325**

Dynamic Events (EV)	Points
Skidpad	75
Acceleration	75
Autocross	100
Endurance	325
Efficiency	100
Total	**675**

*Varies from competition to competition

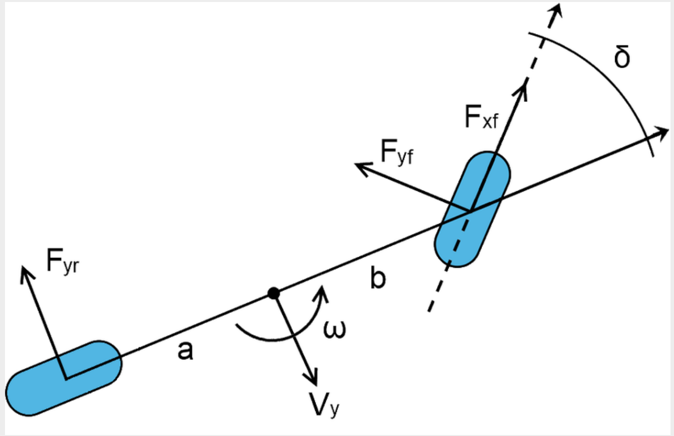
4. Pre-design simulations. Overall Vehicle Concept

This is **a valid vehicle dynamics model**



- Detailed MBD Model. Crafted by a fully-dedicated team.
- Estimated workload +1000h.

This is **<u>also</u> a valid vehicle dynamics model**



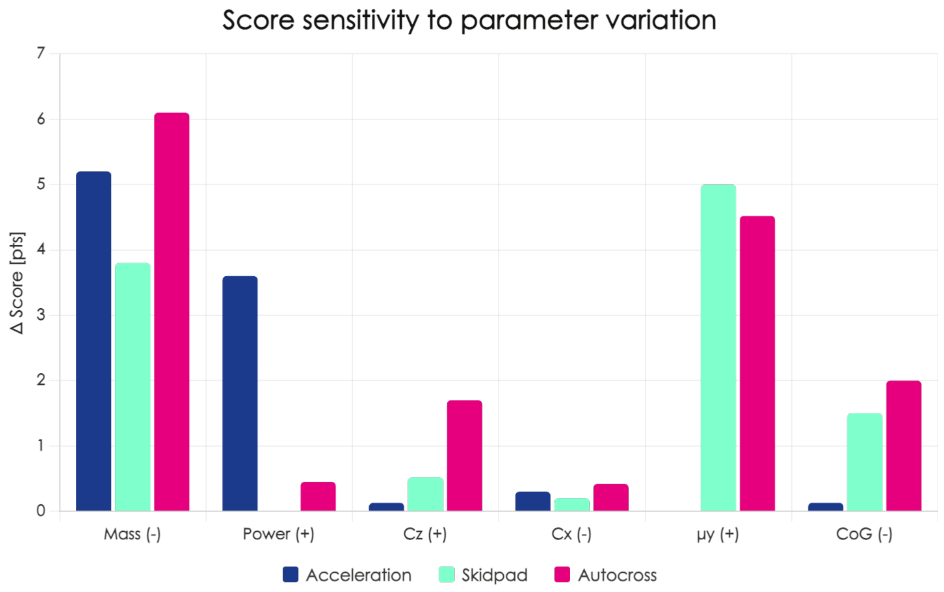
- Simplified bicycle model. Can be developed by a single person.
- Estimated workload 2-20h.

- Do you really need all the level of accuracy from the beginning of your studies?
- **Work smarter. Not harder**

4. Pre-design simulations. Overall Vehicle Concept

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

- Start by running some basic lap time simulations to define the overall vehicle concept.
- Use a simplified single mass point model and extend it if you have the workforce to do so.
- Focus on **helping your decision making**, **not absolute accuracy** at this point.
- Translate your lap time improvements into points. Remember, **you are chasing points, not seconds!**



N.B. Results are only orientative and only valid for a certain car architecture.

Please, don't copy this into your EDR and do your own simulations!

4. Pre-design simulations. Overall Vehicle Concept

You should be able to start answering some of these questions

- Is an aerodynamic package a good idea? Is the downforce worth the extra mass and Inertia?
- Do you have to spend more time and energy into making your car lighter or increasing downforce?
- What's your desired battery size? How much weight are you willing to introduce to increase your score in the endurance?
- Would you rather spend the money on a monocoque or in an bespoke set of springs, dampers and brakes?
- Where are you aiming to set your center of gravity position? Wheelbase? Track width?
- Suspension architecture. One or two ARB's? Directly actuated/rocker?

5. Design

Tire choice

It all should start with the Tire.

- The tire is the only component connecting the vehicle to the track and a key component, dominating vehicle performance.

- More grip = better braking, better traction, better cornering and ultimately better lap time.

- You need to make the call first on which tire you will be running in the car. It will impact all the vehicle dynamics design process and simulations.

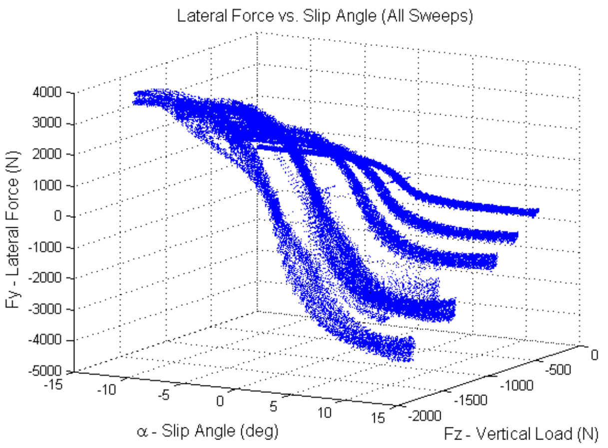
- It can be a lengthy task to decide between all the available options, but there is no good engineering design without a properly justified tire choice.

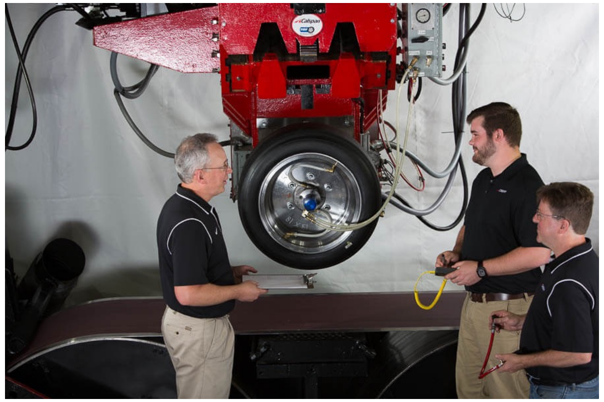
How do we choose our tires?

5. Design

Tire choice

- Some top-level teams and manufacturers can work directly with tire suppliers to develop or specify bespoke tire characteristics tailored to their vehicle concept.
- However, for the vast majority of Formula SAE teams, tire choice is limited to commercially available competition tires.
- The **Tire Test Consortium (TTC)** provides annual databases containing measured data for the most commonly used Formula SAE tires.





Racetrack Dynamics

5. Design

Tire choice

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

- It will be difficult to decide what tire to run in your car without evaluating and anlysing different performance areas independently.

- You can analyse the raw data provided by the TTC directly and only fit your model to the data on your winner or promising candidates.

TIRE CHOICE MATRIX

Analysis	Parameter	Weight	Tire 1	Tire 2	Tire 3	Tire 4	Tire 5	Tire 6	Tire 7	Tire 8	Tire 9
Weight	[redacted]	10	8.7	6.5	6.5	3.1	2.6	7.7	7.2	10.0	8.2
Transient		5	4.6	9.6	2.2	5.5	7.1	9.5	9.7	7.1	8.8
Sensitivities		4	5.0	7.8	5.8	5.0	7.5	5.8	5.8	3.3	5.8
Peak Performance		6	2.7	4.5	5.8	7.9	10.0	5.8	6.5	2.0	4.9
Degradation		4	8.6	7.9	6.3	3.5	4.5	3.5	5.1	2.4	3.7
Temperature Behaviour		5	5.0	3.2	10.0	3.7	2.0	5.8	4.1	7.0	6.0
TOTAL			206	219	209	158	179	226	224	205	223

- Now... **What does "fit your model to the data" mean?**

5. Design

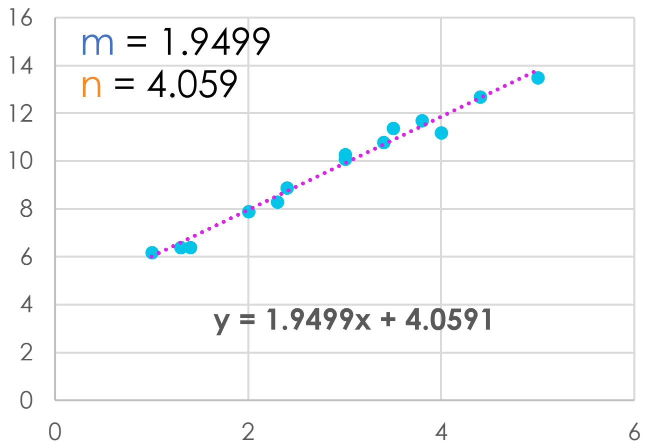
Tire choice

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

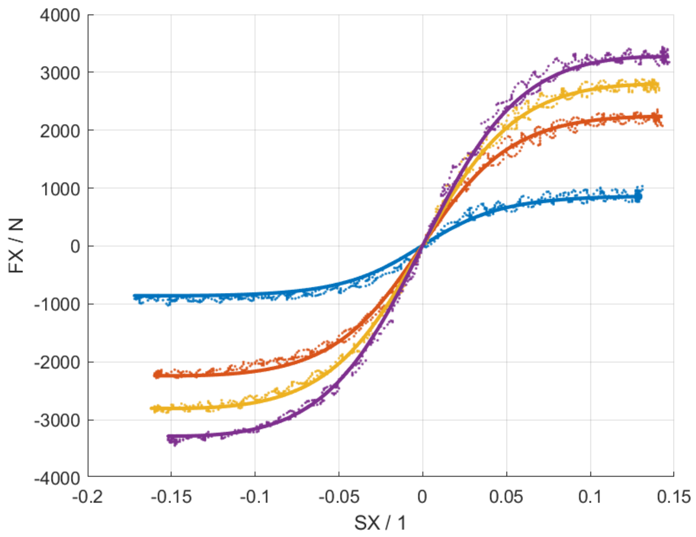
- To characterize a tire, it needs to be tested, data needs to be generated, and a **model needs to be fitted to it.**

- Think of linear regression example, when you have a set of points and your fit your line to it. The y = mx + n equation allows you now to interrogate your system at any given point (x).

The model: y= **m**x+**n**



Same exercise for tires. Just with more complex equations and more data points!



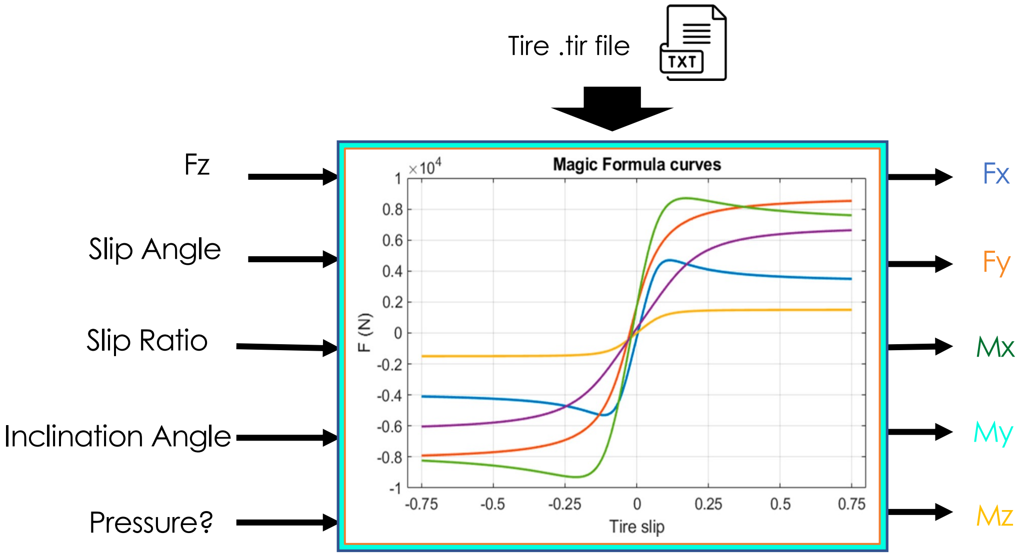
5. Design

Tire choice

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

- The most common set of equations are the semi-empirical Tire model equations of Pacejka. Each version of these equations with increased level of modelling and mathematical complexity.

- For example, **5.2 and 6.0 equations don't model pressure effects.**

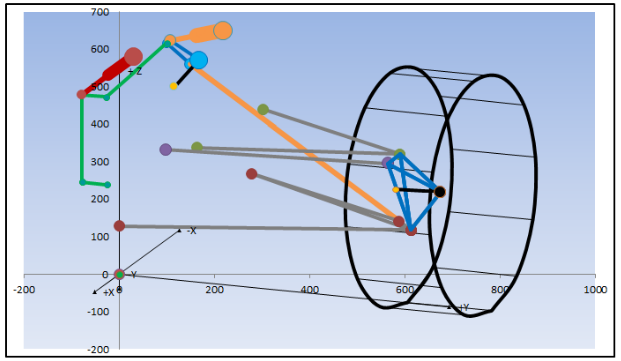


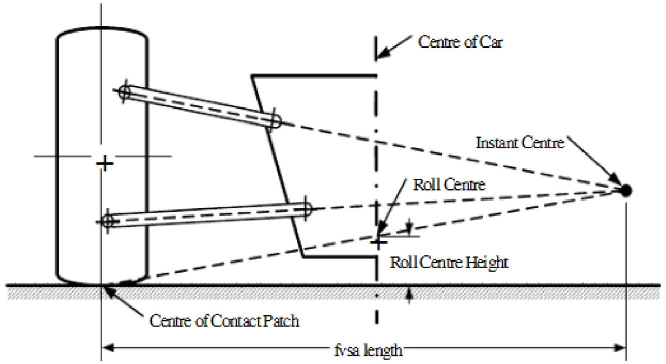
	Tyre property file		MF-Tyre 6.2	MF-Swift 6.2	MF-Tyre 6.1	MF-Swift 6.1	MF-Tyre 6.0	MF-Swift 6.0	MF-Tyre 5.2	SWIFT 1.2	MF-MCTyre 1.1
	[LATERAL_COEFFICIENTS]										
r_{By1}	RBY1	Slope factor for combined Fy reduction	x	x	x	x	x	x	x	x	x
r_{By2}	RBY2	Variation of slope Fy reduction with alpha	x	x	x	x	x	x	x	x	x
r_{By3}	RBY3	Shift term for alpha in slope Fy reduction	x	x	x	x	x	x	x	x	x
r_{By4}	RBY4	Influence of camber on stiffness of Fy combined	x	x	x	x	x	x			x
r_{Cy1}	RCY1	Shape factor for combined Fy reduction	x	x	x	x	x	x	x	x	x
r_{Ey1}	REY1	Curvature factor of combined Fy	x	x	x	x	x	x	x	x	x
r_{Ey2}	REY2	Curvature factor of combined Fy with load	x	x	x	x	x	x	x	x	x
r_{Hy1}	RHY1	Shift factor for combined Fy reduction	x	x	x	x	x	x	x	x	x
r_{Hy2}	RHY2	Shift factor for combined Fy reduction with load	x	x	x	x	x	x	x	x	x
r_{Vy1}	RVY1	Kappa induced side force Svyk/Muy*Fz at Fznom	x	x	x	x	x	x	x	x	x
r_{Vy2}	RVY2	Variation of Svyk/Muy*Fz with load	x	x	x	x	x	x	x	x	x
r_{Vy3}	RVY3	Variation of Svyk/Muy*Fz with camber	x	x	x	x	x	x	x	x	x
r_{Vy4}	RVY4	Variation of Svyk/Muy*Fz with alpha	x	x	x	x	x	x	x	x	x
r_{Vy5}	RVY5	Variation of Svyk/Muy*Fz with kappa	x	x	x	x	x	x	x	x	x
r_{Vy6}	RVY6	Variation of Svyk/Muy*Fz with atan(kappa)	x	x	x	x	x	x	x	x	x
p_{py1}	PPY1	Pressure effect on cornering stiffness magnitude	x	x	x	x					
p_{py2}	PPY2	Pressure effect on location of cornering stiffness peak	x	x	x	x					
p_{py3}	PPY3	Linear pressure effect on lateral friction	x	x	x	x					
p_{py4}	PPY4	Quadratic pressure effect on lateral friction	x	x	x	x					
p_{py5}	PPY5	Influence of inflation pressure on camber stiffness	x	x	x	x					

6. Design

Suspension Kinematics

- Only now that you understand your tire, you can make it work.
- Hardpoints definition is needed early to pass this information to chassis/frame deparment, as these points will be **the most structurally critical points in the frame** and stiffness/triangulation needs to be prioritized around them.
- Track and Wheelbase should be clear from your pre-design simulations and studies.
- Start by defining your package constraints: tire size, brakes, upright…





6. Design

Suspension Kinematics – Front View

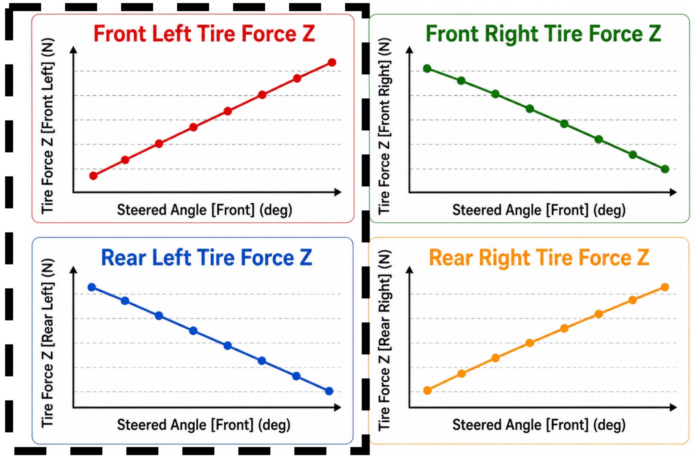
- Front View Instant Center
  - IC in the centerline of the car (FVSAL = track / 2)
    100% camber compensation in roll & terrible camber loss in heave
  - IC far past the opposite wheel (FVSAL = infinite)
    0% camber compensation in roll & no camber loss in heave
- **Scrub is not going to be a problem** if your Front View IC Height lies in a reasonable place, so locate it in a place that gives you your desired Roll Center Height.
- A good practice is to **make the Front Roll Center sit lower than the Rear Roll Center**. There is no correct answer, but **30-40mm for the front is a reasonable number** to start if you are lost. It gives plenty of authority on your elastic elements to adjust the Mechanical Balance on the car.
- Don't get lost in the details, roll center is a fancy term but it just represents one of the 100 things we need to get done, so **don't get clogged** here and move on!

6. Design

Suspension Kinematics – Front View

- Kingpin, scrub radius and spindle length are affected by outerball joints. **Aim for a low kingpin angle and positive scrub radius.**
- Watch out your spindle offset (wheel center to steering axis distance) **if you have an AWD** as it can create **Torque Steer**. Minimize it. For a RWD, spindle offset won't hurt you much.
- **Higher Kingpin angle => Higher Camber Loss with steering => US**
- If your car has some Caster and/or Anti-Ackerman Steering:
  - Higher Kingpin angle => Diagonal weight shift, front outside more loaded => US

(Right hand turn example)



6. Design

Suspension Kinematics – Side View

- Caster angle induces a "favourable" camber gain with steering, which compensates for the loss of the kingpin. No right value, as it depends on your full philosophy. It can be used to alter mid-corner balance and gain rotation (max SWA @ apex -> more camber).

- **You can meet your target mechanical trail and caster targets**. More freedom now to move the axis longitudinally than laterally with the kingpin angle (packaging).

- **Tie rod location should be such that the arc described by the outer tie rod hardpoint matches as closely as possible the arc of the movement imposed by the suspension links to minimize bump steer.**

- Distance to the steering axis (outer ball joints) will affect your steering feel, make the lever arm accordingly. The steering wheel maximum torque should be designed with driver preference in mind. **If you don't have a reference**, **targeting 10 Nm** at the steering wheel (including your tires self-aligning moment) **is a good place to start**.

6. Design

Suspension Kinematics – Side View

- Anti geometries are next. The more your car is sensitive to ride heigh, the more anti squat and dive you should be using.
- If you don't run aero in your car, your reasons to use anti-dive are very small
- Don't abuse the antis:
  - **They remove driver feedback (terrible!)**
  - The suspension becomes less compliant
  - They limit spring compression and wheel travel (are you exploring non-linear rocker characteristics?)

6. Design

Suspension Kinematics – Compliance

- Kinematics are a good place to start, but remember that **nothing is rigid and your car's suspension links will move and deform under loads.**
- At the **bare minimum**, aim at **quantifying the following figures** in your car:
  - Brake Camber Compliance (Camber loss under braking)
  - Brake Steer Compliance (Toe loss under braking)
  - Lateral Steer Compliance (Toe loss under cornering)
  - Lateral Camber Compliance (Camber loss under cornering)
- Compliance is not neccesarily bad (when understood and calculated)
- **If you don't have particular compliance strategies, aim to reduce them as much as possible by efficient designing.**

6. Design

Suspension Kinematics – Compliance

What is an efficient design? A picture is worth a thousand words.

We don't need to be pro mechanical designers (or even engineers) to spot the differences

Remember:

- **it is ok to have some mild** and **intencional** compliance.
- It is **not ok to have excessive** and **unknown** compliance

6. Design

Spec your springs

How stiff do you want to run your car? How much is your car allowed to move under load?

- The exact answer depends on your car concept. If running ARB, Allow 35-45% of your roll stiffness budget to your ARB.

You can build a **ride model (7 DoF)** and a **Double track model** to understand your trade-off:

- **Double Track Model**: Stiffer Suspension ⟶ **Enhanced response time (Step Steer)**
- **Ride Model**: Stiffer Suspension ⟶ **Increased CPL (Heave/Roll Sine Sweep)**

Directionally:

- Higher ARB contribution to roll stiffness -> Less independent suspension. Forces transmitted from Left to Right
- Higher ARB contribution to roll stiffness -> for iso roll stiffness, better ride performance (you can run softer springs)
- **ARBs are also engaged in single wheel travel events!!**

6. Design

Spec your ARBs

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

- Roll stiffness philosophy will depend on the amount of aerodynamics you run in your car.

- Increased roll stiffness will:

  - Limit the amount of body roll
  - Reduce response time
  - Degrade road compliance and ride

Generally speaking:

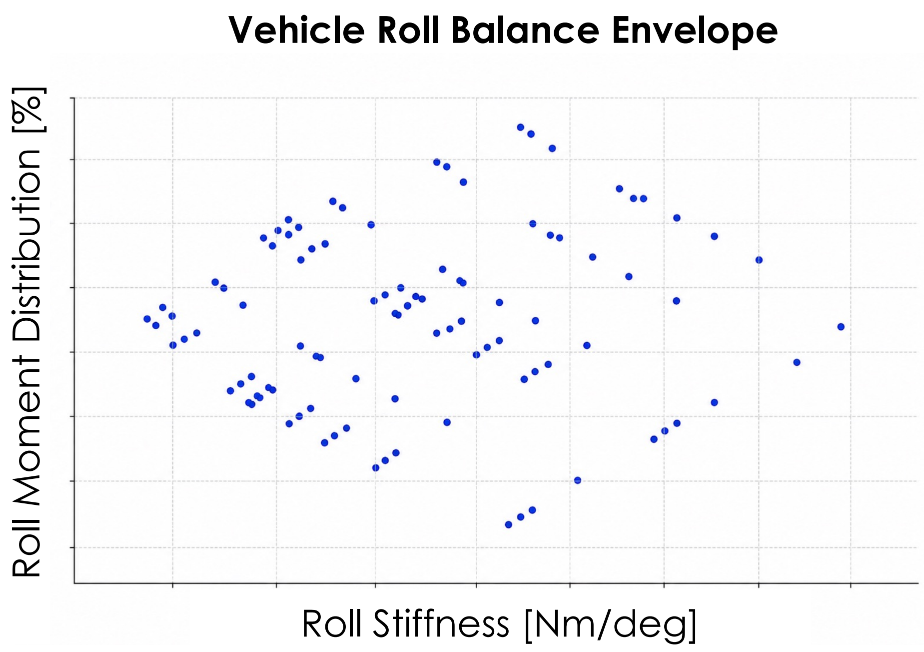
- No aero -> Softer Roll Rates
- High aero -> Stiffer Roll Rates

6. Design

Spec your ARBs

- Planning
- Resources
- Rules and Scoring
- Vehicle Concept
- Design
  - Tire Choice
  - Kinematics
  - Springs
  - ARB
  - Dampers
- Test and Validate
- Compete

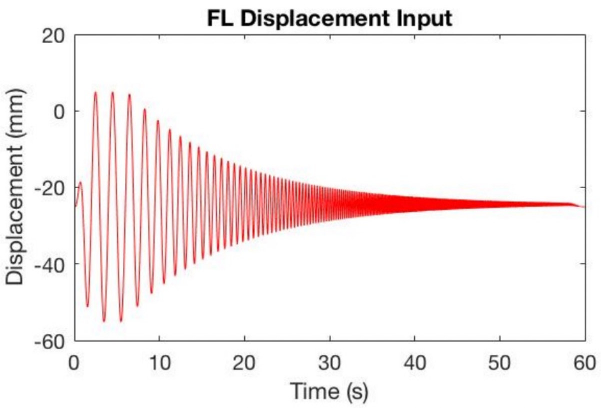
- Don't forget to make your car adjustable and give plenty of options to tune it
- **Roll Moment Distribution** needs to "**marry**" **Aero Balance** and **Center of Gravity** Location for Balance.

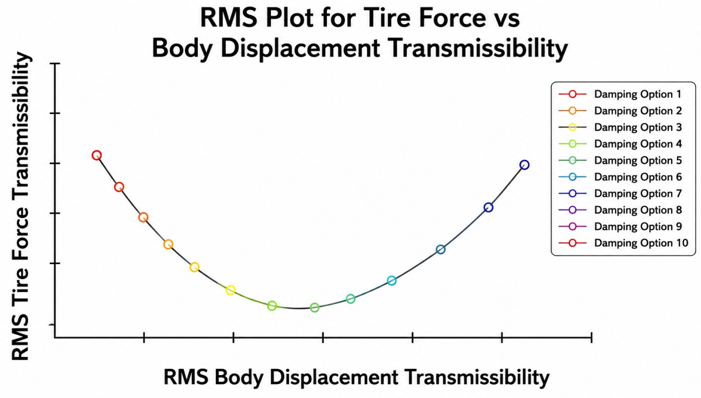


6. Design

Spec your Dampers

- Build a ride model (7 DoF) to spec your dampers appropriately. **In FSAE your main goal should be to reduce the Contact Patch Load Variation**
- Dampers need to match your springs. **Stiffer rates -> More Damping**
- Remember that **everytime you change your springs and anti roll bars, your optimum damper settings change**! If you increase spring stiffness without changing your dampers, your car will be under-damped!





7. Testing and Validation

Test, test and test.

- Top-performing FSAE teams consistently dedicate significant time and resources to vehicle testing.

Why does testing correlate with success?

1) Testing is a consequence of strong project execution

2) Testing exposes weaknesses before competition

- It is always better to have a lower arm failure in testing than in the competition (ideally, don't have it at all!)

- When designing, it is extremely important that you keep your options open for testing, so you have full adjustability on the car.

- When something didn't work as planned, use this opportunity to learn why that was the case, correlate your model and improve. This is the flowpath in high performance environments, so adopt it from your early steps!

8. Compete

Learn, enjoy and Make friends

- Do your best in every event, but do not be too harsh on yourself when things do not go as planned.
- Take the opportunity to see how other teams solve engineering problems and learn from their approaches.
- Make friends! Remember that many of the people you meet at competition will soon be working in Formula 1, motorsport, automotive, aerospace, and technology companies.
- Create memories, enjoy the atmosphere, and have fun with your teammates.

Racetrack Dynamics

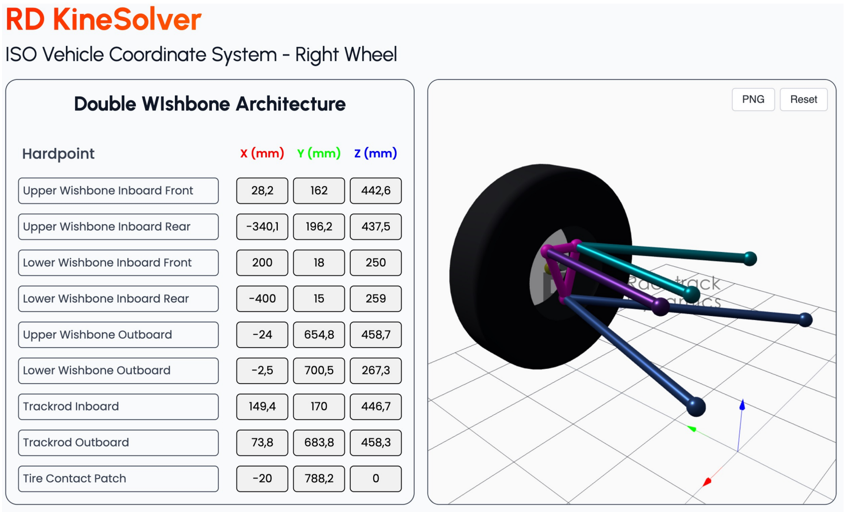
The FSAE Toolkit

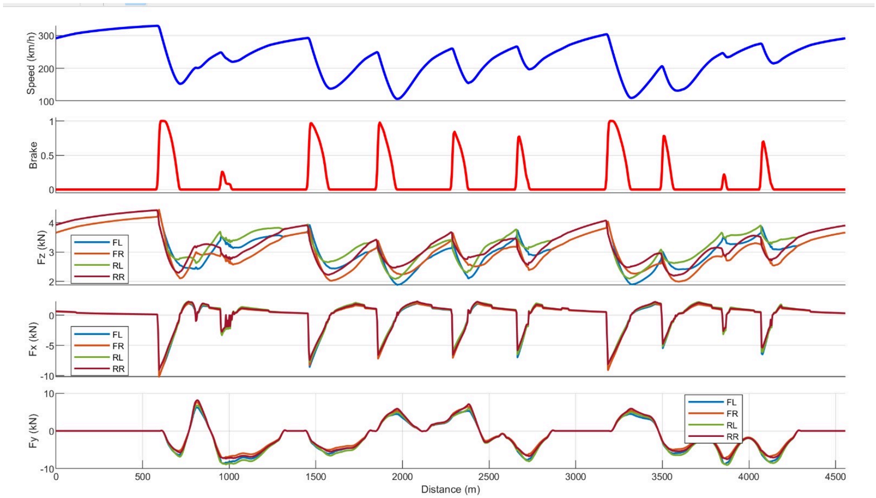
Our contribution to FSAE

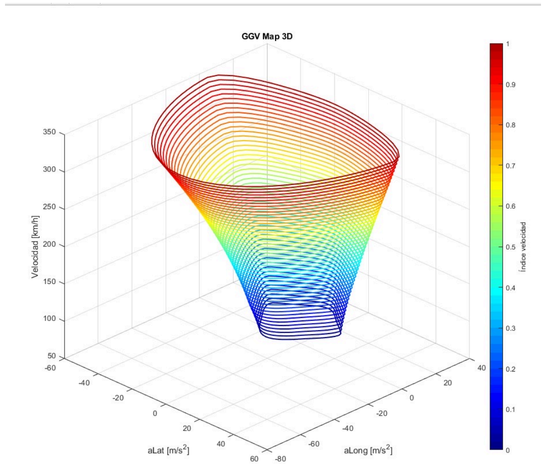
- To thank you for your joining us today, we would like to share with you our FSAE Toolkit.

www.racetrackdynamics.com/fsae-toolkit

- Containing a handful of useful and free resources:
  - This presentation
  - Our Suspension Kinematics Simulation tool (RD KineSolver)
  - Our Laptime Simulator (RD LapSim)
  - Our complete VD-Pedia







Thank you for your attention

To download this presentation, find our free web-based simulation tools and FSAE resources go to:

www.racetrackdynamics.com/fsae-toolkit