Vehicle Dynamics
FE8 Final Design Review

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Table of Contents

Takeaways:
Comprehensive Status of VD

Vehicle Dynamics' Purpose

How does the Vehicle Dynamics subteam support FRUCD's mission of developing Formula SAE vehicles for competition?

VD's Roles within FRUCD

- Teach – Ensure team understands fundamental vehicle principles
- Simulate – Predict complex design implications on performance
- Target – Direct a cohesive early system level vehicle concept
- Adjust – Accommodate arising low level constraints by refining concept
- Verify & Validate – Support predictions through experimentation

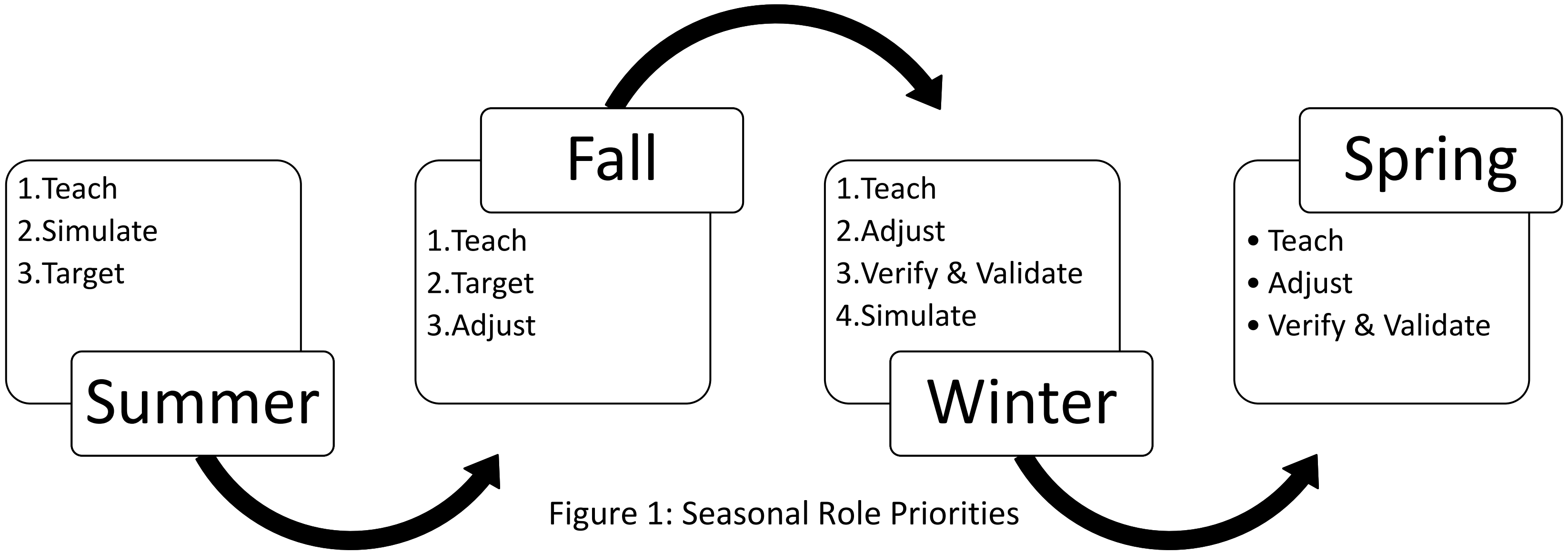

Figure 1: Seasonal Role Priorities

Promoting Systems Engineering Approach

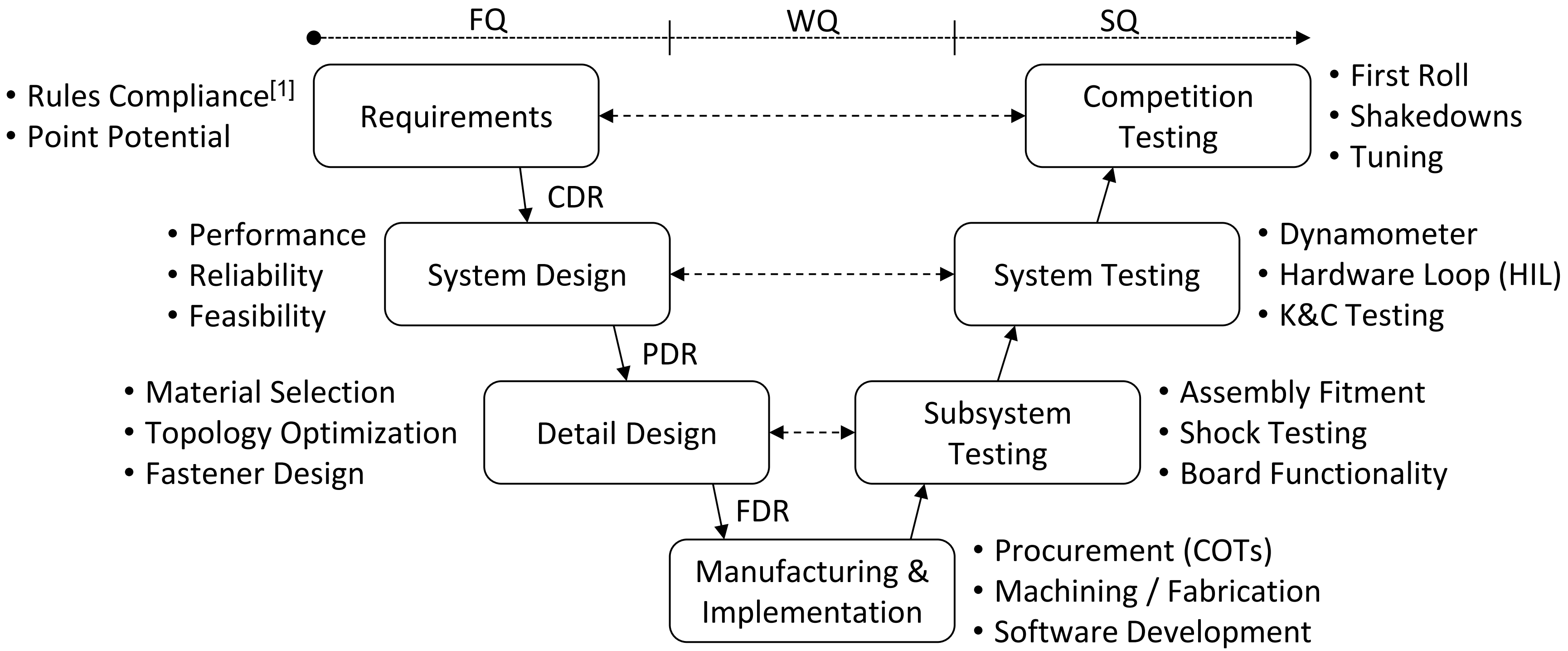

Figure 2: Systems Engineering "V" Diagram

- Cohesive design:
  - Propagates down
  - Integrates up
- Points sensitivities drive decisions
  - One overarching goal: **Competition**
- System oriented designs are often more apparent and effective
  - Leverage constraints and priorities established at higher levels

Guiding Vehicle Concept Tradeoffs

- Often subsystem objectives conflict
  - Creates engineering tradeoffs ("Pareto Fronts")
- Sensitivity analysis provides priorities
  - Mechanical grip is king with FSAE
  - Mass reduction is a distant second

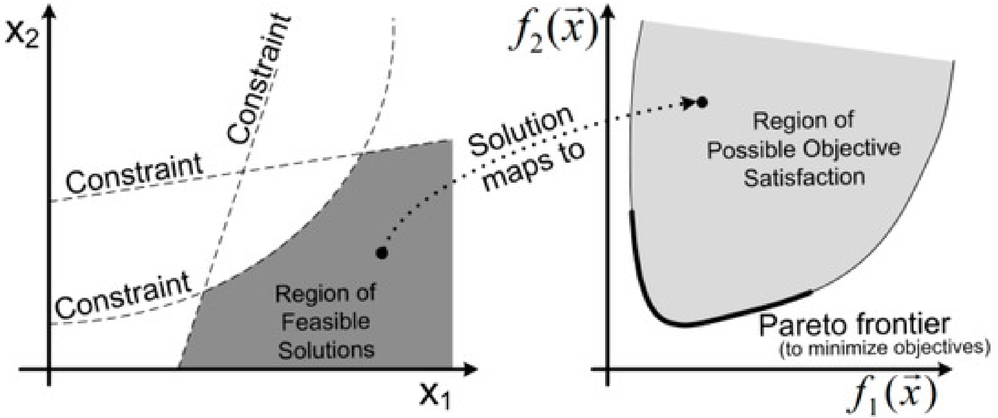

Figure 3: Multi-Objective Pareto Fronts[2]

Parameter	Sensitivities $[\%/\chi]$					
	Sapienza[3]	GFR[4]	Eindhoven[5]	Belfast[6]	Nominal $[\chi]$	5% Delta(1) [%]
Mass, m $[kg]$	0.025	0.029	0.021	0.023	275	**0.337**
Drag, C_D [ ]	0.157		1.097	0.478	0.6(2)	**0.017**
Downforce, -C_L [ ]	-1.890			-1.433	1.9(2)	**-0.158**
Lat. Grip, μ_y [ ]	-23.387			-28.634(3)	1.5	**-1.742**
Long. Grip, μ_x [ ]	-5.646				1.5	**-0.421**
Power, P $[kW]$	-0.058	-0.140	-0.076		60	**-0.274**

Table 1: Endurance Lap Time Parameter Sensitivities

(1) 5% Delta $\equiv \frac{\partial \bar{T}}{\partial x} \cdot x_0 \cdot 0.05$

(2) Nominal C_D, C_L chosen based on estimates from aerodynamics.

(3) Belfast study lumped lateral & longitudinal grip.

Vehicle Simulation Overview

What are the major requirements of vehicle simulation and how have these formed FRUCD’s simulation approach?

Provide Flexible Simulation for Design

- Fidelity: Representational accuracy
  - How close is the model to reality?

Multifidelity simulation uses a range of models to predict outcomes

- Systematic design evolution
  - Simple models inform complex models
- Knowledge transfer
  - Model progression supports learning
- Resource optimization
  - Cheaply eliminates large sets of designs

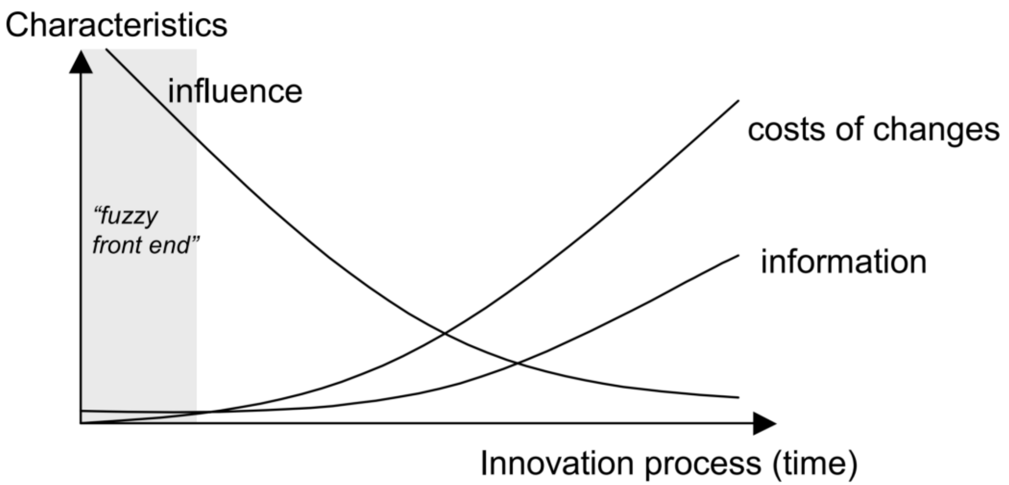

Figure 4: Project Evolution[7]

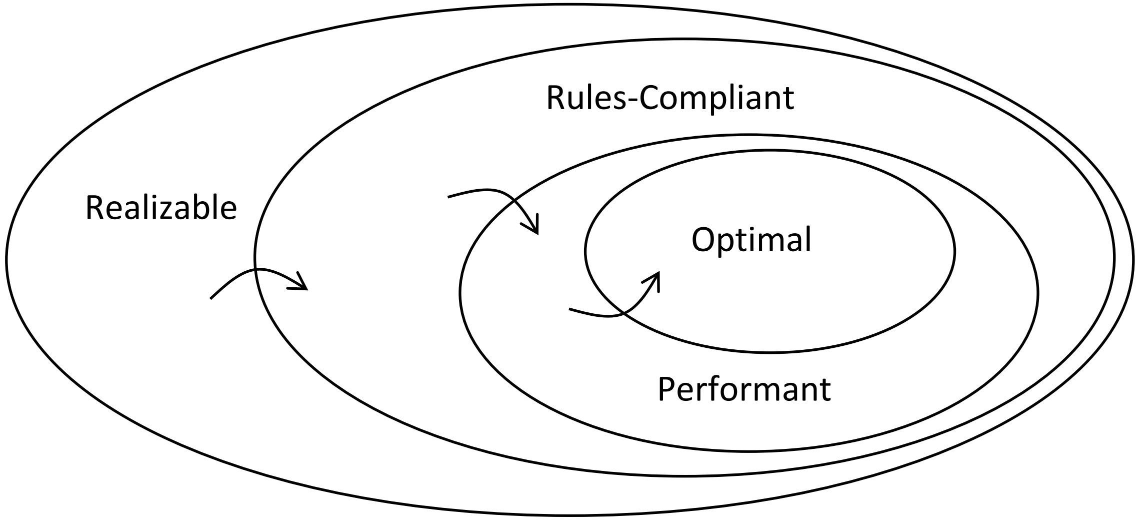

Figure 5: Vehicle Design Space Concentration

Simulation Workflows & Platforms

- Fidelity is manipulated by both:
  - Vehicle Model: Structural Error
  - Simulation: Computational Error
- Most design simulations value efficiency
  - Mostly addressed by performance envelopes and QSS lap sims
  - Transient simulation is only needed in ISO7401 for stability
- Focus is currently addressing design needs and not tuning
  - Expanding vehicle model resource function library
  - Developing performance envelopes and lap time simulation
- Transient simulations will be much more useful for tuning
  - Much higher fidelity required for purposeful tuning information

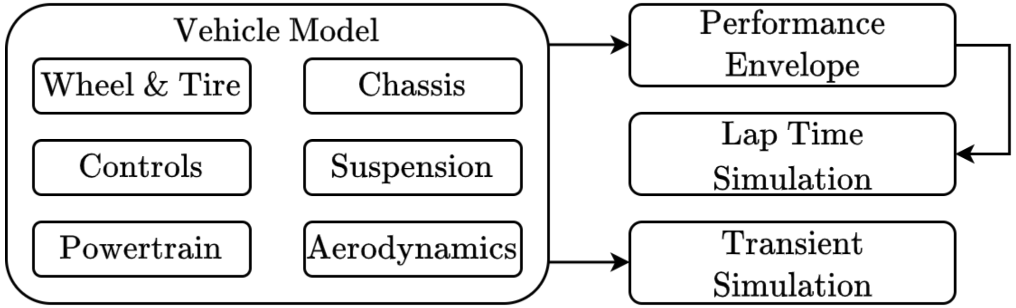

Figure 6: Planned Vehicle & Platform Interactions

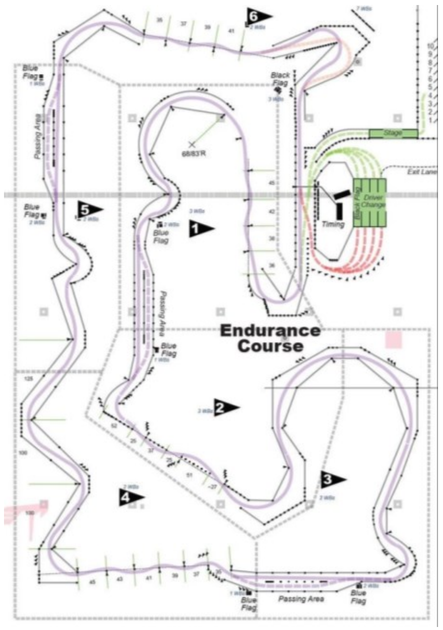

Figure 7: Lincoln 2019 Endurance Layout[8]

Established Conventions

How can the complexities of automotive engineering be communicated efficiently and systematically?

Nomenclature, Coordinate & Unit Systems

- Adopted SAE-J670-2008[9] Z-Up
  - Descriptive nomenclature
  - Coordinate systems (sign conventions)
    - World, Intermediate, Body, Wheel, Tire
- Model handbook[10] documents general symbolic nomenclature

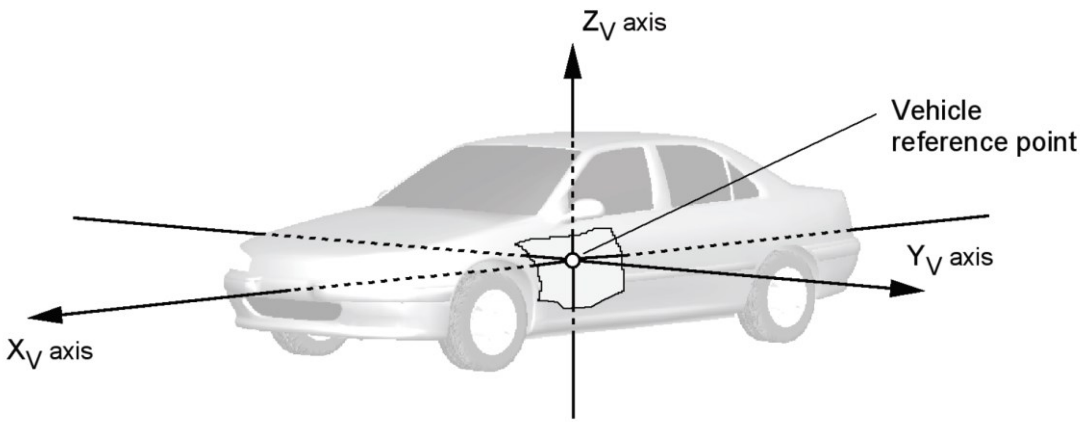

Figure 8: SAE Z-Up Vehicle (Body/Chassis) Coordinate[9]

- All vehicle simulation is performed in metric
  - Imperial inputs can be scripted but should be immediately converted
  - Angular unit is not standardized (beware of using degrees in differential equations)

Data Management

MDO	Multidisciplinary Design Optimization
HPC	High Performance Computing
FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics
CAM	Computer Aided Machining
CAD	Computer Aided Design

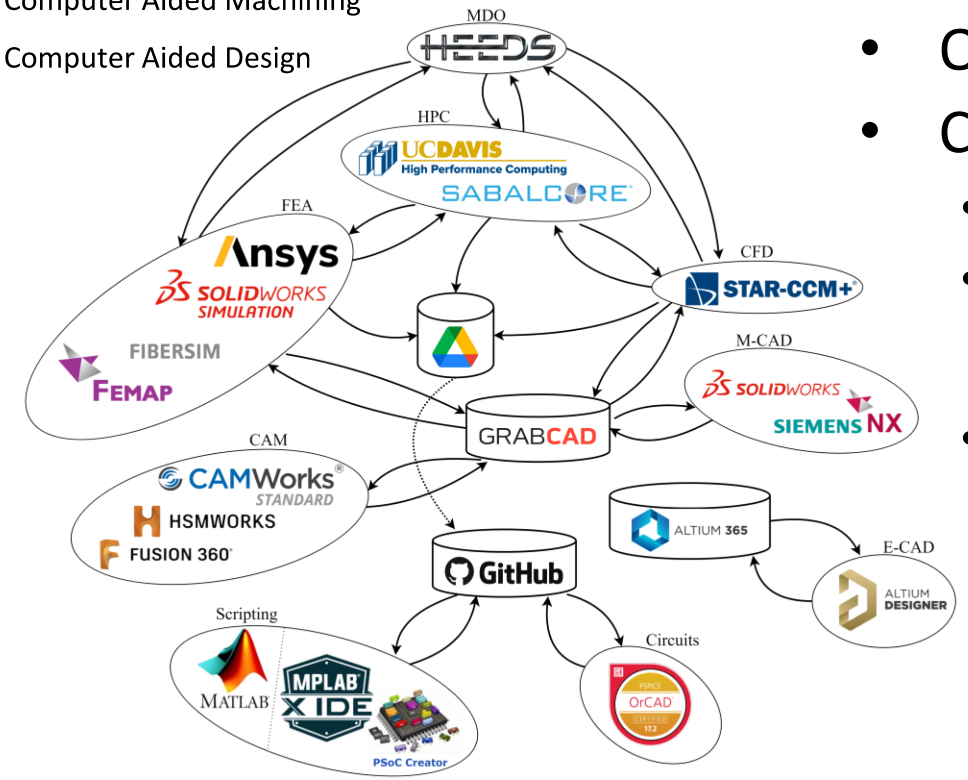

Figure 9: FRUCD Data Management Network[11]

- Simulation infrastructure has grown rapidly
  - Accommodating expanding analyses
- Simulations and data are now stored in Github
  - Operating processes still maturing
  - Currently separating public and private data
    - Store simulation scripts in public “ “-Modeling repos
    - Store simulation inputs/outputs in private “ “-Data repos
- Still hurdles in managing long workflows
  - FEA derived compliance lookup tables
  - CFD derived aerodynamic load map

Software Development Conventions

- Previous simulation development efforts have failed due to the following:
  - Documentation: Lack of documentation prevents transfer
    - Implemented standardized comment requirements to ensure readability
  - Interdependency: Software inflexible to necessary architecture changes
    - New parsing – resource function development architecture standardizes sustainable functions
  - Variance: Code base written in many different styles and symbolic naming
    - Adopted uniform syntax[12] and descriptive naming (e.g. $Beta \rightarrow BodySlip$)

```
function [Output, …] = FunctionName(Input, …)
%% FunctionName - Short Description
% Detailed Description …
%
% Inputs:
%   Input  - (dataType) Description {symbol} [unit]
%   …
%
% Outputs:
%   Output - (dataType) Description {symbol} [unit]
%   …
%
% Notes:
%   Recommendations, References, …
%
% Author(s):
% First Last (email@ucdavis.edu) [MMM YYYY - MMM YYYY]
%
% Last Updated: DD-MMM-YYYY
```

Figure 10: Standardized Comment Header

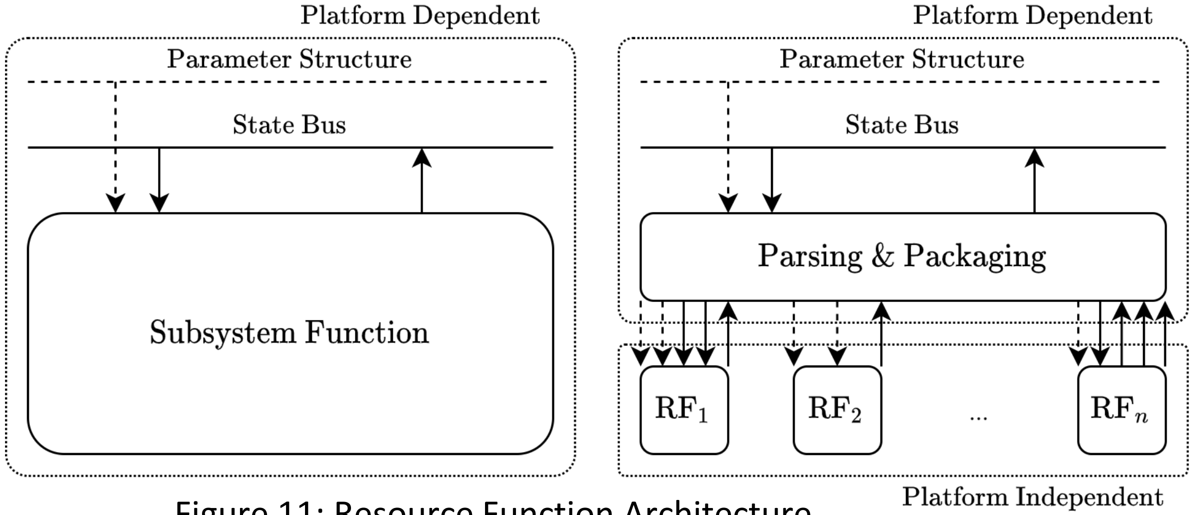

Figure 11: Resource Function Architecture

Vehicle Systems Decomposition

- Vehicles are complex nonlinear systems
  - 1000’s of parameters, 100’s of constitutive relationships, & 10’s of dynamic states
- Decomposition promotes accessibility
  - Members can directly develop in their area of expertise
- Subsystems broken down in resource functions
  - Highly modular across platforms & fidelities

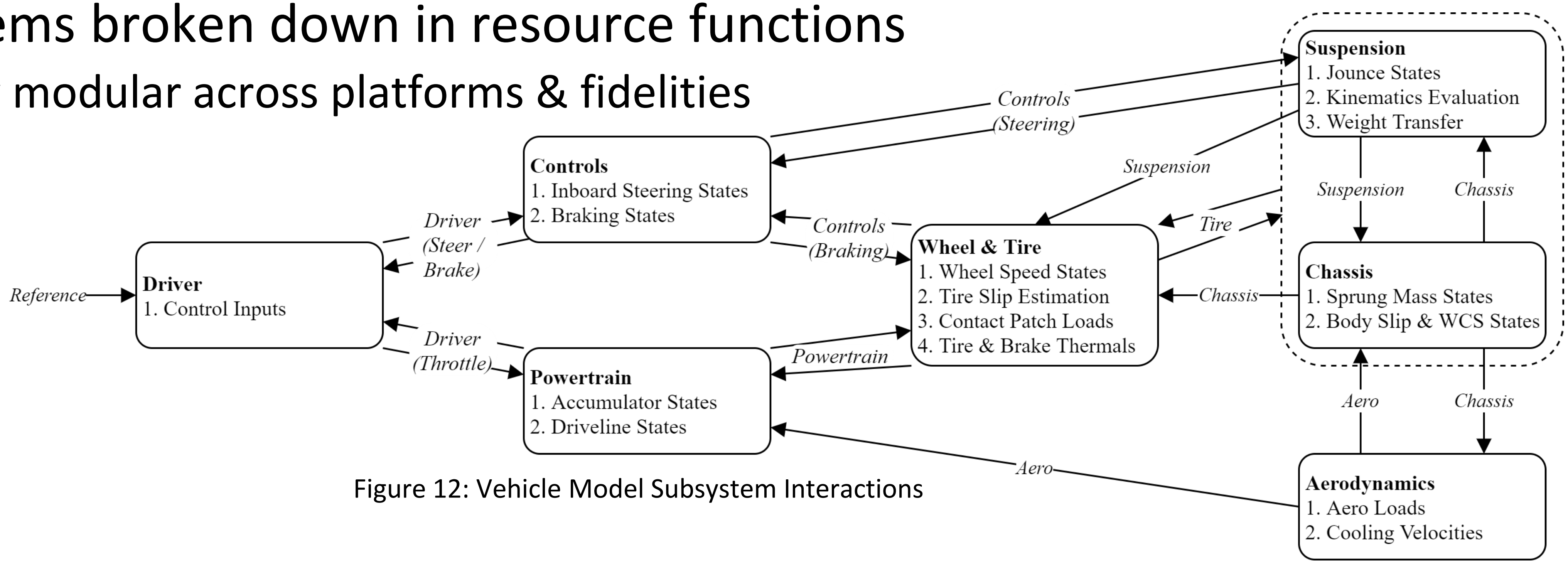

Figure 12: Vehicle Model Subsystem Interactions

Tire Mechanics

How do we represent the most important interaction between the vehicle and its environment?

Snapshotting Tire Selection

- Tire selection is very constrained
  - Limited market for slicks of correct size
    - Continentals only available through sponsorship
- Quick Notes[13]:
  - Avon 13"s have no redeeming qualities
  - Avon 10"s have lateral peaks (hard to drive)
  - Hoosier is the main supplier
    - 13": Heavy and do not provide more grip than 10"
    - 6.0: Reduced tread widths destroy available grip
    - LCO: Compound requires low temps and wears quickly
- This leaves two contenders:
  - Hoosier R25B 16.0x7.5-10x7
  - Hoosier R25B 18.0x7.5-10x7

Tire			Cornering	Braking
Hoosier	R25B	16.0x7.5-10x7	8-[1,2,4]	X
Hoosier	R25B	16.0x6.0-10x7	8-[11-13]	X
Hoosier	LCO	16.0x7.5-10x7	8-[17-19]	X
Hoosier	LCO	16.0x6.0-10x7	8-[23-25]	X
	Avon	7.0/16.0-10x7	7-[1-3]	X
Hoosier	R25B	18.0x7.5-10x7	6-[20-22]	6-[34-36]
Hoosier	R25B	18.0x6.0-10x7	X	X
Hoosier	R25B	20.5x7.0-13x7	6-[8-10]	6-[54-56]
Hoosier	R25B	20.5x6.0-13x7	8-[11-13]	6-[51-53]
	Continental	205/510R13x7	6-[14-16]	6-[60-62]
	Continental	205/470R13x7	8-[35-37]	8-[47-49]
	Avon	7.2/20.0-13x7	7-[14-16]	7-[32-34]
	Avon	6.2/20.0-13x7	7-[23-25]	7-[29-31]

Table 2: Tire Data Availability

(Supplier) (Compound) (Tire Diameter)x(Tire Width)–(Rim Diameter)x(Rim Width)

Figure 13: Tire Naming Convention

Tire Modeling Conventions

- Tires are the most critical and complex aspect of the vehicle model
  - Describe the main interaction between the vehicle and its environment
- Operating conditions determine a complex load and radial deflections

$$[F_x, F_y, M_z, M_x, M_y, r_e, r_l] = f(\alpha, \kappa, F_z, P_i, \gamma, T_C, v_T)$$

Equation 1: Tire Functional Relationship

Inputs	Symbol	Unit	Outputs	Symbol	Unit
Slip Angle	α	$[deg]$	Longitudinal Force	F_x	$[N]$
Slip Ratio	κ	$[\ \ ]$	Lateral Force	F_y	$[N]$
Normal Load	F_z	$[N]$	Aligning Moment	M_z	$[Nm]$
Inflation Pressure	P_i	$[kPa]$	Overturning Moment	M_x	$[Nm]$
Inclination Angle	γ	$[deg]$	Rolling Resistance	M_y	$[Nm]$
Carcass Temperature	T_C	$[°C]$	Effective Radius	r_e	$[m]$
Contact Patch Velocity	v_T	$[m/s]$	Loaded Radius	r_l	$[m]$

Table 3: Tire Mechanics Nomenclature

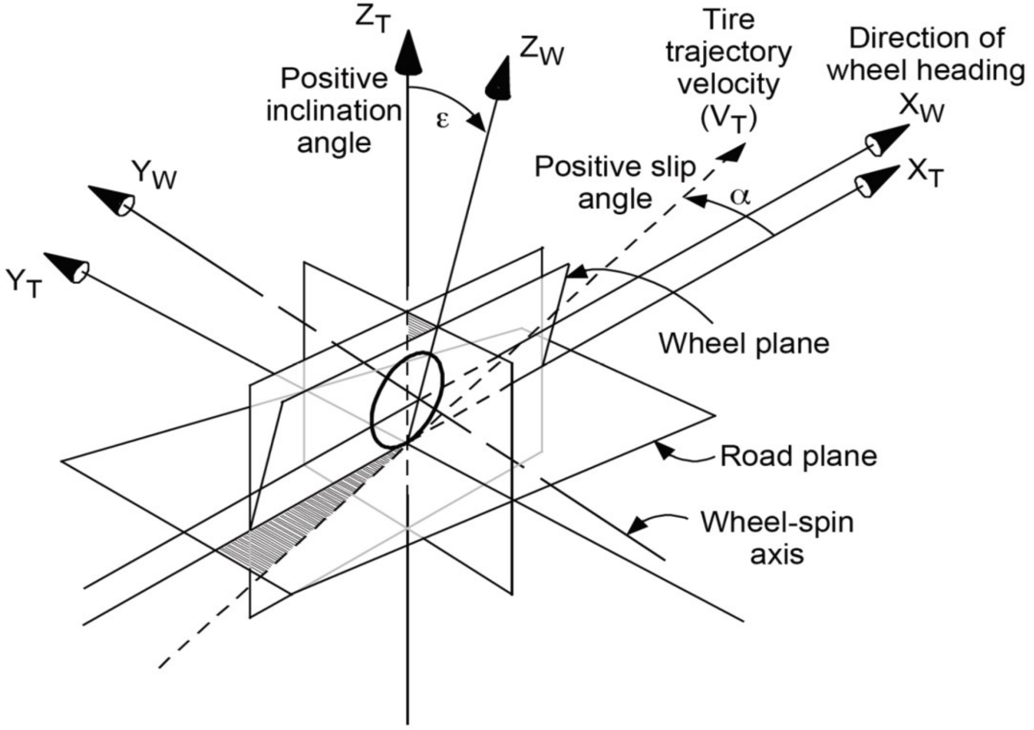

Figure 14: SAE Z-Up Wheel & Tire Coordinates[9]

Tire Model Decomposition

- Evaluation involves a cascading set of models which improve predictions
  - Pure: No longitudinal-lateral interaction effects
  - Combined: “Friction Ellipse” behavior
- Recent Additions:
  - Overturning Moment
  - Relaxation Length
- Current Priorities:
  - Radial Deflection
  - Combined Slip Aligning Moment
  - Rolling Resistance
  - Thermal Effects

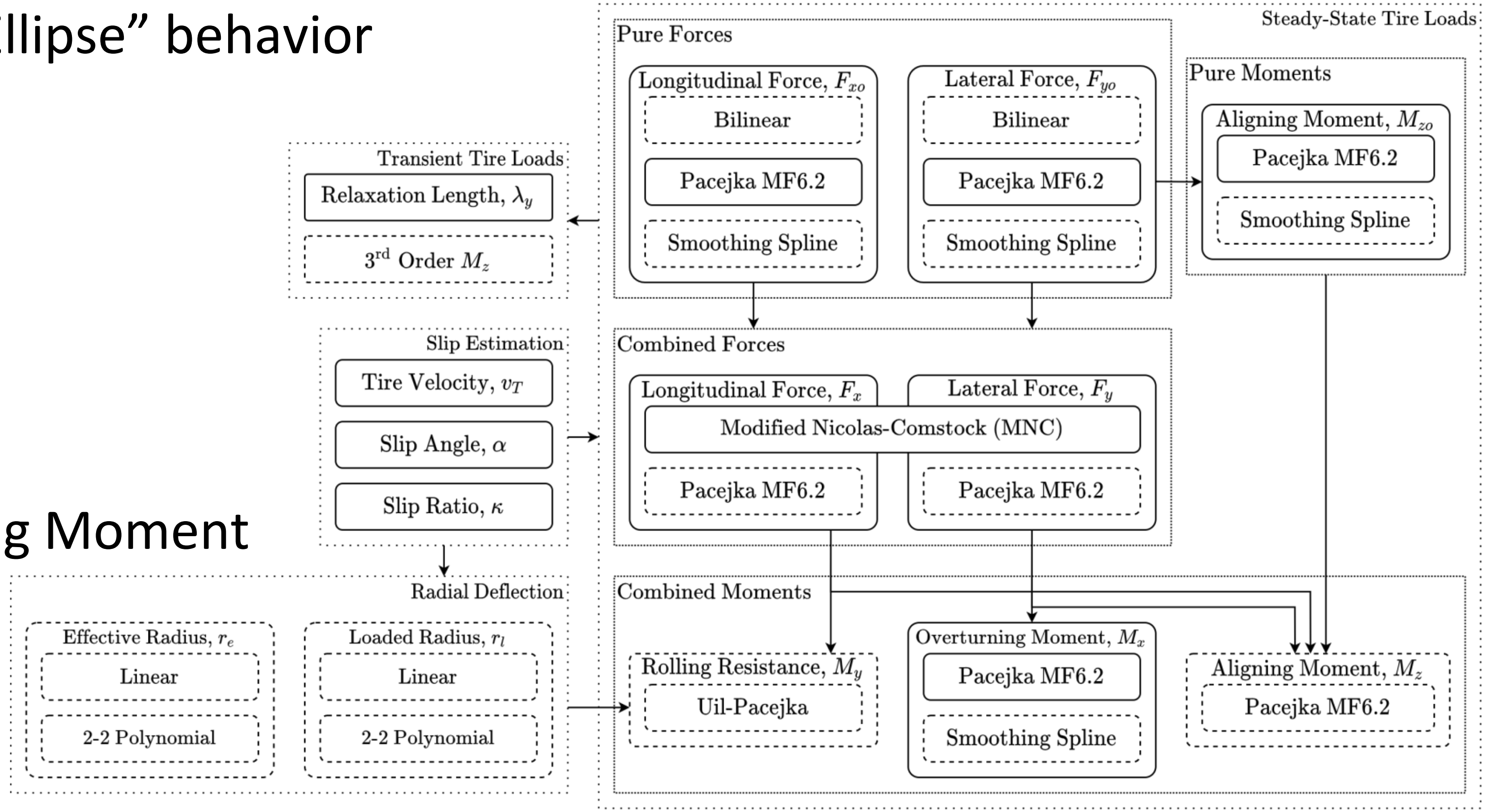

Figure 15: Tire Computation Flowchart

Tire Contact Patch Load Methodology

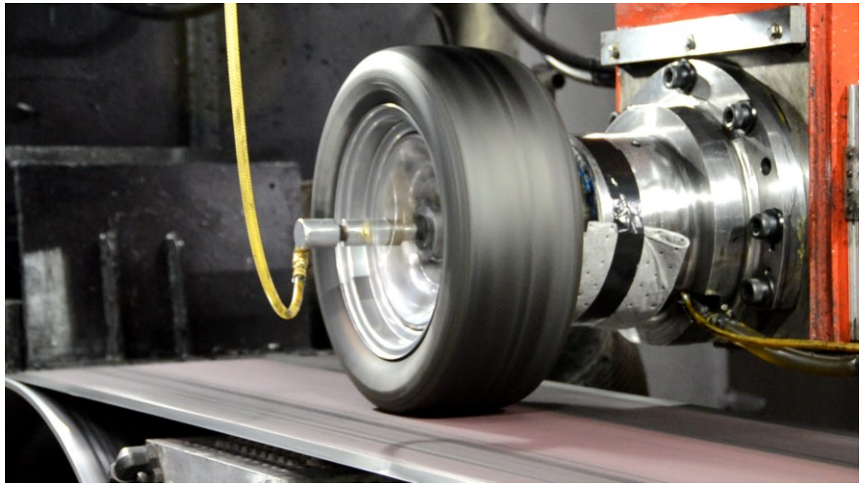

Figure 16: FSAE Tire Testing Consortium[17]

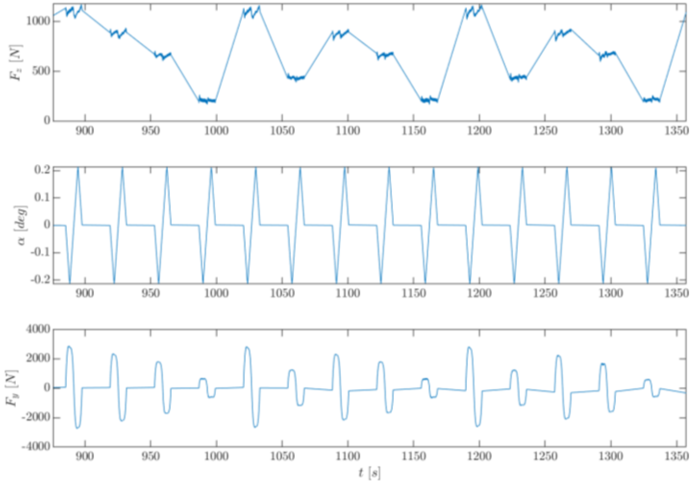

Figure 17: Tire Data[18]

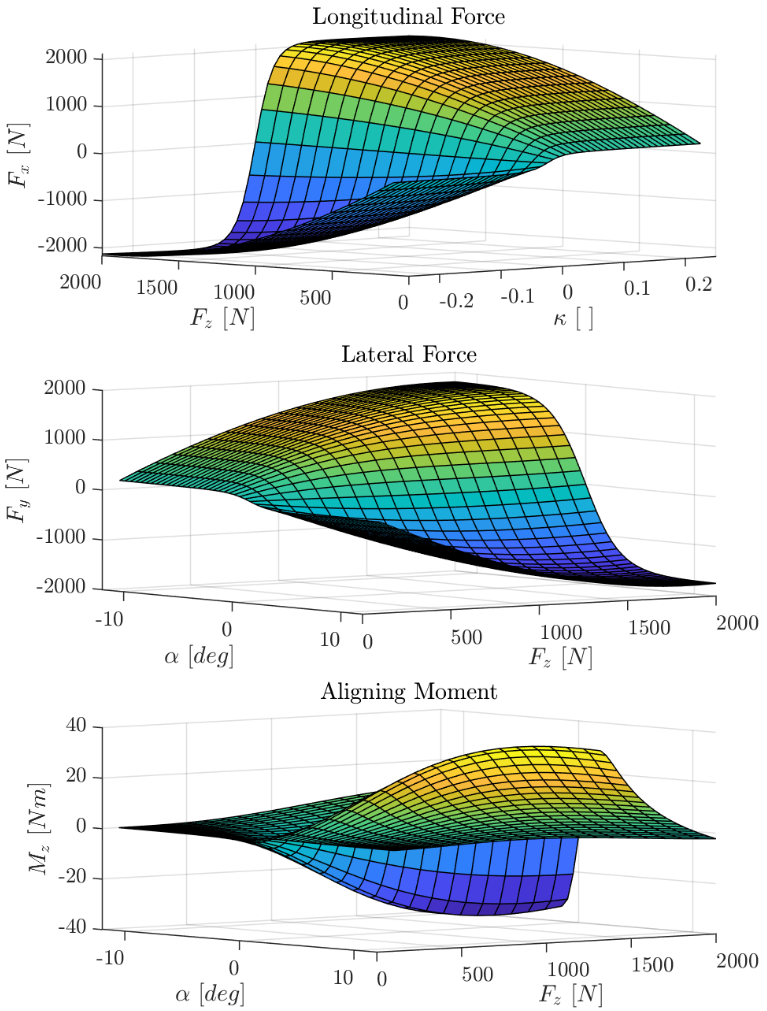

Figure 18: Pacejka Pure Slip Surfaces

- Data-driven Pacejka[14] model
  - Quick to evaluate and scales nicely
  - Smoothing spline models will be more locally accurate
- Modified-Nicolas-Comstock[15] (MNC) model is used to overcome longitudinal data limitations of 16”s
- Wong-Pacejka[16,14] rolling resistance model is used again due to data limitations for all tires

Overturning Moment, M_x

- Heavily influences load distribution between A-Arms
  - Manipulates roll dynamics
  - Complex behavior at large inclination
- Fitted with single regression
  - No need for bootstrapping since $p = 12$
- Fits are functional, but not tuned
  - Diverging behavior at high load

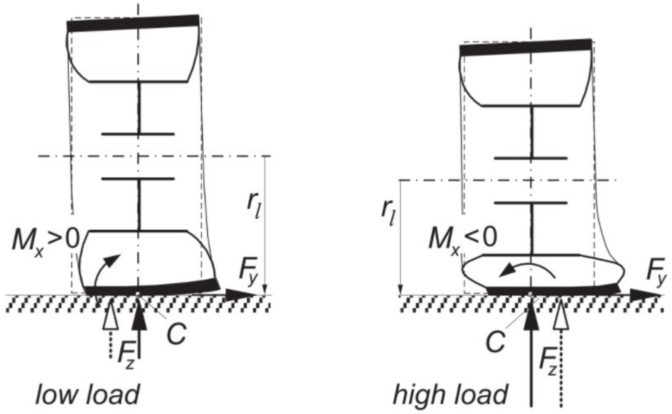

Figure 19: Overturning Moment Diagram [14]

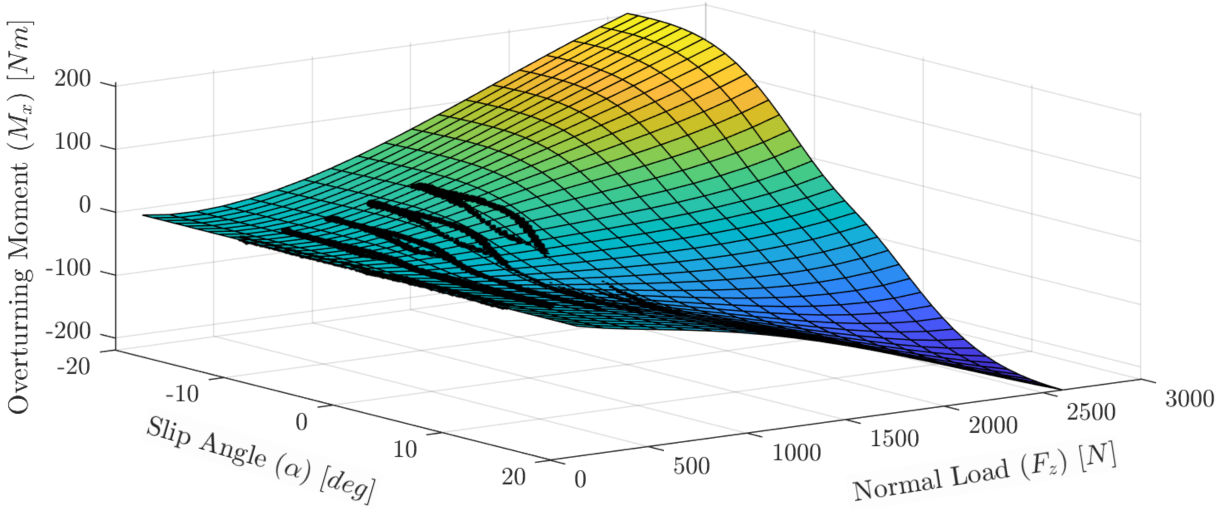

Figure 20: Overturning Moment Fit Example

Transient Tire Modeling - Relaxation Length, λ

- FSAE style racing is highly transient due to tight corners
- A first order step response is fitted to TTC data:

Equation 2: $\dot{F_y} = F_{y_{t\to\infty}}\left[1 - \exp\left(\frac{-t}{\tau}\right)\right]$ $\qquad \lambda = \tau \dot{x}_T$

- The relaxation length was dependent on conditions:
  - Tire responded slower at high normal loads
  - Tire responded faster at high pressures
  - Unexpectedly tire responded faster on larger slip steps
- Transient response differentiates the 18"s and 16"s
  - Thinner sidewall 16"s respond faster in theory
  - λ is 45.6% shorter for the 16" tire

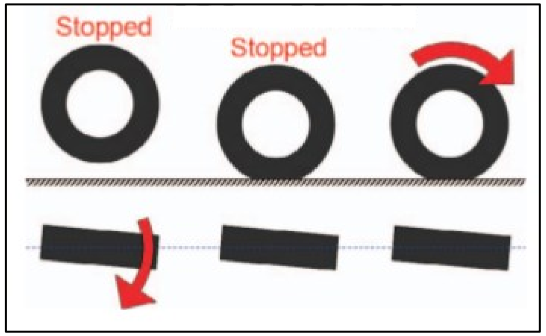

Figure 21: Lateral RL Test Procedure[19]

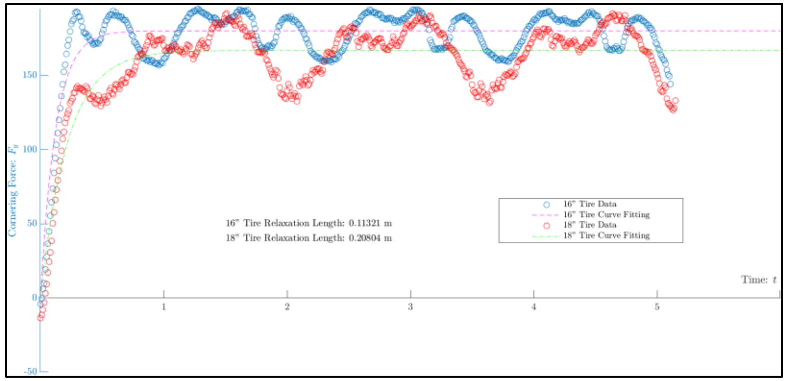

Figure 22: Lateral Force Response Comparison

Combined Slip Aligning Moment

- Gives feedback from longitudinal forces to driver
  - Gives scrub constraints on front wheel package
- Current method involves fitting larger tires
  - Will overpredict and over constrain targets
  - Data is limited compared to pure slip
- Fitting process involves scrub parameters
  - Only 4 parameters to fit total
  - Other parameters have already been fit

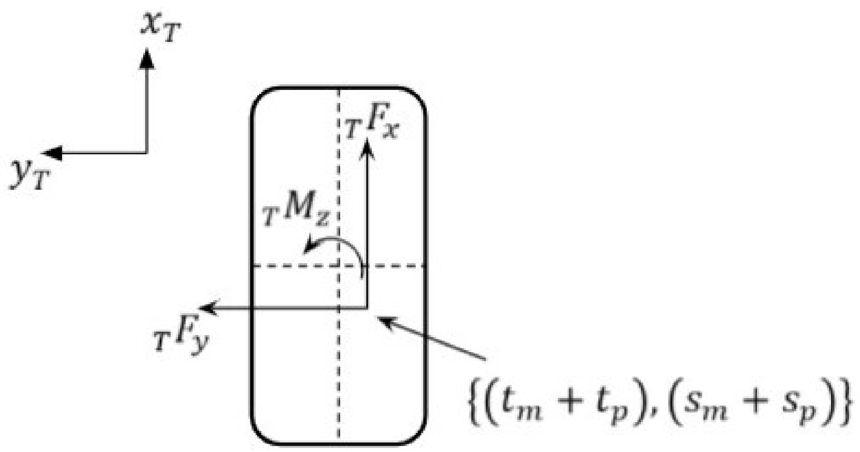

Figure 23: Combined aligning moment diagram

Thermal Tire Behavior

- Influential in force/moment generation
  - Changes how tire behavior generates
  - Creates pressure differences (impacts above)
- Tire Thermals are hard to compute
  - Very limited data (if any available)
  - Data to fit equations requires heat transfer properties
  - Many parameters to fit using these complex data sets
- Modelling will be hard to justify
  - Direction to be completed by end of sq

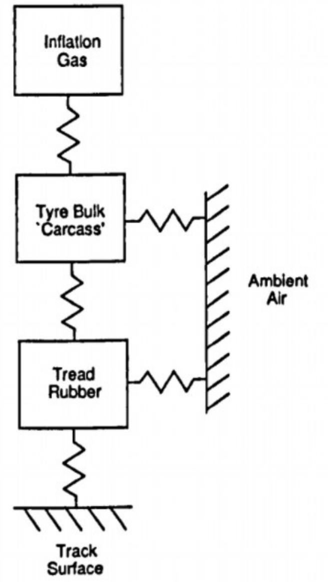

Figure 24: Thermal Schematic of Tire

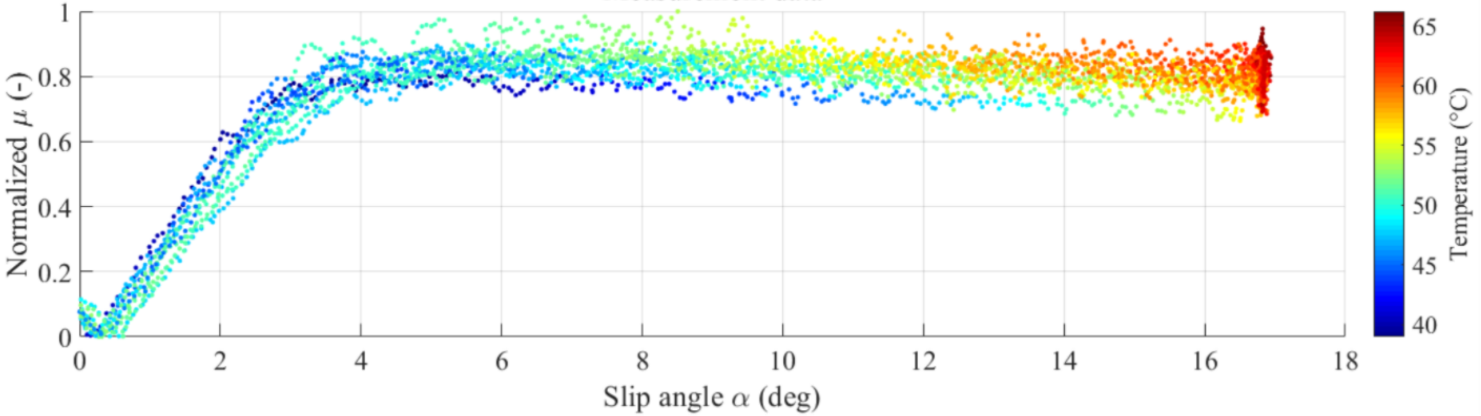

Figure 25: Coefficient of Friction vs Slip Angle

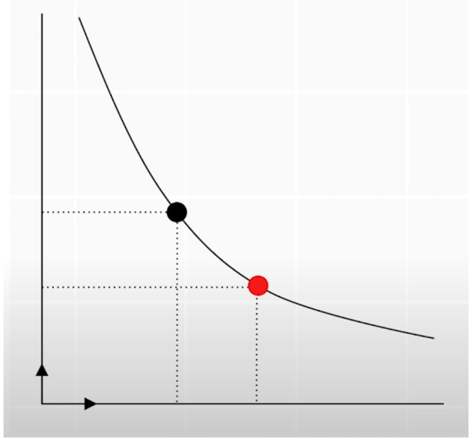

Figure 26: Grip vs Pressure Relationship

Tire Model Validation Needs

- Friction scaling between data and reality
  - Discrepancies in testing and racing surfaces
  - Test data overpredicts by $\mathrm{x}1.25 - \mathrm{x}1.6$
- Tires cannot be verified in isolation
  - Requires expensive testing infrastructure
- Other systems must be tightly controlled
  - Allows for system error to be clearly attributed to tire uncertainty

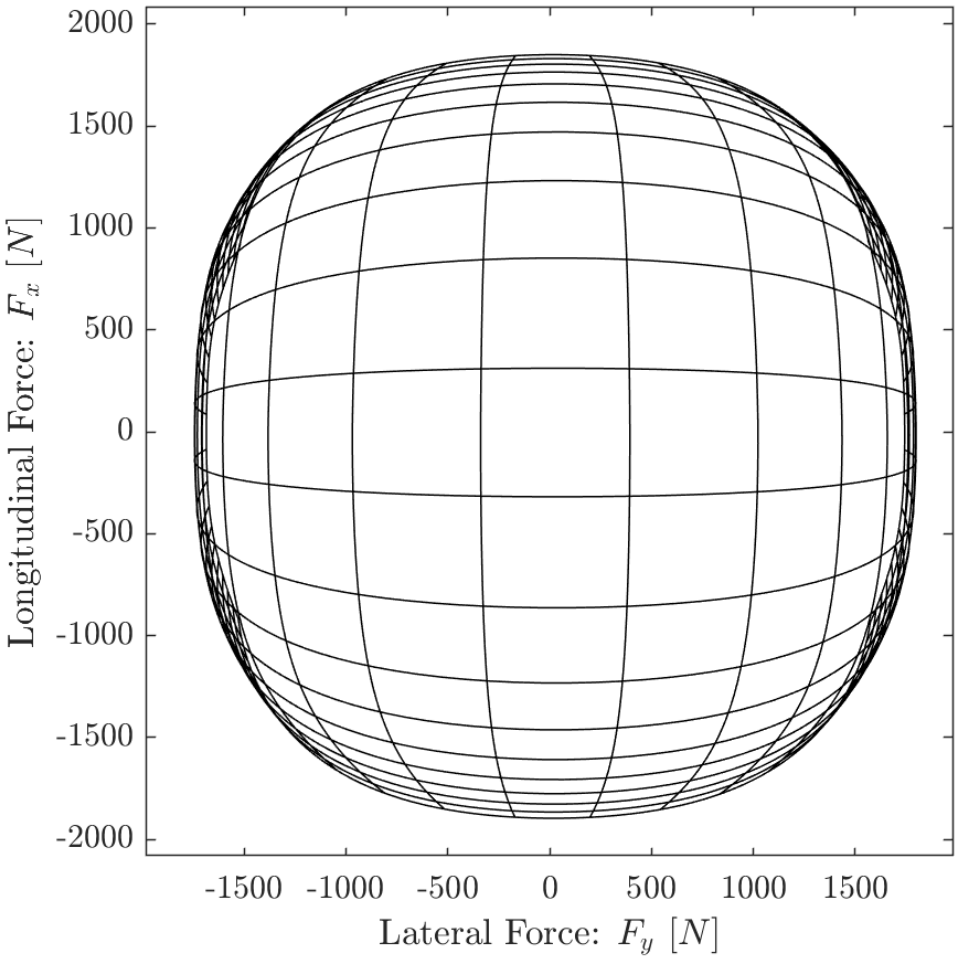

Figure 27: Friction Ellipse Example

Suspension and Chassis Dynamics

How do we represent the relationship of tire loads, suspension, and the body frame of the car?

Suspension and Chassis Overview

- Suspension and tire loads
  - Reaction forces affect tire loads
  - Tire load manipulated by suspension
- Chassis
  - Reacts to the loads from suspension
- Body coordinate frame
  - x axis parallel to car heading
  - y axis is normal to diver's side of the car
  - z axis is positive upwards

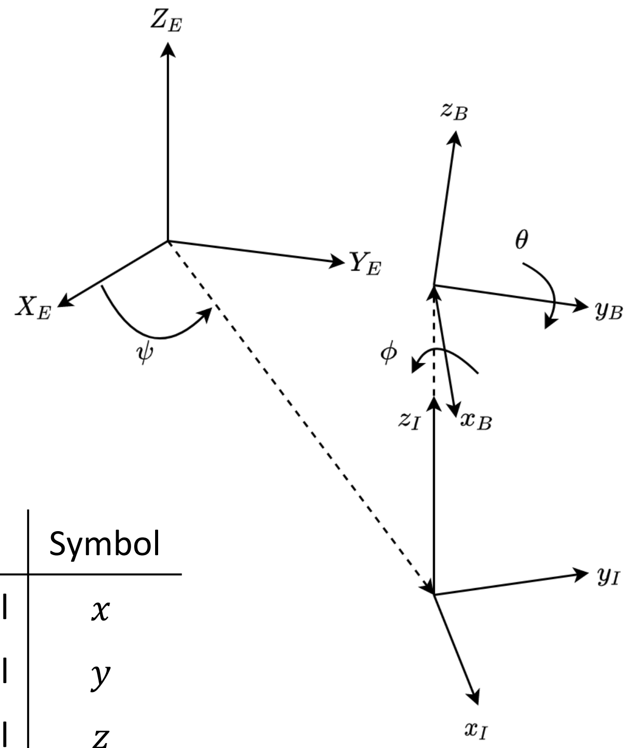

Figure 28: Body, Intermediate, and World Frames

Mode	Symbol
Longitudinal	x
Lateral	y
Vertical	z
Pitch	θ
Roll	ϕ
Yaw	ψ

Table 4: Chassis Mode Nomenclature

Underlying Physics

- Newton's laws govern reaction in the chassis
  - Tire loads from acceleration, braking, bumps
  - Aero loads
- Grip, balance, stability, & control
  - Grip and yaw moment
  - Quantifying stability and control
- Key decisions influenced by modeling
  - Mass distribution, center of gravity height, spring stiffness, wheelbase
- Suspension dynamics include jounce
  - Which are vertical DOFs which are coupled to chassis dynamics

Chassis & Suspension Modeling

3DOF Bicycle Model

- Basic yaw response
- Straight line performance
- Initial pitch and roll rates

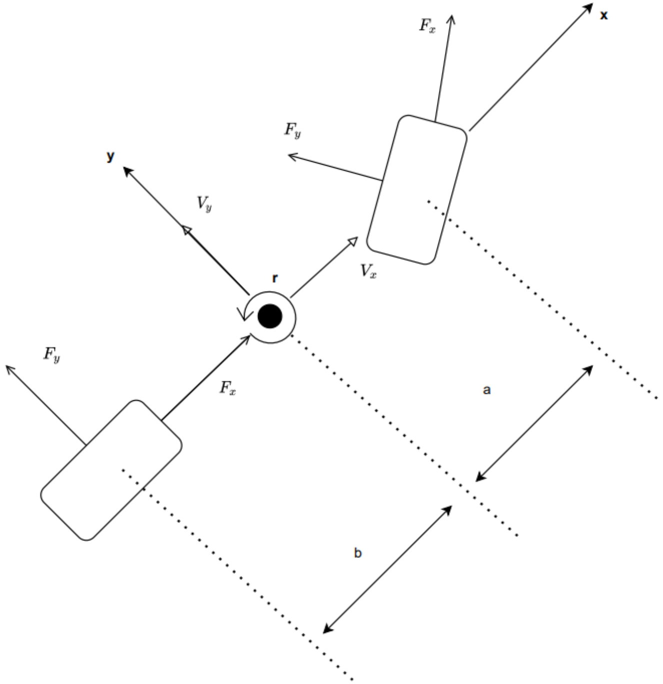

Figure 29: 3DOF Bicycle Model

Table 5: Chassis & Suspension Model Configurations

Model Name	Dynamics			Weight Transfer	Chassis Compliance
	Corner	Attitude	Planar		
10DOF FBRC	X	X	X	TD	
6DOF FBRC		X	X	RB	
5DOF Sampo		X	X	RB	X
4DOF Half Car	X	X		TD	
3DOF Table			X	RB	
3DOF Bicycle			X		

TD = Tire Deflection, RB = (Spring) Rate Based

Chassis & Suspension Modeling (2)

3DOF Table Model

- Lateral load transfer studies
- Initial Ackerman steering design

4DOF Half Car Model

- Brake & acceleration design
- Initial roll and pitch rate design

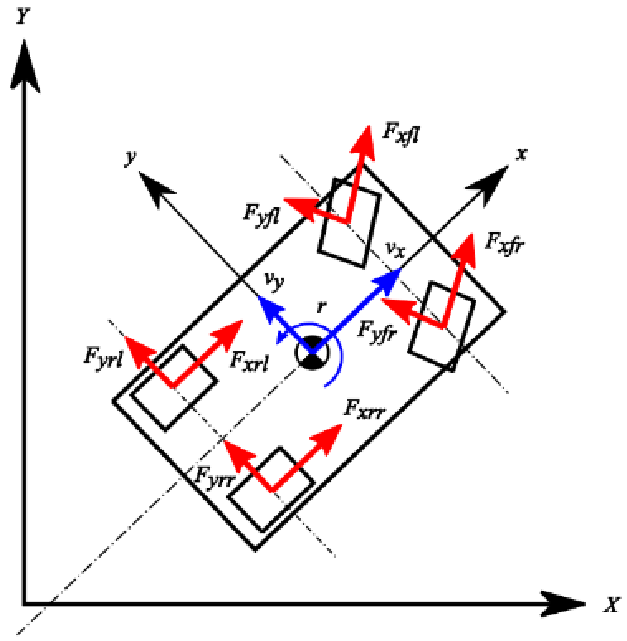

Figure 30: 3DOF Table Model[?]

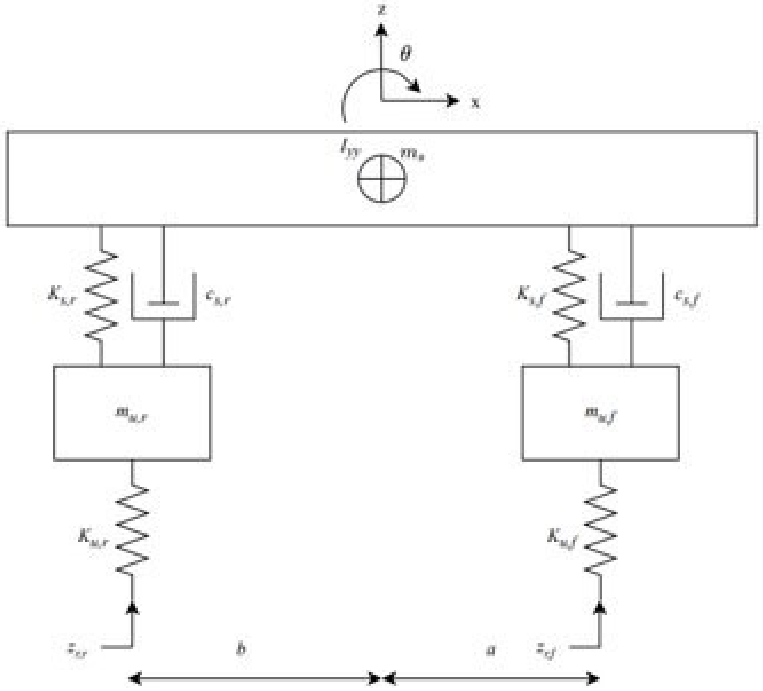

Figure 31: 4DOF Half Car Model

Chassis and Suspension Modeling (3)

5DOF Sampo Model

- Validate chassis torsional stiffness target

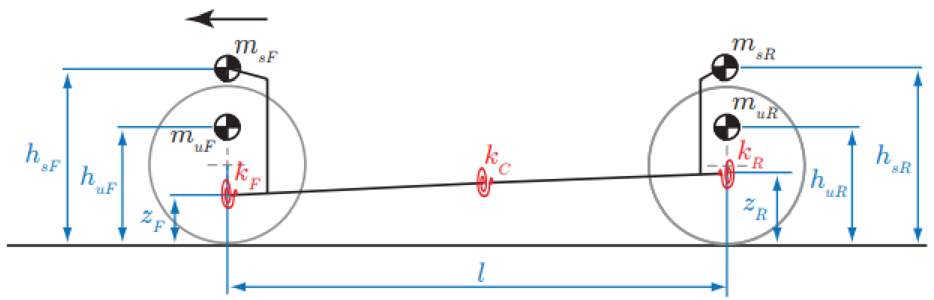

Figure 32: 5DOF Sampo Flexible Lateral Load Transfer Model[?]

6DOF Force Based Roll Center

- Lap Time Simulation

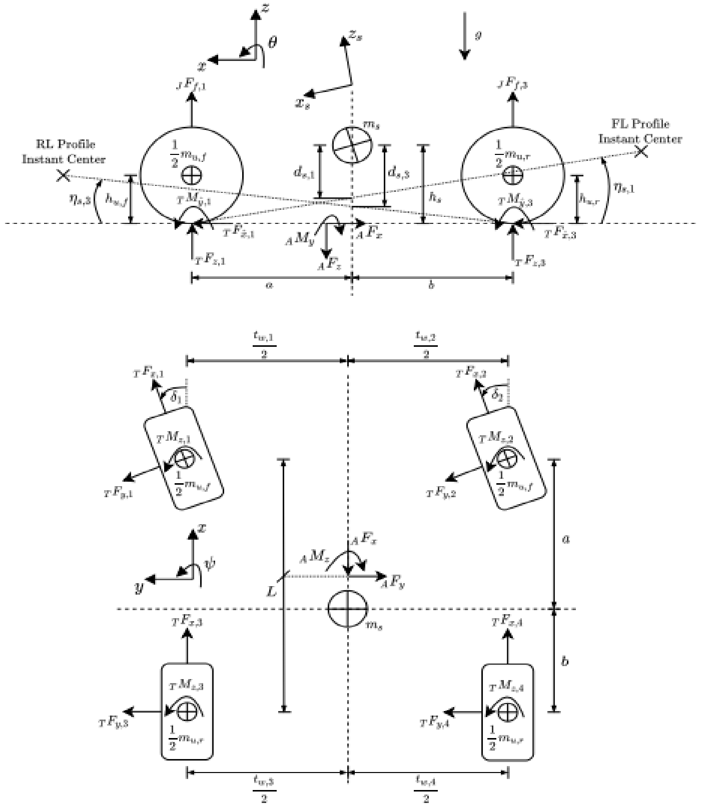

Figure 33: 6 DOF Force Based Roll Center Model

Chassis and Suspension Modeling (4)

10DOF Force Based Roll Center

- Suspension instant center design
- Final spring rates and damping design

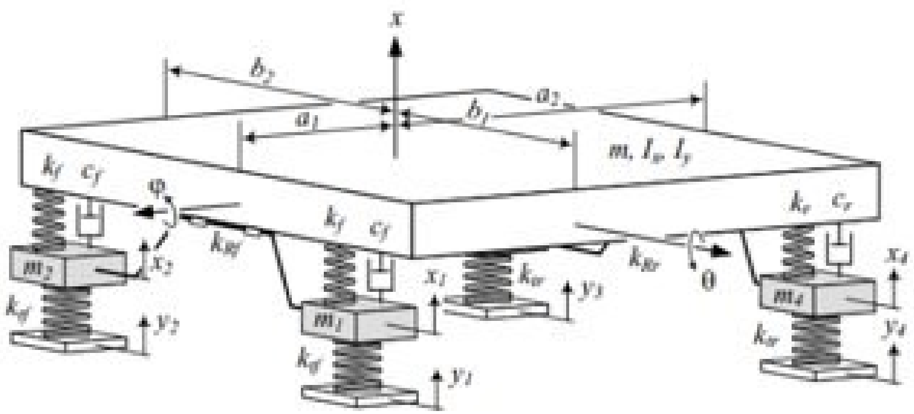

Figure 34: 10DOF Force Based Roll Center (FBRC) Model[6]

Resource Functions

- Advantages
  - Reusability
  - Flexibility
  - Standardized conventions
- Weight Transfer
- Kinematics Evaluation
- Jounce States
- Sprung Mass States
- WCS States

Controls Modeling

How is the driver integrated with the rest of the vehicle?

Controls Overview

Inboard Steering

Description	Symbol	Unit
Steering Torque	τ_{sw}	$[Nm]$
Pedal Displacement	δ_{sw}	$[deg]$
Rack Displacement	δ_r	$[m]$
Rack Force	F_r	$[N]$

Table 6: Steering State Nomenclature

- Models are very simplistic
- Incorporates nonlinear U-Joints

Brake System

Description	Symbol	Unit
Pedal Force	F_P	$[N]$
Pedal Displacement	θ_P	$[m]$
Line Pressure	$P_{b,i}$	$[MPa]$
Brake Torque	τ_B	$[Nm]$

Table 7: Brake State Nomenclature

- Models are very simplistic
- Use algebraic relationships to convert force into brake torque
- Displacements are currently unavailable (see next)

Open Ended Controls Modeling Questions

- Controls models are simplistic, but estimating parameters is not
  - Physics heavily depend on finicky friction parameters
- Steering nonlinearities have a large impact on feedback
  - Deadzones created by joint lash
  - Hysteresis from rack and column collar friction
- Braking pressure and pedal displacement are dependent on compliances
  - Hardlines and fluid compliance are reliably estimated
  - Softline compliance must be tested due to the complexity of softline construction

Powertrain Modeling

How is the power generated and distributed to the tire?

Powertrain Overview

- Differential modeling efforts have stalled
- Powertrain models will be oversimplified
- Will require major future efforts to provide justification for design parameters

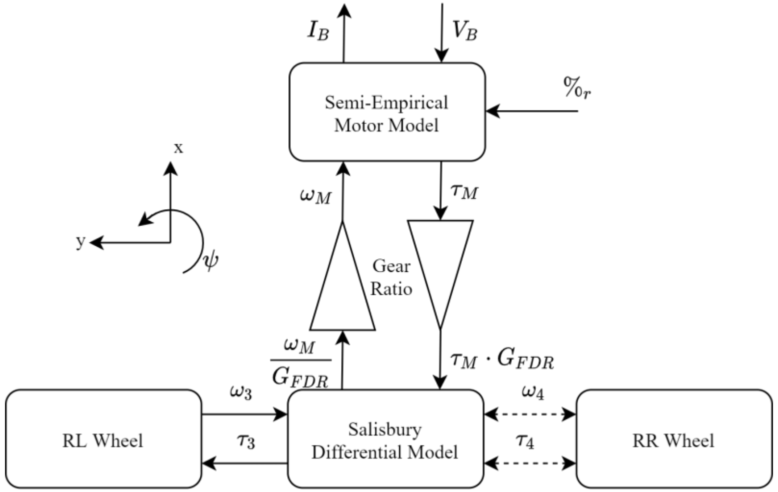

Figure 35: RWD Powertrain Block Diagram

Symbol	Description
V_B	Voltage Supplied to Motor
$\%_r$	Torque Request
I_B	Current Drawn by Motor
τ_A	Axle Torque
$\omega_{3,4}$	Left & Right Wheel Speeds
$\tau_{3,4}$	Left & Right Wheel Torque
ω_D	Rotation Speed of Differential
η_D	Differential Efficiency

Table 8: Powertrain Nomenclature Table

Integrated Simulation Platforms

How are vehicle models evaluated to characterize performance?

Performance Envelope Generation (1)

- Provides steady state performance envelope
  - Steady state is less expensive allowing for large studies
    - Enables vehicle level optimization (p>100)
- Plots Yaw Acceleration vs Lateral Acceleration
  - Mesh of body slip and steer and combinations
- Final oversteer and understeer
  - Limit stability & trim acceleration are easily marked

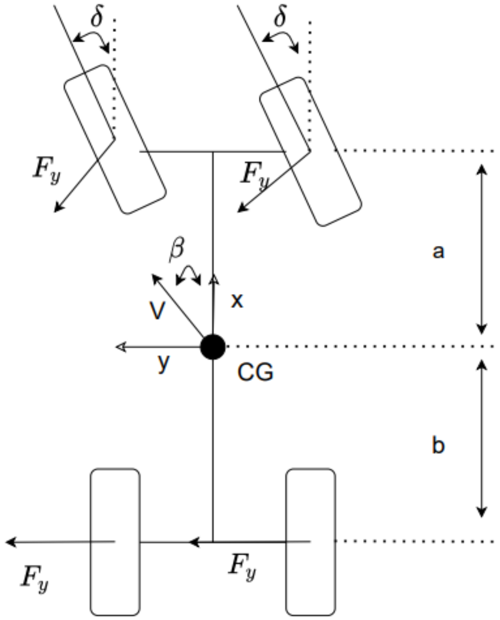

Figure 37: Body Slip Angle Diagram

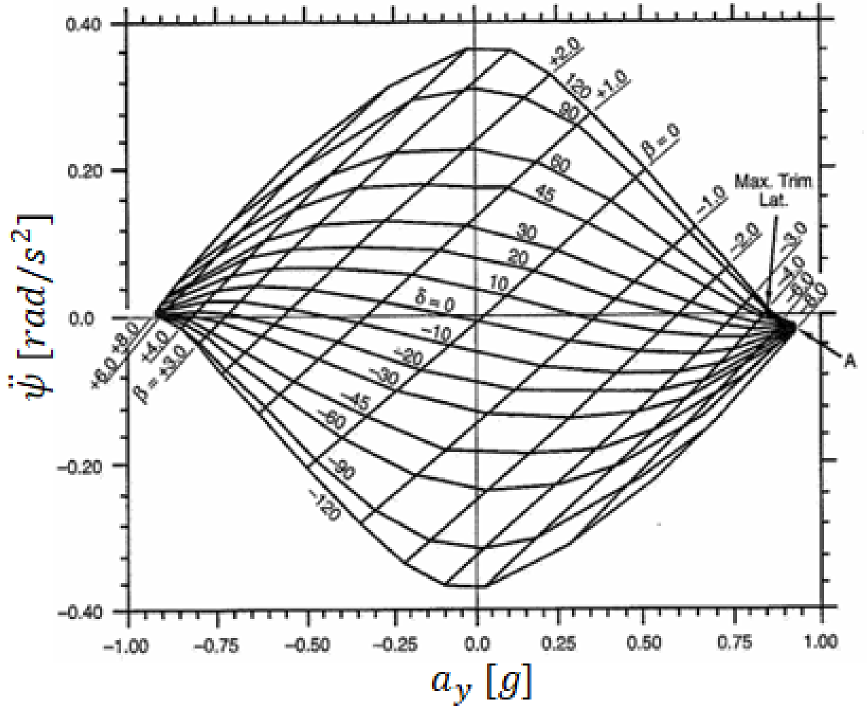

Figure 38: Typical MMM Diagram[?]

Symbol	Description
δ	Steering Wheel Angle
β	Vehicle Sideslip
a_y	Lateral Acceleration
$\ddot{\psi}$	Yaw Acceleration

Table 10: MMM Nomenclature Table

Performance Envelope Generation (2)

- Chassis
  - Chassis Dynamics, Sideslip
- Wheel and Tyre
  - Wheel Speeds, Tire Evaluation, Slip estimation
- Suspension
  - Kinematics and Compliances
- Controls
  - Driveline and Brakes
- Powertrain
  - Driveline and Brakes
- Aerodynamics

- Timeline
  - Debugging, adding more systems/models
  - Goal to have it running by end of quarter

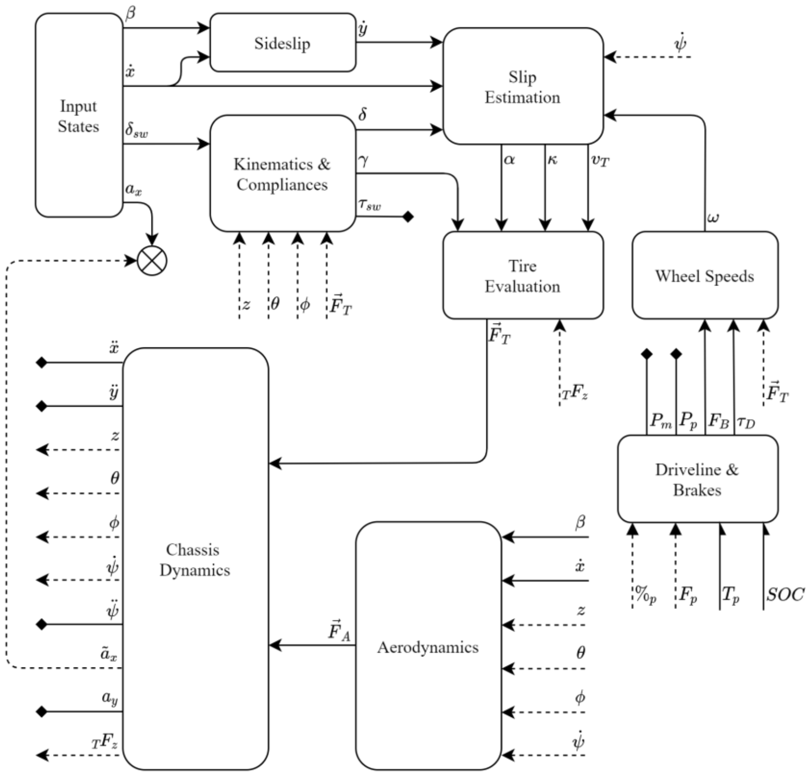

Figure 39: Vehicle Model Flowchart

Quasi-Transient Lap Time Simulation

- Leverages performance envelopes
- Solves planar curvilinear motion with a body slip
  - Fully addresses yaw dynamics
- Projected to simulate 5 sec / simulation
- More to come at the end of SQ

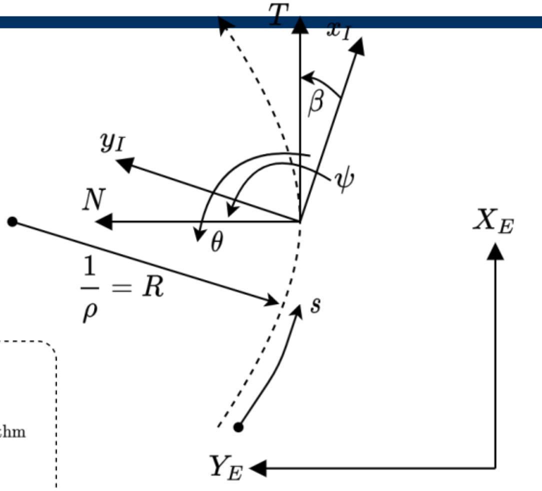

Figure 40: Curvilinear Motion

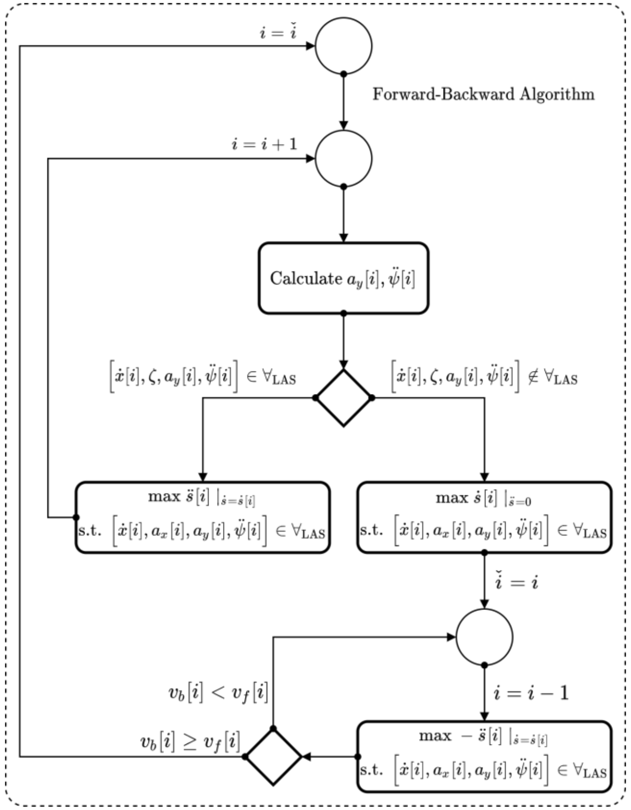

Figure 41: Stepping Solver

Summary

Recapping Actions on FE8 Goals

- Maximize knowledge transfer to ensure consistent VD growth
  - Season had the largest and most active VD subteam in FRUCD history
  - Next year will present challenges; however, VD is in a good place
- Expand VD knowledge across team for more integrated system design
  - Accomplished via All-Hands, and integration lectures
- Develop user-friendly vehicle simulation platforms to expediate design
  - Created more sustainable simulation software architecture
  - Did not finish implementation of a vehicle simulation platform
- Prepare future leads on how to correlate models with testing data
  - Not addressed completely, will be a focus in remaining time

Goals for VD

- Complete performance envelope generator
- Utilize senior design LTS tool to establish and justify vehicle concept
- Vehicle modeling platform will make dynamic simulation more accessible
    - Allows future efforts to be focused on specific thrusts instead of architecture

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