USING MODEL-BASED DESIGN FOR VEHICLE DYNAMIC SIMULATION

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6/23/2020

Project Background

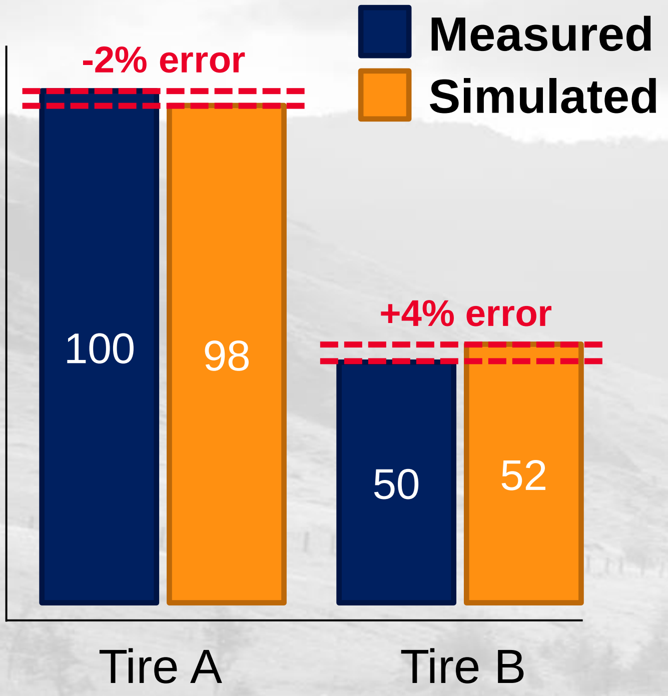
- Cooper Tire & Rubber Company
  - Sid Attravanam – Manager, Tire & Vehicle Dynamics
  - Bennett Norley – Engineer, Tire & Vehicle Dynamics

- **GOAL:** Reliably simulate on-track, vehicle maneuvers
  - Reduce product development cost and cycle time
  - Increase testing efficiency at our test track
  - Establish a predictive link between tire and vehicle test data

Vehicle dynamics simulation will predict vehicle performance from tire data

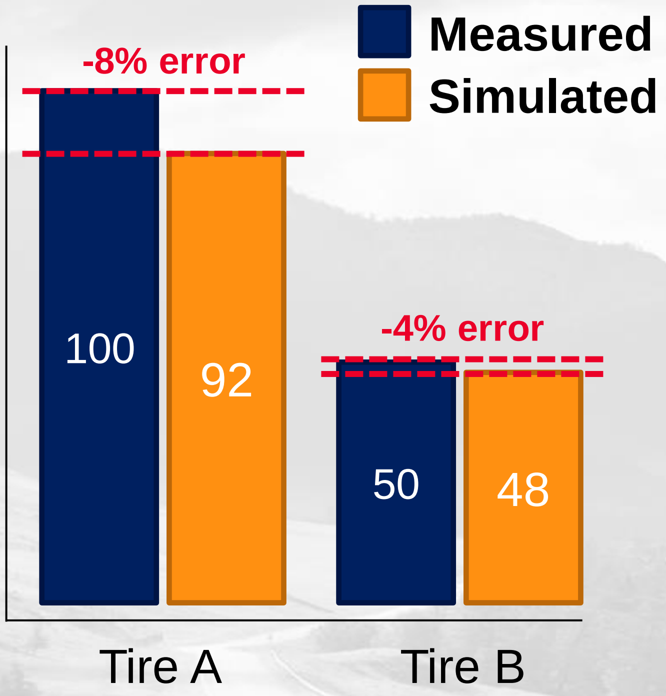
Is absolute magnitude the holy grail of simulation?

Absolute Magnitude Only



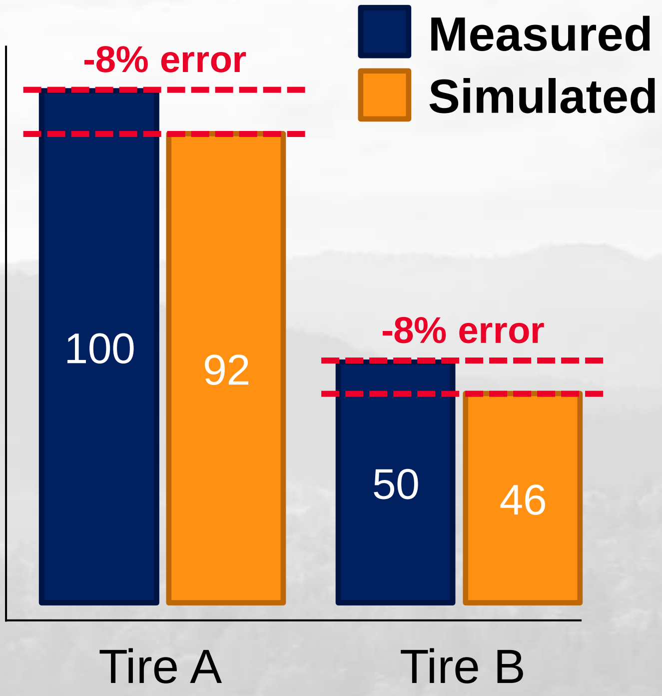
- < 5% simulated **error**
- Predicts the incorrect **rank order**

Including Rank Order



- < 10% simulated **error**
- Predicts the correct **rank order**
- Different simulated error **(delta)** for each tire

Including Delta



- <10% simulated **error**
- Predicts the correct **rank order**
- Same simulated error **(delta)** for each tire

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Prioritizing Rank Order

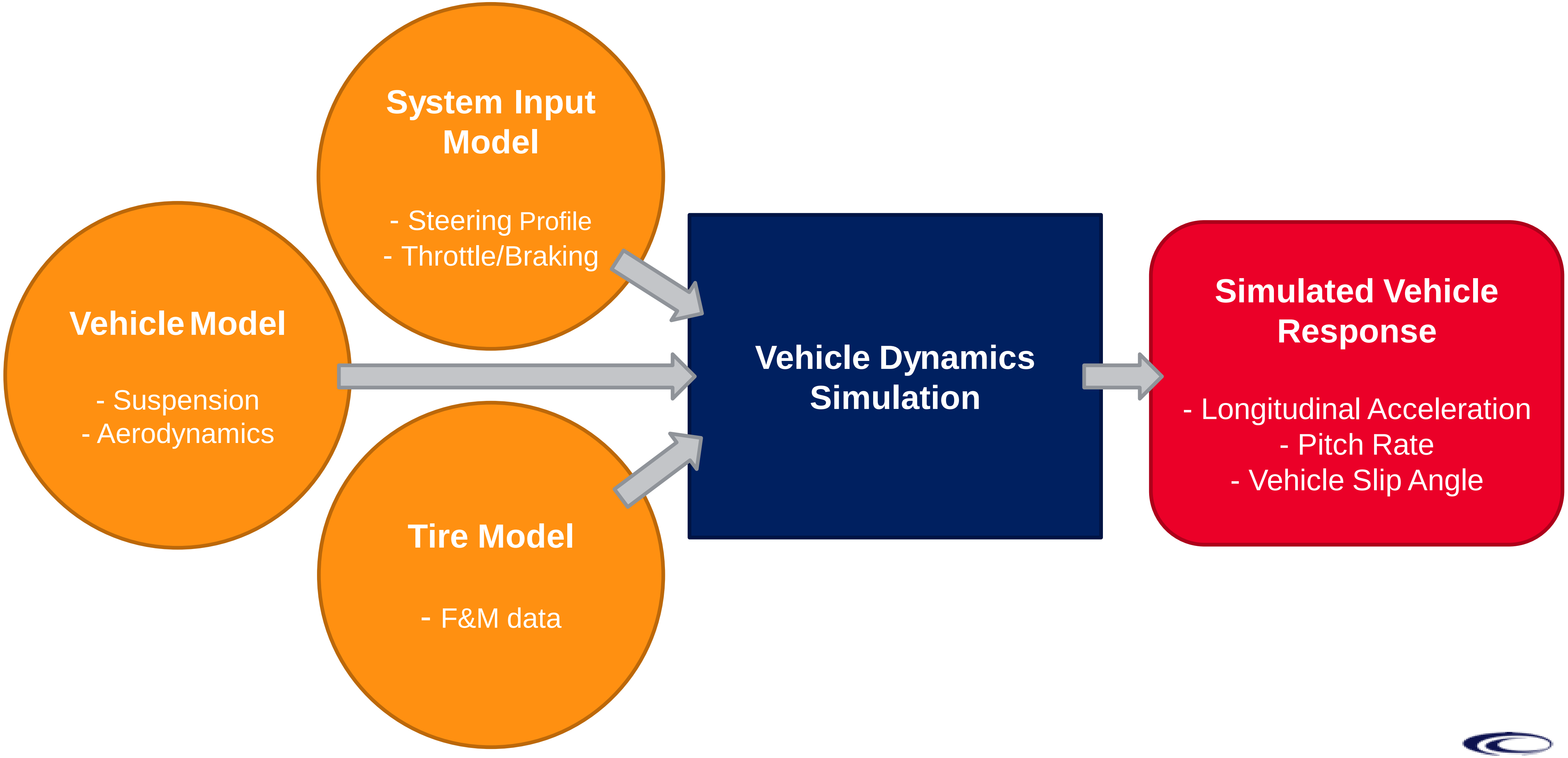
- Optimize ROIC for reliable simulation
  - "Chasing the last 5%" can be expensive and exhausting
  - Prioritize rank order, delta, and absolute magnitude
    - Accept slightly higher simulation error
    - For more reliable rank order
    - For more repeatable delta

Simulating multiple tires in the correct *rank order* → **Simulating repeatable *deltas* between tires** → **Simulating *magnitudes* absolutely**

First Priority | Second Priority | Third Priority

Rank Order > Delta > Absolute Magnitude

Simulation Flow Chart



Our Dilemma

- Issues developing a robust vehicle model
  - Rapid vehicle turnover in the replacement market
    - Need to continually characterize several vehicles
  - Unable to access OEM-specific subcomponent-level data
- Will require significant technical resources
- We need a simulation that gives us:
  - Visibility in the underlying models (not a black box system)
  - Easy-to-tune parameters (for sensitivity analyses)

Using existing vehicle simulation packages can be resource-intensive

MathWorks Collaboration

- Technical collaboration will greatly reduce development time

MathWorks will Provide

- Technical Support
- Software Licenses
  - Vehicle Dynamics Blockset
  - Powertrain Blockset
  - Model-Based Calibration Toolbox
  - Simulink Design Optimization
  - Much More

Cooper will Provide

- Testing data
- Tire and vehicle dynamics consultation
- Simulation validation

Phase 1

Longitudinal Vehicle Simulation (Braking)

Phase 2

Lateral (Constant Speed) Vehicle Simulation

Phase 3

Combined Maneuver Transient Simulation

Iteratively work on improving and modify existing models & software

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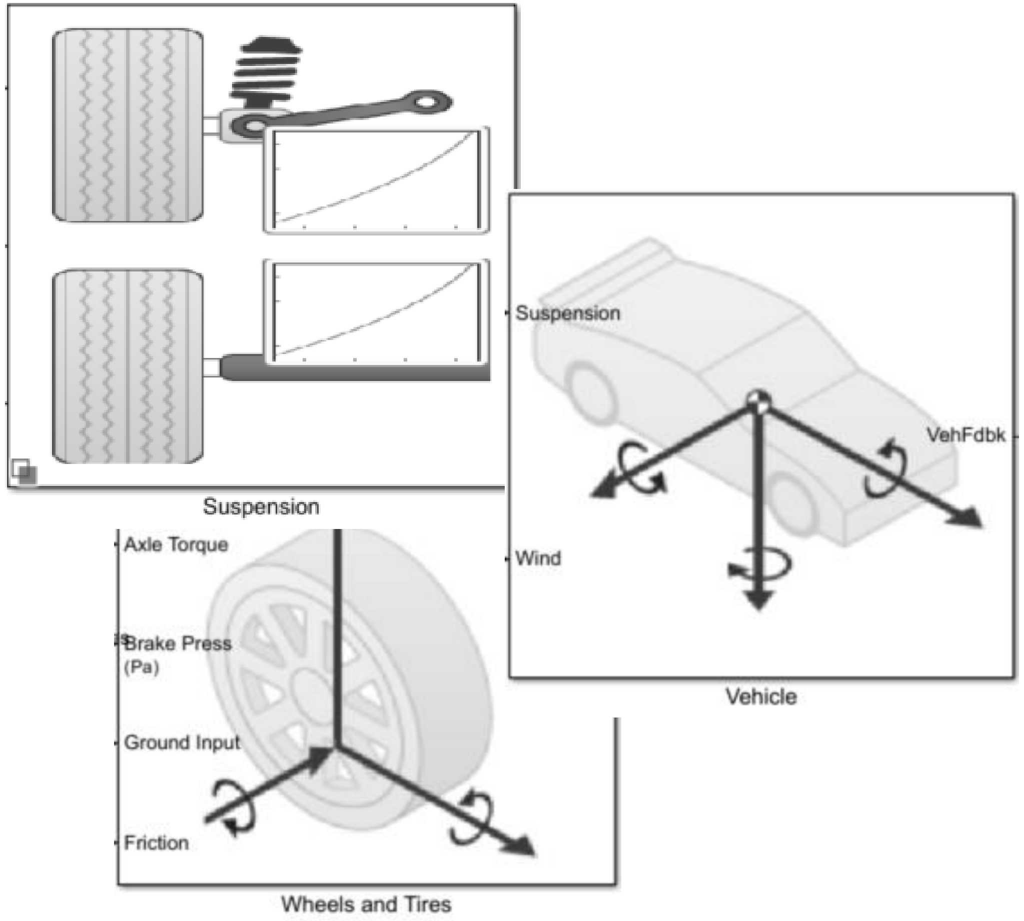
Vehicle Model

Vehicle Model Overview

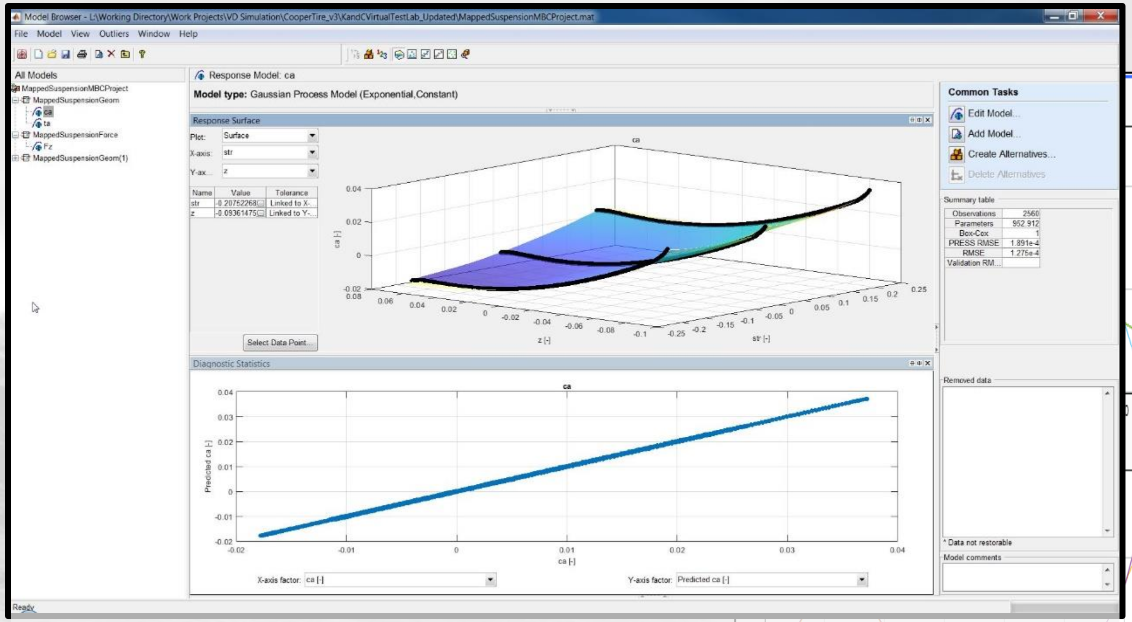
- MathWorks' Passenger Vehicle Model
  - 14 Degree of Freedom Model
    - Vectorized Tire Models
    - Customizable Suspension Kinematics
    - Integrated Friction and Scaling Effects
  - Ideal Mapped Engine Calibration
  - Tunable Steering, Transmission, Driveline, and Brake Models



- Parameterizing the Model
  - Cooper's internal suite of testing
    - 4-Post Shaker Rig Testing
    - Kinematic and Compliance Testing
    - Moment of Inertia Testing

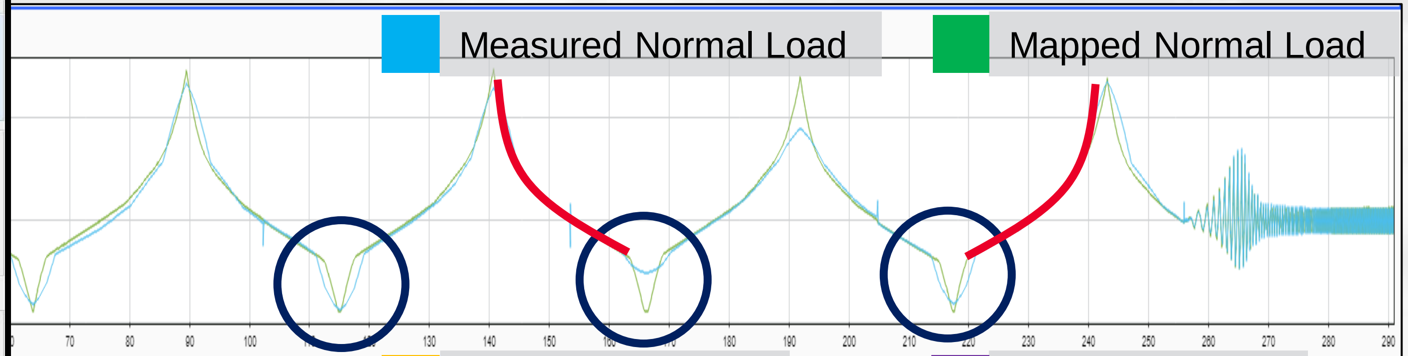
Figures taken from MathWorks' Jason Rodgers – Suspension Model Fitting Process Presentation

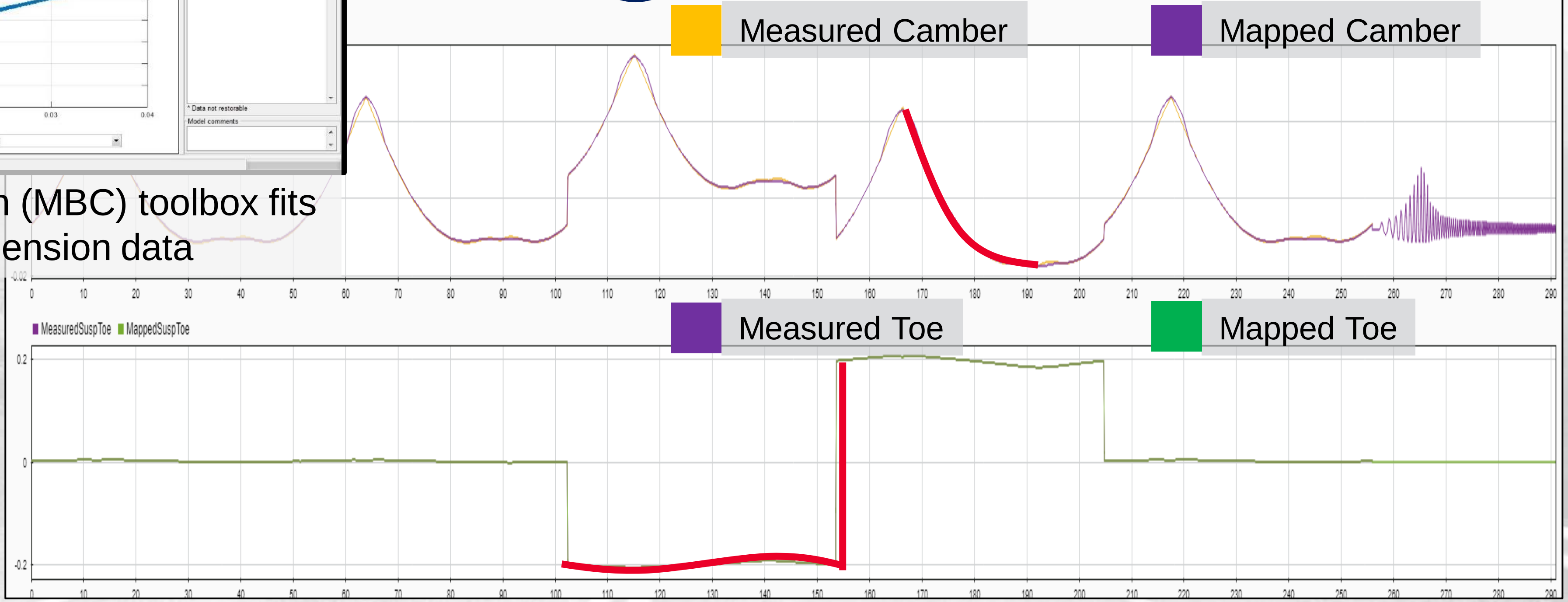
Model-Based Calibration Toolbox

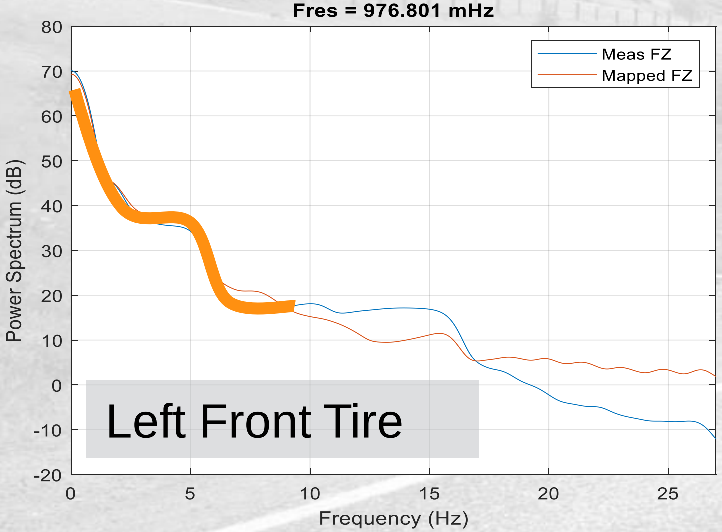


MathWorks' Model-Based Calibration (MBC) toolbox fits surface maps to vehicle suspension data

Good model fits **Model/Data Deviations** **Good fit up to 7 [Hz]**







Vehicle model fit to K&C & 4-post Shaker Rig Data

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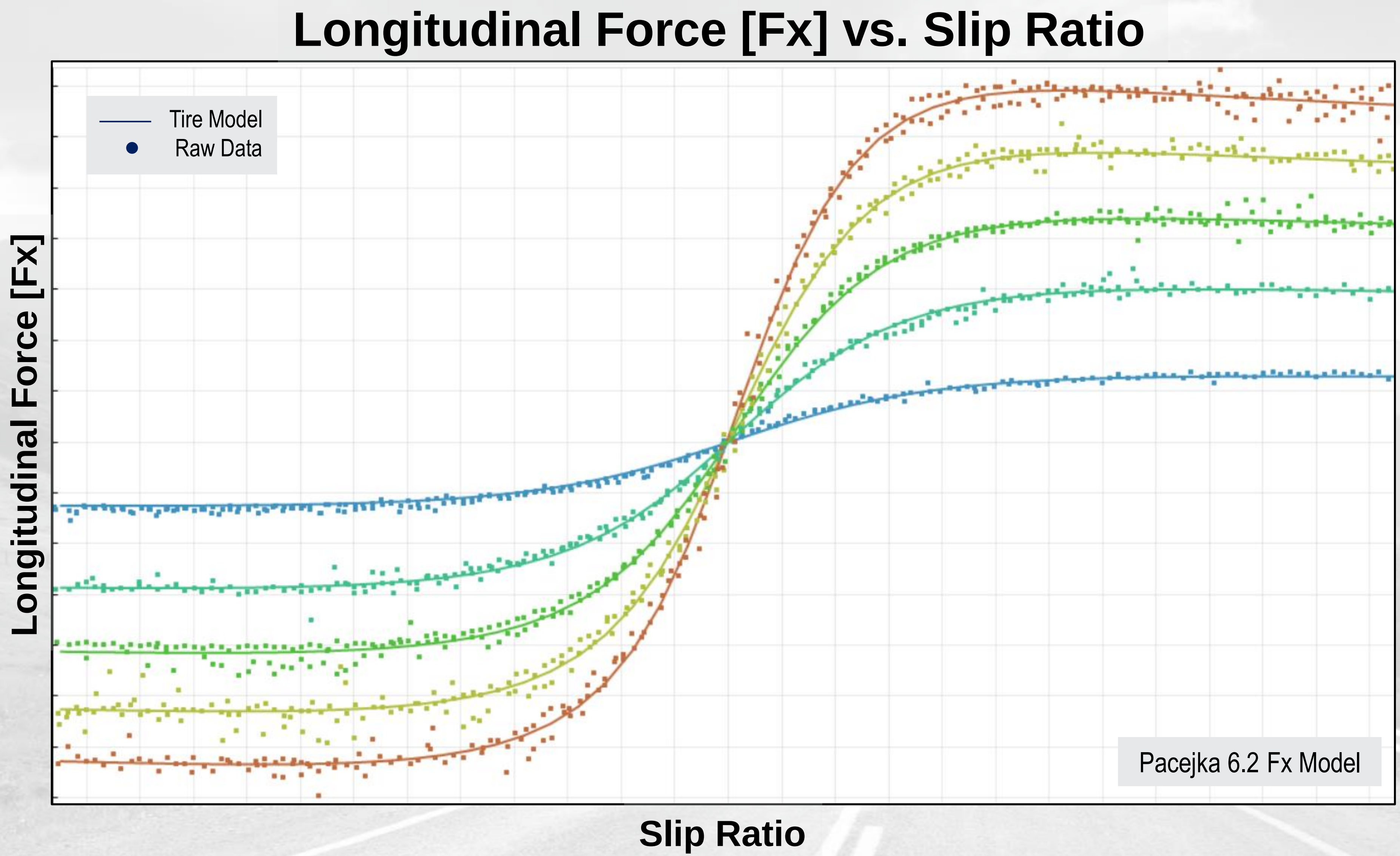
Tire Model

Tire Model Overview

- Tire Force and Moment (F&M) Testing
  - Measuring competitor tires
    - Larger presumed difference in data
  - Highlighting longitudinal properties of the tire
- Collecting wheel force transducer and tire temperature data
  - Use with on-track results for surface normalization
- Modeled with Pacejka Magic Formula 6.2 Tire Model
- Imported into simulation via *.TIR files

The input to the vehicle dynamics simulation is *.TIR Files

Tire Model Example



Example of Longitudinal Force vs. Slip Ratio Tire Model

Running the Simulation

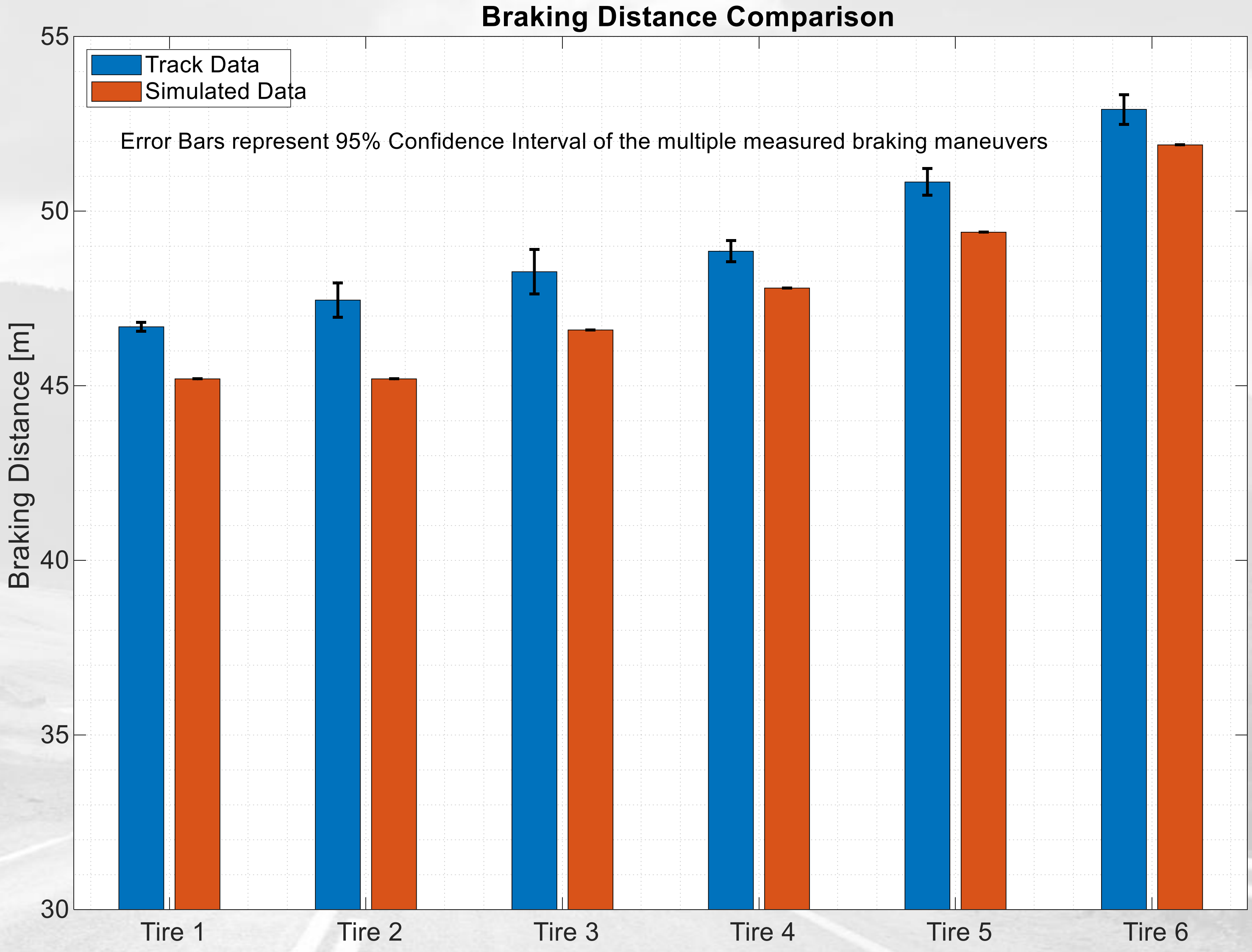
Running the Simulation Overview

- Input
  - Tire Model – fit from tire force and moment data
  - System Input Model – driver commands from Cooper braking test
  - Vehicle Model – fit from K&C, Moment of Inertia, 4-post Shaker Rig data
- Output
  - Vehicle response under braking
  - Tire response under braking
- Simulation Validation
  - Validated against real world braking data
  - Used Wheel Force Transducers for surface normalization

Simulation set to mimic Cooper's on-track braking procedure

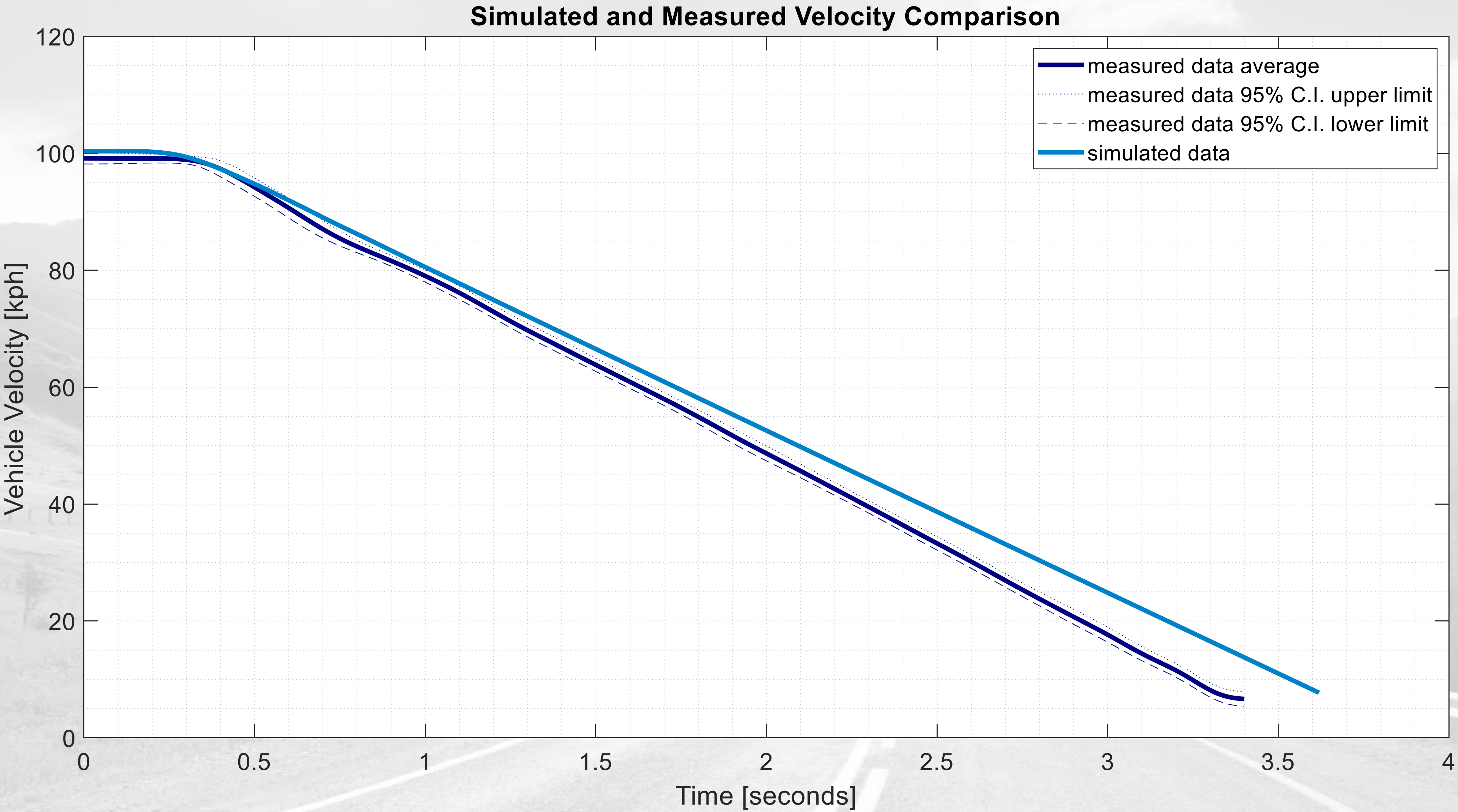
Initial Simulation Results – Braking Distances

	Measured Braking Distance [m]	Simulated Braking Distance [m]	Simulation Error [%]
Tire 1	47.2	45.2	4.4
Tire 2	48.0	45.2	6.1
Tire 3	48.3	46.6	3.6
Tire 4	48.4	47.8	1.2
Tire 5	50.8	49.4	2.9
Tire 6	52.9	51.9	2.0



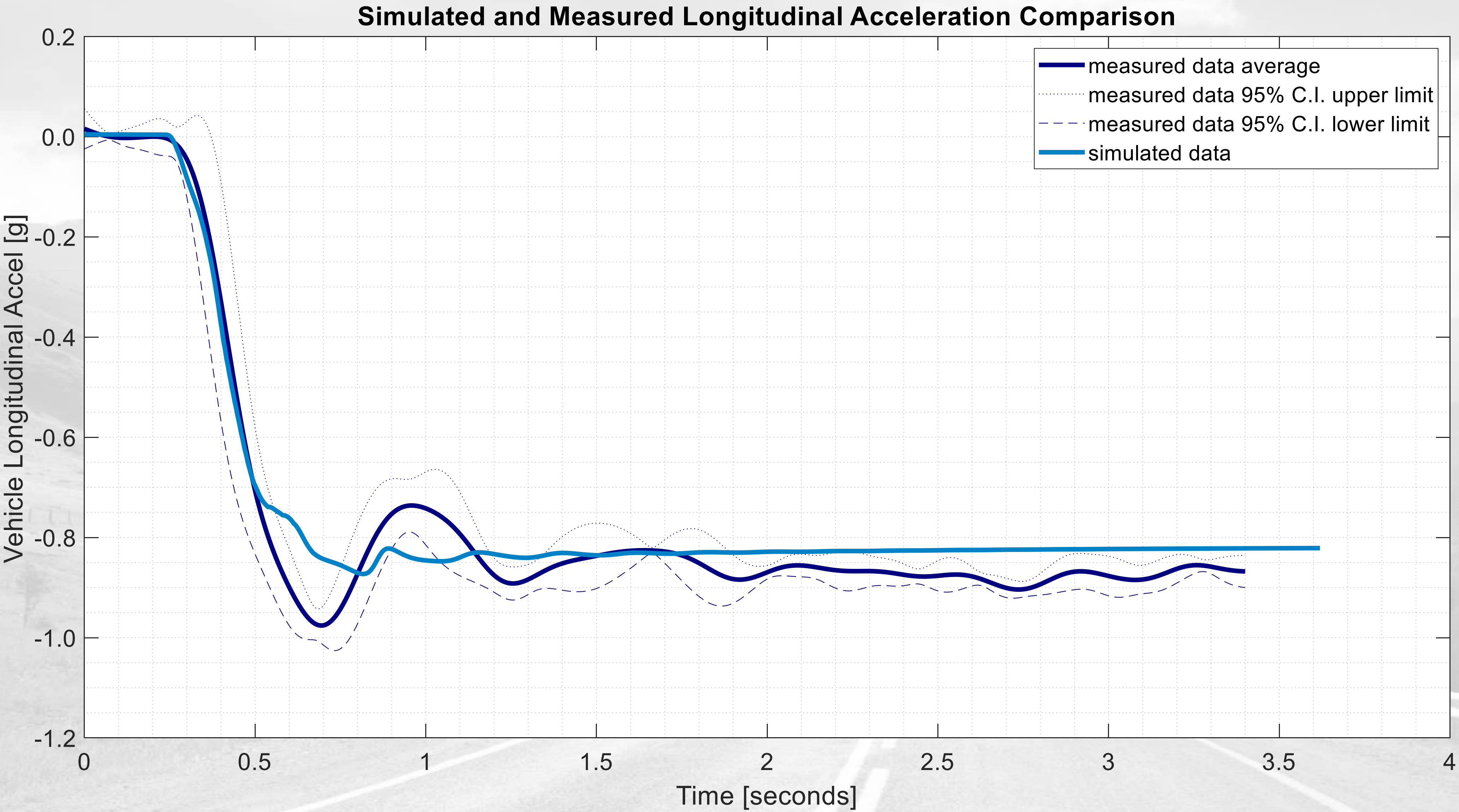
Error bars represent: 2x Standard Error

Initial Simulation Results – Vehicle Response: VELOCITY



Error bars represent: 95% Confidence Interval of Track Data

Initial Simulation Results – Vehicle Response: LONGITUDINAL ACCELERATION



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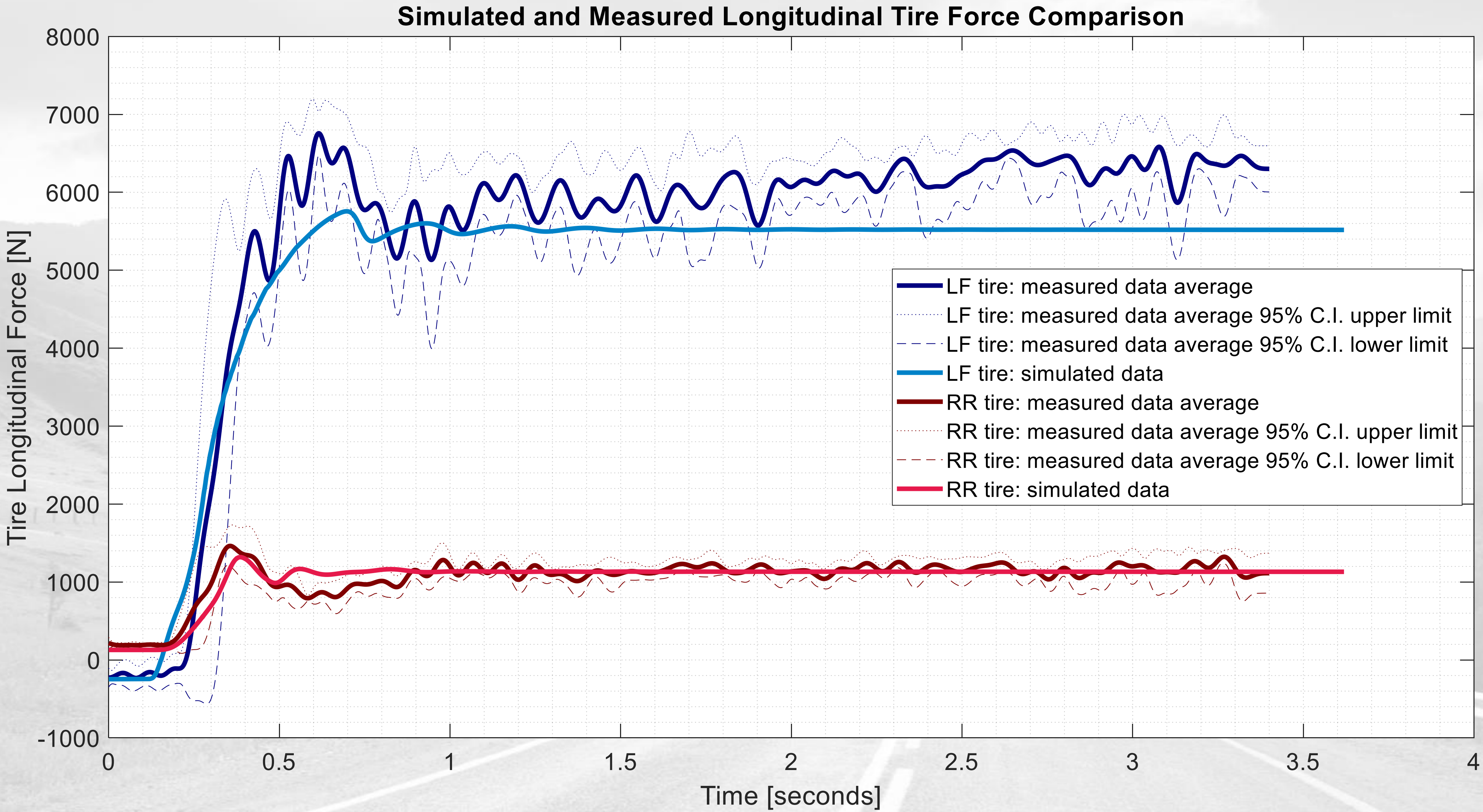
Initial Simulation Results – Tire Response: LONGITUDINAL FORCE



Error bars represent: 95% Confidence Interval of Track Data

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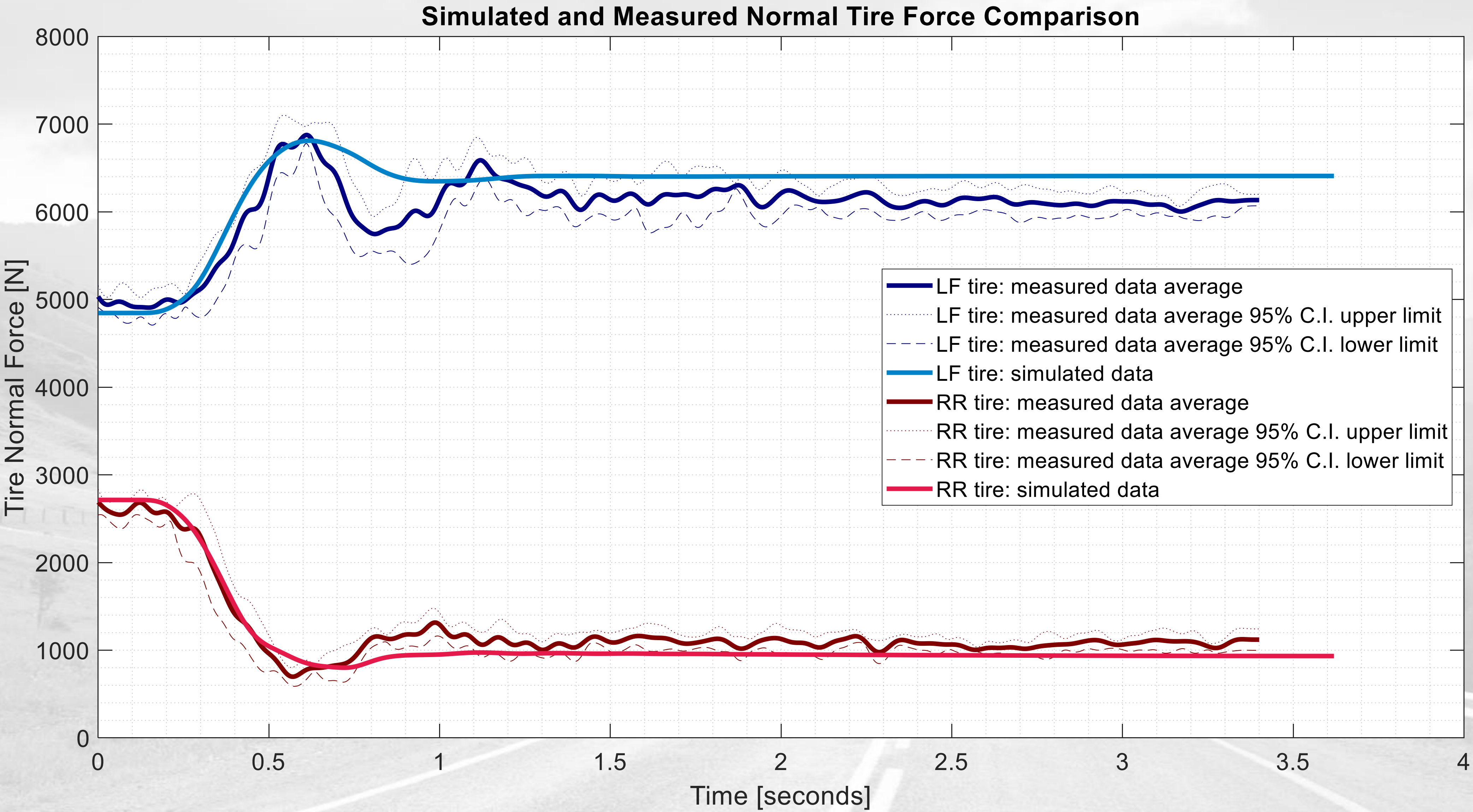
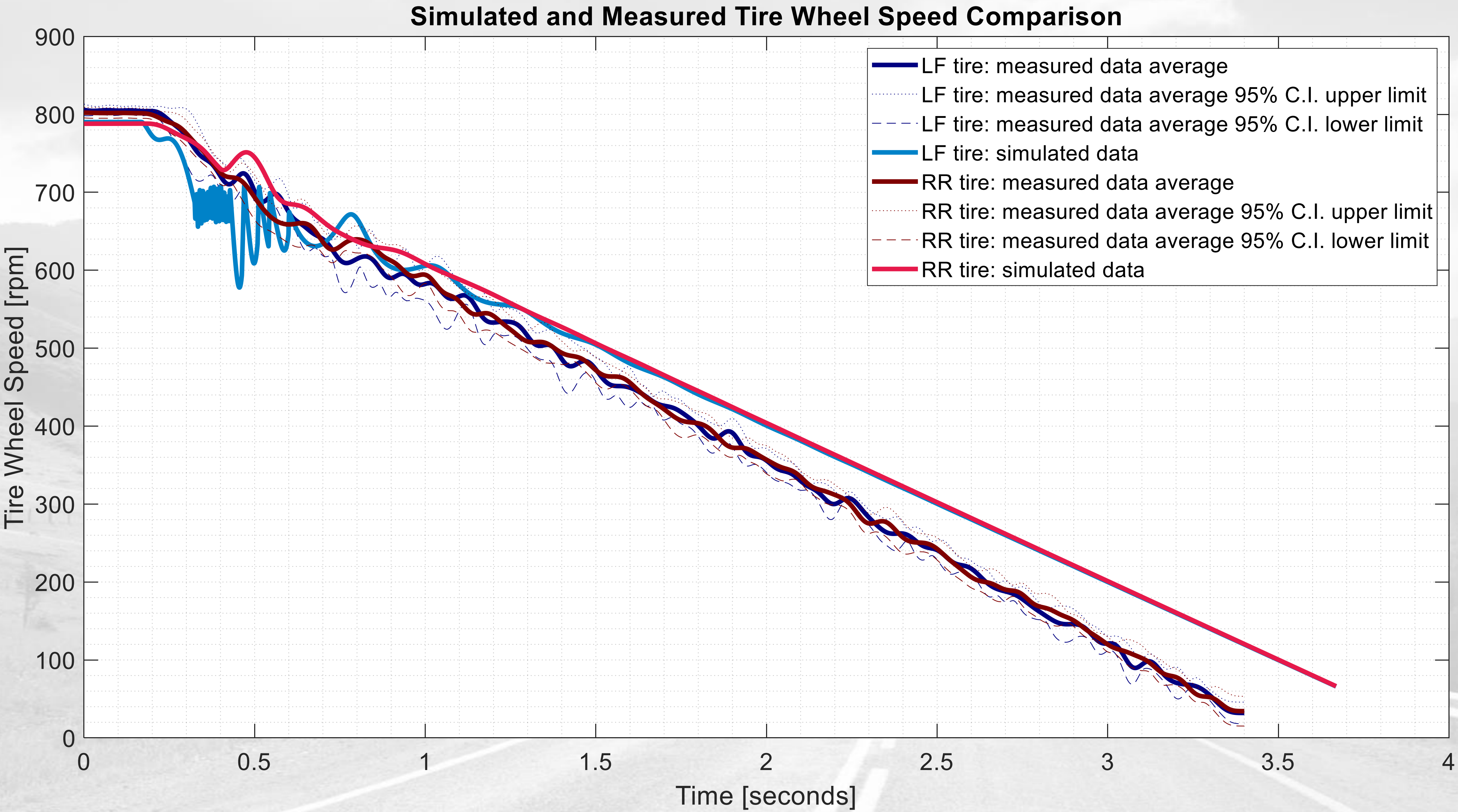
Initial Simulation Results – Tire Response: NORMAL FORCE



Error bars represent: 95% Confidence Interval of Track Data

Initial Simulation Results – Tire Response: WHEEL SPEED



Error bars represent: 95% Confidence Interval of Track Data

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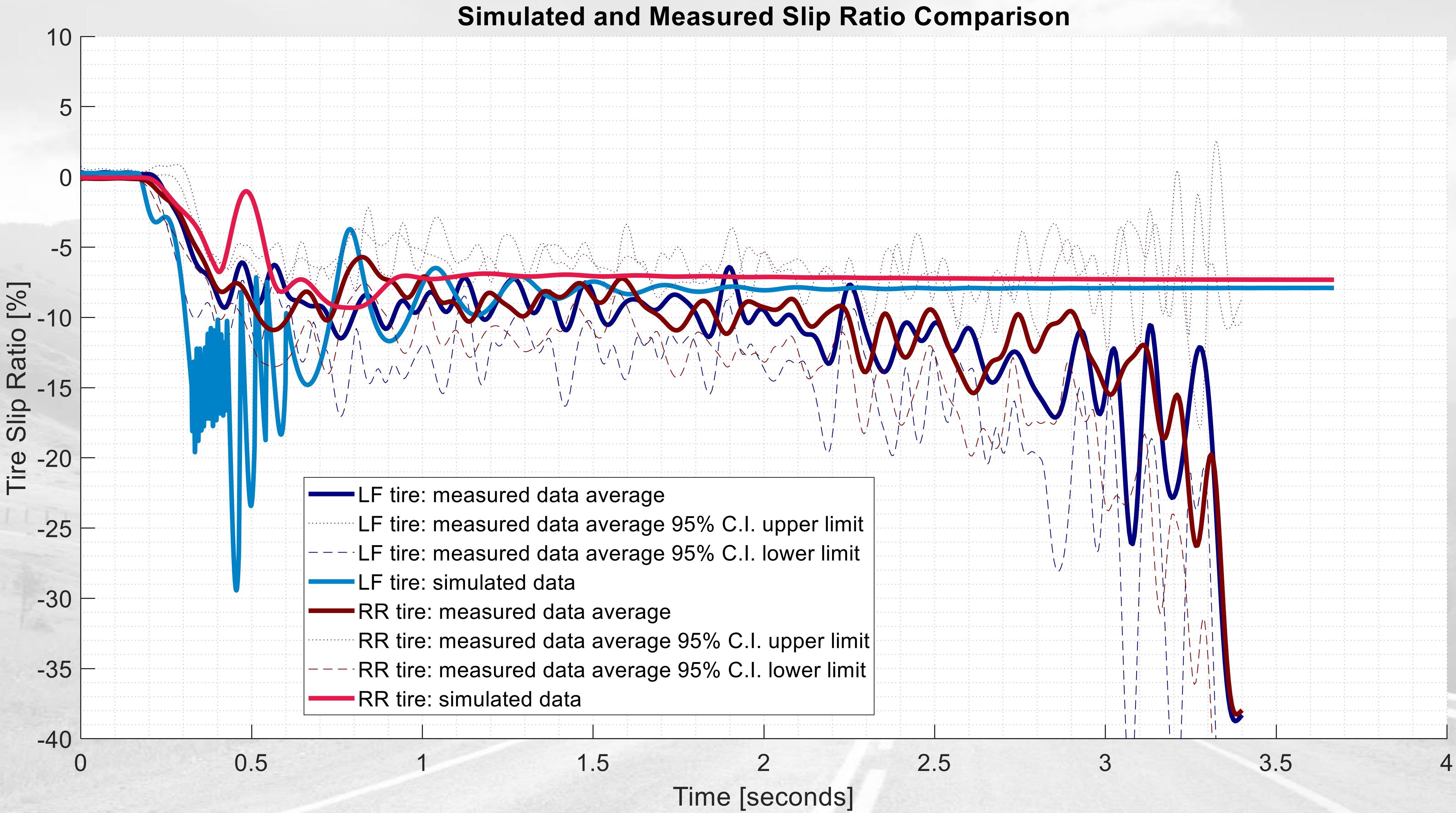
Initial Simulation Results – Tire Response: SLIP RATIO



Error bars represent: 95% Confidence Interval of Track Data

Tuning the Vehicle Model

- Iterative and Ongoing

Macro-Level Model Tuning

- Ensuring underlying physics are sound
  e.g. Damper Curve Fitting
- Checking interactions between tires and vehicles
  e.g. Vehicle and Tire Model Coordinate Frames
- Validating mathematical equations
  e.g. Toe angle and Weight Distribution

Micro-Level Model Tuning

- Populating individual system parameters
  e.g. Brake Pad Parameters, Tire Scaling Factors
- Using the Simulink Design Optimization Toolbox
  e.g. Parameter Estimation and Sensitivity Analysis

Going Forward

- Continue Micro-Level Tuning
  - Sensitivity Analysis on input parameters
    - Are they relevant?
  - Estimate parameters that are not easily measured
- Determine error band for simulated values
  - How does the error compound in the simulation?
- More measured data validation
  - Varying braking and ambient conditions
- Expand to additional test maneuvers
  - Lateral, open-loop maneuvers

Next Steps will be model tuning and parameter estimation

Summary

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THANK YOU
Questions?