• 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
Is absolute magnitude the holy grail of simulation?

**Absolute Magnitude Only**

- Tire A:
  - Measured: 100
  - Simulated: 50
  - Error: -2% (measured: 98)

- Tire B:
  - Measured: 98
  - Simulated: 52
  - Error: +4% (measured: 92)

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

**Including Rank Order**

- Tire A:
  - Measured: 100
  - Simulated: 50
  - Error: -8% (measured: 92)

- Tire B:
  - Measured: 92
  - Simulated: 48
  - Error: -4% (measured: 46)

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

**Including Delta**

- Tire A:
  - Measured: 100
  - Simulated: 50
  - Error: -8% (measured: 92)

- Tire B:
  - Measured: 92
  - Simulated: 46
  - Error: -8% (measured: 46)

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

Prioritizing Rank Order

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**
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)
MathWorks Collaboration

- Technical collaboration will greatly reduce development time

<table>
<thead>
<tr>
<th>MathWorks will Provide</th>
<th>Cooper will Provide</th>
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<tbody>
<tr>
<td>• Technical Support</td>
<td>• Testing data</td>
</tr>
<tr>
<td>• Software Licenses</td>
<td>• Tire and vehicle dynamics consultation</td>
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<tr>
<td>• Vehicle Dynamics Blockset</td>
<td>• Simulation validation</td>
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<td>• Powertrain Blockset</td>
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<td>• Model-Based Calibration Toolbox</td>
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<td>• Simulink Design Optimization</td>
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<td>• Much More</td>
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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
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
Figure 1: Model-Based Calibration Toolbox

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

Good model fits

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

Longitudinal Force [$F_x$] vs. Slip Ratio

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

<table>
<thead>
<tr>
<th></th>
<th>Measured Braking Distance [m]</th>
<th>Simulated Braking Distance [m]</th>
<th>Simulation Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire 1</td>
<td>47.2</td>
<td>45.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Tire 2</td>
<td>48.0</td>
<td>45.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Tire 3</td>
<td>48.3</td>
<td>46.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Tire 4</td>
<td>48.4</td>
<td>47.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Tire 5</td>
<td>50.8</td>
<td>49.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Tire 6</td>
<td>52.9</td>
<td>51.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Error bars represent: 2x Standard Error
Initial Simulation Results – Vehicle Response: VELOCITY

Simulated and Measured Velocity Comparison

Error bars represent: 95% Confidence Interval of Track Data
Initial Simulation Results – Vehicle Response: LONITUDINAL ACCELERATION

Simulated and Measured Longitudinal Acceleration Comparison

- Error bars represent: 95% Confidence Interval of Track Data
Initial Simulation Results – Tire Response: LONGTUDINAL FORCE

Simulated and Measured Longitudinal Tire Force Comparison

Error bars represent: 95% Confidence Interval of Track Data
Initial Simulation Results – Tire Response: NORMAL FORCE

Simulated and Measured Normal Tire Force Comparison

- Error bars represent: 95% Confidence Interval of Track Data
Simulated and Measured Tire Wheel Speed Comparison

Error bars represent: 95% Confidence Interval of Track Data
Initial Simulation Results – Tire Response: SLIP RATIO

Simulated and Measured Slip Ratio Comparison

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
• 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
• **GOAL:** Reliably simulate on-track, vehicle maneuvers
  • Reduce product development cost and cycle time
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  • Establish a predictive link between tire and vehicle test data
THANK YOU
Questions?