USING MODEL-BASED DESIGN FOR VEHICLE DYNAMIC SIMULATION

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• Cooper Tire & Rubber Company
  • Sid Attravanam – Manager, Tire & Vehicle Dynamics
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• **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: 98
  - Error: -2% error

- **Tire B**
  - Measured: 50
  - Simulated: 52
  - Error: +4% error

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

### Including Rank Order

- **Tire A**
  - Measured: 100
  - Simulated: 92
  - Error: -8% error

- **Tire B**
  - Measured: 50
  - Simulated: 48
  - Error: -4% error

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

### Including Delta

- **Tire A**
  - Measured: 100
  - Simulated: 92
  - Error: -8% error

- **Tire B**
  - Measured: 50
  - Simulated: 46
  - Error: -8% error

- <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**

- **First Priority**: Simulating multiple tires in the correct *rank order*
- **Second Priority**: Simulating repeatable *deltas* between tires
- **Third Priority**: Simulating *magnitudes* absolutely

*Rank Order > Delta > Absolute Magnitude*
Simulation Flow Chart

Vehicle Model
- Suspension
- Aerodynamics

System Input Model
- Steering Profile
- Throttle/Braking

Tire Model
- F&M data

Vehicle Dynamics Simulation

Simulated Vehicle Response
- Longitudinal Acceleration
- Pitch Rate
- Vehicle Slip Angle
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

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
Vehicle Model
• 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
MathWorks’ Model-Based Calibration (MBC) toolbox fits surface maps to vehicle suspension 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
Tire Model Example

Example of Longitudinal Force vs. Slip Ratio Tire Model

Longitudinal Force \([F_x]\) vs. Slip Ratio

Pacejka 6.2 Fx Model
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>Tire</th>
<th>Measured Braking Distance [m]</th>
<th>Simulated Braking Distance [m]</th>
<th>Simulation Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.2</td>
<td>45.2</td>
<td>4.4</td>
</tr>
<tr>
<td>2</td>
<td>48.0</td>
<td>45.2</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>48.3</td>
<td>46.6</td>
<td>3.6</td>
</tr>
<tr>
<td>4</td>
<td>48.4</td>
<td>47.8</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>50.8</td>
<td>49.4</td>
<td>2.9</td>
</tr>
<tr>
<td>6</td>
<td>52.9</td>
<td>51.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Error bars represent: 2x Standard Error

### Braking Distance Comparison

Error Bars represent 95% Confidence Interval of the multiple measured braking maneuvers.
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: LONGITUDINAL ACCELERATION

Simulated and Measured Longitudinal Acceleration Comparison

Error bars represent: 95% Confidence Interval of Track Data
Initial Simulation Results – Tire Response: LONGITUDINAL 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
Initial Simulation Results – Tire Response: WHEEL SPEED

Simulated and Measured Tire Wheel Speed Comparison

- LF tire: measured data average
- LF tire: measured data average 95% C.I. upper limit
- LF tire: measured data average 95% C.I. lower limit
- LF tire: simulated data
- RR tire: measured data average
- RR tire: measured data average 95% C.I. upper limit
- RR tire: measured data average 95% C.I. lower limit
- RR tire: simulated data

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
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
• **GOAL:** Reliably simulate on-track, vehicle maneuvers
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THANK YOU

Questions?