USING MODEL-BASED DESIGN FOR VEHICLE DYNAMIC SIMULATION

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6/23/2020
• 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**

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

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<td>98</td>
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**Including Rank Order**

- < 10% simulated **error**
- Predicts the correct **rank order**
- Different 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

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 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

MathWorks Collaboration

• Technical collaboration will greatly reduce development time

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

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

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

Left Front Tire

Vehicle model fit to K&C & 4-post Shaker Rig Data
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
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>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>
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![Braking Distance Comparison](chart)

Error bars represent 95% Confidence Interval of the multiple measured braking maneuvers.

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

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
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THANK YOU

Questions?