Overview of Current Vehicle Dynamics

Thomas D. Gillespie, Ph.D.
Mechanical Simulation Corp.
Evolution of the Automobile

**REMOTE SENSING, COMMUNICATION, DRIVING INTERVENTION**

- Collision avoidance systems, V-to-V and V-to-I communications, driver assist systems (ADAS)
- Adaptive cruise control, electronic stability control

**INTRODUCTION OF ELECTRONICS**

- Electronic engine control, anti-lock brakes, traction control

**MECHANICAL VEHICLES**

- 1900
- 1920
- 1940
- 1960
- 1980
- 2000

Time
Mechanical Complexity

- Mechanical complexity has grown exponentially
- First cars had about 2000 parts
- Modern cars have about 14,000

1966 Mustang

2003 Mustang
Electronic Complexity

- Electronics augment mechanical systems for
  - Sensing
  - Computing
  - Control
- Result:
  - ECUs proliferate
- Functions of multiple ECUs need to be coordinated
- Many influence vehicle dynamic behavior

Growth in Microcontroller Use

- Typical Number of Microcontrollers

<table>
<thead>
<tr>
<th>Year</th>
<th>Luxury</th>
<th>Mid-range</th>
<th>Low-end</th>
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<td>2002</td>
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</table>
Electronics Influence All Vehicle Dynamics

Lane tracking cameras
EPS, EPAS
TCS, ECM
Remote Sensors
_active, Semi-active
ESC, RSC, RSS
TPM
Brakes, ABS
Tires
Stability Control
Advanced Driver Assist Systems
Powertrain, TCS
Steering
Trailer Dynamics
Trailer yaw control
ABS
Functional Complexity

Advanced Safety Technology Stream

- Collision Avoidance (Steering)
- Vehicle – Vehicle Communication
- Steer-by-Wire
- Vehicle-to-Infrastructure Communication
- Lane Keeping
- Forward Collision Avoidance (Braking)
- Driver Performance Monitor
- Lane Sensing/Warning
- Active Roll Control
- Forward Collision Warning
- Adaptive Cruise Control
- Vision Enhancement
- Near Obstacle Detection
- Electronic Stability Control
- Adaptive Variable Effort Steering
- Semi-Active Suspension
- Traction Control
- Anti-Lock Braking System

Time

Technical Complexity

Larry Burns, General Motors, “Automotive Trends and Opportunities”
ABS – The Paradigm Shift with Electronics

• 1970 -- Introduction of Anti-Lock Brake Systems
  – Pre ABS Control Paradigm
    
    Brakes apply in accordance with the pressure on the brake pedal
  
  – Post-ABS Control Paradigm
    
    Brakes may be released for brief periods during braking maneuver
    “There are times when the controller knows better than the driver”

• The ability to sense, compute and actuate means we can change the behavior of the car to suit driving conditions
• Places new and greater responsibility on the automotive engineer to
  – Design for known driving situations
  – Have tolerance for the unknown

• The need for testing increased dramatically
• Vehicle dynamic simulation provided the solution
What is Vehicle Dynamics Simulation?

Vehicle Data

Animation

Maneuver

Math Model

Road and Wind

Plots

Road course, skidpad, grades, cross-slopes, split-mu, crosswind
Where is Simulation Used?

- **Product Launch**
  - Marketing Tools - Animations, driving simulators

- **Vehicle Testing**
  - Proving Ground Optimization
  - Regulatory certification

- **Component Testing**
  - Test with CarSim and Hardware in the Loop (HIL)

- **Controls Development**
  - Test with CarSim and other Software in the Loop (SIL)

- **System Definition**
  - Simulate with CarSim Answers to “What if...?”

- **Vehicle Definition**
  - Vehicle Requirements, Capabilities, and Capacities

- **Aftermarket**
  - CarSim Example
**CarSim**
- Cars, light trucks, SUVs, race cars
- CarSim + Trailer option
- 25 example vehicles
- 150+ test examples

**TruckSim**
- Combination vehicles (trucks and trailers)
- Dual tires, multiple axles
- 12 sample truck-trailer-axle configurations
- 100+ test examples
- Custom configurations available

**BikeSim**
- Motorcycle dynamics
- Touring, racing, motocross, and scooters
- 10 sample bikes
- 40+ test examples
The CarSim Vehicle Family

- Simulate immediately – choose from 25 generic vehicles

A-class
- Hatchback

B-class
- Hatchback, Sports car

C-class
- Hatchback

D-class
- Minivan, Sedan, SUV

E-class
- Sedan, SUV

F-class
- Sedan

F3

3-Wheeler

GT

Euro Van

Pickup

Mini Truck

Tractors

Trailers
Tire Modeling Options in CarSim

- Built-in combined slip model with enhancements
- Built-in Pacejka 5.2
- Built-in MF-Tyre (licensed from TNO)
- Support* for MF-Swift
- Support* for FTire – Flexible Ring Tire Model
  - 3D nonlinear in-plane and out-of-plane tire model
  - Designed for ride/comfort simulation

*Separate license required
How is Simulation Used?

- Simulation tools like CarSim can be used Stand Alone,
  and with:

**Software in the Loop (SIL)**
- Software controller model
- CarSim vehicle and environment
- No timing control
- Runs as fast as possible
- Full “virtual” test

**Hardware in the Loop (HIL)**
- Hardware controller (ECUs, actuators)
- CarSim vehicle and environment
- Real time operating system
- Integration time step must be fixed
- Partial “virtual” test

![Diagram showing SIL and HIL with components like Vehicle Plant Model, Controller, Software Model, and Hardware Model.](image)
Stand Alone Example – Regulatory Compliance

- U.S. Government regulates rollover behavior with Fishhook test
  - Requires steering robot for precise control input
  - Tests at multiple speeds and loads
- Virtual tests are easily conducted in CarSim (and virtually free)
- Evaluate and certify Fishhook compliance at early design stage
Simulink – A Popular Choice for SIL

- Simulink models electronic controllers for CarSim (e.g., ABS, ESC)
- CarSim models are S-functions in Simulink
- Run Simulink from CarSim or CarSim from Simulink
- Batch run from either environment for optimization, DOE, etc.
SIL Example – Traction Control

Delphi Co-simulation in Development of TraXXar
Simulink® used for both the Traxxar® model and interface to AMESim® and CarSim®

SIL Example – ABS in Simulink

• **Issues**
  • Wide variety of variables
    • Inconsistent friction
    • Hills
    • Curves
    • Payloads
    • Driver behaviors
    • Climates
  • Requires complete vehicle

• **CarSim Solution**
  • Integrate ABS with Simulink
  • Optimize ABS algorithms
  • Simulation battery of tests
**SIL Example – Complex Stability Test**

**FMVSS 126 Test Procedure**

- Run tests to find steer for $A_y = \pm 0.3 \text{ g}$ at 80 km/h
- Run series of “sine with dwell tests”
- Check lateral position ($T = 1.07$)
- Compare yaw rate at two times to peak yaw rate
- Test until steer $> 270^\circ$
Failure:
Yaw rate > 35% peak
Advantages of HIL Testing

• Validate hardware for design intent at prototype or production stages
• Test controllers long before vehicle hardware is available
• Simulation facilitates testing with:
  – All environmental conditions (simulated roads and friction conditions)
  – Hardware stress conditions (temperature, voltage, vibrations, EMI)
  – Test safely in dangerous maneuvers (rollovers)
  – Safely test malfunctions and failures (shorts, open circuits, etc.)
  – Perfect repeatability
• Investigation of cause-effect relationships
• Track variables that cannot be measured
• Incorporate behavior of components that are difficult to model (e.g., brake lining temperature sensitivity)
HIL Example – Ford Brake System Development

- Brake pad friction is hard to model
- Brakes were put on dynamometer
- CarSim supplied:
  - Car model
  - Maneuver control
  - Test site(s)
- Brake lining materials were certified!

Wei-Yi Loh, Ford Motor Company, “Hardware in the Loop Simulation, Chassis Systems Applications”
HIL Example – GM Chassis Controls

• “The fundamental idea behind HIL is to use simulation for the vehicle systems that can be modeled with high confidence and actual vehicle hardware for the systems that are difficult to model in real-time software.”

HIL Example – Truck ESC Evaluation

- **Goal** – evaluate performance of truck ABS, ESC, RSC, RSS combinations
- **Solution** – set up a HIL laboratory with TruckSim
  - Truck brake system hardware is installed in the laboratory
  - Simulation evaluates performance over a broad range of real-world conditions


HIL Example – Driving Simulators

Traditional Applications
- Human factors testing
- Influence of drugs on driving
- Driver training
- Entertainment

Engineering Applications
- A/B testing of vehicle components
- Full-emersion systems tests
- Development & test engineer training
- Pre-construction road design evaluation
Simulation Improves Performance Prediction

- Cost of change increases throughout the development process
- Design refinement early in the process saves money

*John Krouse, 1993*
Benefits of Math-Based Technology

- 50% productivity improvement in last several years
- Over $10^9$ savings
- VDP time reductions >18 months

- CAE today is 7-10 times faster than hardware verification
- CAE costs are a fraction of test verification costs
- CAE will become the principle design verification & direction methodology!
CAMP – crash avoidance metrics partnership

VSC I
2002 - 2004

DSRC/WAVE Testing System

Potential Safety Applications

Vehicles - Vehicle
- Approaching Emergency Vehicle Warning
- Blind Spot Warning
- Cooperative Adaptive Cruise Control
- Cooperative Collision Warning
- Cooperative Forward Collision Warning
- Cooperative Vehicle Highway Automation System
- Emergency Electronic Brake Lights
- Highway Merge Assistant
- Highway/Rail Collision Warning
- Lane Change Warning
- Pedestrian Warning
- Pre-Crash Sensing
- Vehicle-Based Road Condition Warning
- Vehicle-to-Vehicle Road Feature Notification
- Visibility Enhancer
- Wrong Way Driver Warning

Vehicle - Infrastructure
- Blind Merge Warning
- Curve Speed Warning
- Rollover Warning
- Emergency Vehicle Signal Preemption
- Highway/Rail Collision Warning
- Intersection Collision Warning
- In-Vehicle Amber Alert
- In-Vehicle Signage
- Pre- Crash Warning
- Right-In-Time Report Notification
- Left Turn Assistant
- Low Bridge Warning
- Low Parking Structure Warning
- Pedestrian Crossing Information at Intersection
- Road Condition Warning
- Safety Recall Notice
- SOS Services
- Stop Sign Movement Assistance
- Stop Sign Violation Warning
- Traffic Signal Violation Warning
- Work Zone Warning

Draft SAE Message Set
- Longitude
- Latitude
- Height
- Time
- Heading Angle
- Speed
- Lateral Acceleration
- Longitudinal Acceleration
- Yaw Rate
- Throttle Position
- Brake Applied Status
- Brake Applied Pressure
- Steering Wheel Angle
- Headlight Status
- Turn Signal Status
- Traction Control State
- Anti-Lock Brake State
- Vehicle Length
- Vehicle Width

VSC Message Composition

- One common message supports all safety applications.
- Exchange with neighboring vehicles.
- Send periodically (heartbeat) or event-triggered.

<table>
<thead>
<tr>
<th>SAE J2735 Basic Safety Message (BSM)</th>
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</thead>
<tbody>
<tr>
<td><strong>Part I</strong></td>
</tr>
<tr>
<td>Basic Vehicle State Message Part I</td>
</tr>
<tr>
<td>(Veh. ID, Seq. #, time, position, motion, control, veh. size)</td>
</tr>
<tr>
<td><em>Part I is mandatory in BSM</em></td>
</tr>
<tr>
<td><strong>Part II</strong></td>
</tr>
<tr>
<td>Vehicle Event Object (hard braking, control loss, etc.)</td>
</tr>
<tr>
<td>Vehicle Path History Object</td>
</tr>
<tr>
<td>Vehicle Path Prediction Object</td>
</tr>
<tr>
<td>Relative Positioning RTCM 1002 data</td>
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Summary

• Vehicle complexity requires new methods for product development
• Virtual testing in the simulation world serves that purpose
  – Stage 1: Stand Alone
  – Stage 2: Software-in-the-Loop
  – Stage 3: Hardware-in-the-Loop
• These methods are used broadly in industry
• New applications are being conceived every day
  – Diverse applications in driving simulators
  – Evaluating road designs prior to construction
  – Developing experimental test procedures and protocols
• The bottom line
  – Cost savings in the millions
  – Time savings of months to years
  – The only viable solution in many cases
Thank You!

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