Development and Validation Of Hardware in the Loop (HIL) Simulation for Studying Heavy Truck Stability Control Effectiveness

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Introduction

• Project studied the potential safety benefits from stability control systems for heavy truck tractor semitrailers

• Determination of safety benefits is challenging
  – Stability control only recently introduced to heavy truck fleet
  – Limited crash exposure of technology in the field
  – Not possible to do a “before/after” study

• Hardware in the Loop (HiL) used to determine the effectiveness of stability control for common pre-crash scenarios determined from crash data.
Benefits Estimation Overview

- National Crash Databases
- State Crash Analysis
- Fleet Case Studies
- Scenarios
- Hardware in-the-Loop
- Benefit Calculation
- Potential Crash Reductions
Stability Control Systems Tested

- **Roll Stability Control (RSC)**
  - Senses wheel speed and lateral acceleration
  - Applies drive axle and trailer brakes when rollover is imminent

- **Electronic Stability Control (ESC)**
  - Includes RSC functionality
  - Also senses yaw rate and steer angle
  - Applies individual drive/steer axle brakes and trailer brakes to assist a driver in avoiding directional instabilities as a result of an understeer or oversteer mitigation process
Hardware in the Loop System

- **HiL**: hybrid of hardware and software components
- **Hardware**
  - Pneumatic Brake System
  - System ECU - control algorithm for ABS (Baseline), RSC, and ESC
- **Software**
  - Truck Dynamics - generates truck motion, suspension, tires, powertrain, etc.
  - Driver Model - throttle, manual braking, and steering
  - Environment - road geometry and surface properties
System Setup

MAIN MODELS
- RTW SM/SS/SC
- Truck Model
- CAN Data Communication
- Scenario Design & Configuration
- Servo Calibration
- Brake/throttle Control
- End of Line Test

SOFTWARE
- Simulink RTW
- TruckSim RT
- RT-Lab

SOFTWARE

INTERFACES
- high/low-speed CAN interfaces and analog-digital converters
- motion sensor simulators
- pressure transducers

SOFTWARE

HARDWARE
- Treadle
- Tractor ECU & Trailer ECU
- ABS modulators & solenoid values
- Ten brake chambers
- Pneumatic braking system

SOFTWARE
Brake System Hardware

- Transient responses of valves
- Brake actuator
- Air pressure dynamics
- Avoids modeling complex mechanical systems
- Actual control unit for ABS, ESC, and RSC (Meritor WABCO systems)
System Design

• Truck dynamics with TruckSim computer simulation and Simulink for driver model

• System kinematics (speed, acceleration, yaw rate) sent to hardware wheel speeds were converted to actual hardware magnetic pick-ups

• ECU responds by sending braking signals, throttle disengagement, or engine brake

• Pressure measured from hardware, sent to TruckSim to determine brake torque from a 3-D look-up table (pressure-speed-torque)
Trucksim Model Based On Measured Heavy Tractor-trailer System

Mechanical, geometric, and inertial properties were measured.

Torsional stiffness of chassis, fifth wheel were measured.

Tire forces and moments were measured.
HiL Validation

- Simulation results compared to ramp steer maneuver (RSM) experimental data collected at NHTSA VRTC
- Maneuver speed was increased incrementally in HiL until rollover occurred
- HiL simulations are based on models with differences in tires, suspensions, and compliances used on the actual truck
  - Exact match between test data and simulation was not possible
  - Track data were useful for qualitatively checking the response of the HiL
  - Constant speed maintained by driver model vs. dropped throttle in experimental data.
Ramp Steer Maneuver
RSM Video
HiL Simulations

- Simulations are valid for predicting the onset of rollovers (typically > 6°)
- LTR (Load Transfer Ratio) is used for rollover potential

\[
LTR = \frac{\sum_{Left} F_{Ni} - \sum_{Right} F_{Ni}}{\sum_{Left} F_{Ni} + \sum_{Right} F_{Ni}}
\]

- 0<=LTR<=1, a value of 1 is a complete rollover, 0.9 is typically an onset of rollover
RSC Simulation Results

- Lat. Acc (g)
- Time (sec)
- Speed increasing
- Speed = 30 mph
- Speed = 34 mph
- Speed = 36 mph
- Speed = 38 mph

- Roll (deg)
- Time (sec)
- Speed increasing
- Speed = 30 mph
- Speed = 34 mph
- Speed = 36 mph
- Speed = 38 mph

- Yaw Rate (deg/sec)
- Time (sec)
- Speed increasing
- Speed = 30 mph
- Speed = 34 mph
- Speed = 36 mph
- Speed = 38 mph

- Long. Acc (g)
- Time (sec)
- Speed increasing
- Speed = 30 mph
- Speed = 34 mph
- Speed = 36 mph
- Speed = 38 mph
ESC Simulation Results

- **Lat. Acc (g)**
  - Speed increasing
  - Time (sec): 0 to 10
  - Graph shows acceleration values for different speeds.

- **Roll (deg)**
  - Speed increasing
  - Time (sec): 0 to 10
  - Graph shows roll angles for different speeds.

- **Long. Acc (g)**
  - Speed increasing
  - Time (sec): 0 to 10
  - Graph shows longitudinal acceleration values for different speeds.

- **Yaw Rate (deg/sec)**
  - Speed increasing
  - Time (sec): 0 to 12
  - Graph shows yaw rate values for different speeds.
RSC-Baseline
Experimental Results: 2006
Freightliner

Steering
Speed
Lateral Acceleration
Yaw rate
Longitudinal Acceleration
ESC-Baseline Experimental Results: 2006 Freightliner

- Steering
- Speed
- Lateral Acceleration
- Yaw rate
- Longitudinal Acceleration
Crash Data Review

- Large Truck Crash Causation Study (LTCCS)
- 963 Crash cases including 1128 vehicles
- 113 Rollover relevant
- Cases give detailed information about crash events
  - Scene diagram
  - Detailed narrative
  - Detailed coded crash events
  - Physical configuration of the vehicle (weights, lengths, axle count, cargo weight and type, etc.)
- Typical crash situations were selected for simulation
Example LTCCS Rollover Case

Road curved
Dry surface
Cargo: loaded

3-axle tractor pulling van trailer
31,000 lbs cargo
61,800 gross weight
Speed: 40 mph (est.)
Scenario Development

- Road Geometries Based on LTCCS Rollover Crashes
- LTCCS Mean Curve Radii Evaluated
  - Curves with radii < 100 m mean value 68 m
  - Curves with radii > 100 m mean value 227 m
- Rollover Scenarios
  - Four scenarios based on road geometries with curvatures
  - Lane change on a straight road
    - Driver changes lanes aggressively to avoid a slow or stopped vehicle
  - Constant speed maneuvers
Entry to Freeway Exit Ramp: (68 and 227 m)

For RSC, ESC and ABS - Speed $V$ is increased until rollover

Rollover Criteria: $V$
Entry speed just to survive constant radius

Criteria: position after point C.
Lane Change on Exit Ramp

ISO lane change at 90° of turn, to the outside

Rollover Criteria: V
Turn at an Intersection: radius is 20 m

Rollover Criteria: V
Determining System Effectiveness

- Critical Speed $V_c$ - highest speed for which no rollover occurs
- $V_c$ was determined for ABS, RSC, and ESC
- Effectiveness calculated as the area under the distribution curve of $V_c$
Calculating Effectiveness

\[ E = \frac{x}{x + y} \]
Linking Effectiveness to Potential Safety Benefits

- Scenarios derived from pre-crash events
- Populations from national crash databases are associated for each scenario
- Effectiveness for a scenario is expressed in terms of a probability of a crash
  - Prevention ratio
Benefit Equation

\[ B = \text{Benefit in Terms of Reduced Number of Crashes} \]

\[ B = \left[ P_{wo}(C) - P_{w}(C) \right] \times \text{Exposure} \]

\[ P_{wo}(C) = \text{Probability of Crash Without Technology} \]

\[ P_{w}(C) = \text{Probability of Crash With Technology} \]

Exposure = All Trucks in the Population
Benefit Equation For a Given Crash Scenario, $S$

$$B = N_{wo} \times P_{wo}(S \mid C) \times \left[ 1 - \frac{P_w(C \mid S)}{P_{wo}(C \mid S)} \right]$$

From Crash Data

From HIL simulation

$1 - \text{(Prevention ratio)} = E$
Summary

- HiL system developed at UMTRI provided an objective means for determining RSC and ESC effectiveness.
- Effectiveness measures were used to determine system benefits by linking crash data from national databases.
- Methodology provided a means to determine safety benefits for a technology with limited exposure data.
Upcoming Publications


For Further Information

Website: www.nhtsa.gov

Thank You