Methodologies for Design and Analysis of Heavy-Duty Truck Mobility

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Goals

• ARC Goal
  - To develop a flexible, agile simulation system composed of a hierarchy of models of varying resolution that can be tailored to meet a range of simulation objectives.

• This Case Study Goal
  - To demonstrate advances made in meeting the above goal by presenting results from ARC projects, across thrust areas, on the mobility performance of heavy duty trucks.
Specific Objectives

• To develop 2\textsuperscript{nd} generation models and simulation tools for the design of a complete vehicle:
  - Powertrain and Vehicle Dynamics

• To demonstrate for the M916 truck:
  - Proper vehicle dynamics models for mobility studies
  - Active safety design: Rollover Warning
  - Design optimization: Rollover Performance
M916 Vehicle Specifications

- 21 rigid body DOF / 91 state variables
- 126,000 lbf GVW
  - M916A1 3-Axle Tractor (6x6)
  - M870A2 3-Axle Semitrailer
- Thermodynamic simulation with physically based sub-models
- DDC Series 60 engine
  - 475 HP@2100 rpm
  - Turbocharged, intercooled
Flexible Simulation Tool: ArcSim

1. Model Reduction

2. Equation Formulation

3. Model Integration Vehicle/Engine

4. Rollover Warning & Animation

5. Rollover Performance
1. Model Reduction

• Objective
  - Develop methods and tools for a systematic generation of vehicle models that minimize model complexity subject to accuracy constraints.
  - Apply modeling methods to the M916 truck.

• Participants:
  - University of Michigan
Methodology

• Model Reduction:
  - Find the Activity of each element, in a baseline model, based on power flow as a modeling metric.
    \[ Activity = \int_0^T |Power(t)| \cdot dt \]
  - Reduce the model complexity based on Model Order Reduction Algorithm (MORA).

• Application:
  - Generate a hierarchy of models of the M916 truck suitable for mobility studies.
  - Scenario: Acceleration and braking on a flat wet road.
Element Importance

- Developed models:
  - Baseline 3D
  - Pitch Plane
  - Reduced Pitch Plane
Performance Predictions

48% Reduction -> Eliminate Yaw and Roll DOF
59% Reduction -> Eliminate axle vertical inertial forces
Conclusions

• Activity is a powerful model reduction metric.

• Reduced models of vehicles can be systematically generated.

• Reduced models may have sufficient accuracy at greatly reduced complexity.
2. Equation Formulation

• Objective:
  - To improve the numerical efficiency of Reduced Order Models.

• Problem:
  - Small masses / inertias acted upon by large forces / moments produce high frequency dynamics, often not of interest.
  - In the past, either a small time step or a stiff integrator was needed to solve the equations of motion.

• Participants:
  - University of Michigan
Methodology: Inertia Removal Strategy

- Use ODE formulation of equations of full model.
- Replace dynamics of small inertias with constraint equations:
  - Reduce system order.
- Solve constraint equations iteratively at each step.
- Preserve ODE nature of equations.
  - Use larger time step with simple integration methods (e.g. RK2).
- Eliminating high frequencies is local to the source:
  - Error tolerances: Easier and fewer to choose.
Example

Load leveler of the M916 tractor tandem suspension
Results: Removal of load leveler inertia

- Increase integration time step from 0.00025 sec to 0.002 sec.
- Decrease simulation time by a factor of 8.

With inertia:
At $I = I_0 = 0.136$ (kg m$^2$), spectral radius = 93 Hz

No inertia:
spectral radius = 12 Hz

High Frequency
Conclusions

Vehicle Handling and Ride

Vehicle Durability
3. Model Integration - Vehicle/Engine

• Objective
  - Simulate vehicle acceleration on flat road using the high fidelity engine/powertrain system model coupled to reduced (pitch plane) multi-body vehicle dynamics model.
  - Investigate the effect of rough road profile on engine performance.

• Participants:
  - University of Michigan
  - University of Wisconsin
High Fidelity Ground Vehicle Simulation

PowerSim

Diesel Engine System

Driveline

Vehicle Dynamics

3D Multibody Dynamics Model
 Acceleration on Flat Smooth Road

Pitch Plane model runs 3 times faster than Baseline 3D model
Acceleration on Flat Rough Road

Fuel consumption is increased by 1.7%
Conclusions

• Model complexity can have a dramatic influence on simulation time and often without significantly affecting accuracy.

• Advanced fuel economy studies require the integration of vehicle and powertrain dynamics.
4. Rollover Warning & Animation

• Objective:
  - Develop a dynamic rollover prediction algorithm which indicates vehicle rollover threats so that preventative actions can be taken.

• Critical issues:
  - Accurate and fast (60 x real-time) model.
  - Metric to indicate rollover threat accurately under a wide variety of maneuvers.

• Participants:
  - University of Michigan: Rollover warning
  - University of Tennessee: Animation
Simplified roll/yaw models need to be constructed

Roll model

<table>
<thead>
<tr>
<th>Roll Plane Model</th>
<th>Rigid Vehicle</th>
<th>+ Compliant Tires</th>
<th>+ Compliant Suspensions</th>
<th>+ Compliant Fifth Wheel</th>
<th>ArcSim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of States</td>
<td>0</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>91</td>
</tr>
</tbody>
</table>

Model Error (steady-state cornering)

Computation time

Model D = 200 x ArcSim = 70 x Real Time (200 MHz Pentium)
Time to Rollover (TTR): Rollover Threat Metric

Under current condition, the vehicle will rollover in ?? seconds.

The TTR is then fed to a Neural Network to get the NN-TTR.
Simulation Results Under Four Maneuvers

The NN was trained with datasets from all four categories:

- **Ramp steering**
  - Mild
  - Bad
- **Ramp entering**
- **Obstacle avoidance**
- **Worst-Case**

The mean TTR error (msec) for different categories is as follows:

- Mild: 5 msec
- Bad: 22 msec
- Worst Case: 30 msec
Conclusions

• A reduced ArcSim model is critical to the success of the rollover warning system.

• The Neural Network accurately predicts a uniform rollover threat “Countdown” under a wide variety of maneuvers.

• Animation is important to warning system evaluation.
5. Design Optimization for Rollover Performance

• Objective:
  - To integrate ArcSim models with design optimization techniques.
  - To implement worst-case and robust design concepts to achieve improved vehicle rollover performance under:
    » extreme maneuvers (worst-case design),
    » a wide range of maneuvers (robust design).

• Participants:
  - University of Michigan: Worst-case design
  - Clemson University: Robust design
Methodology for Worst-Case Design

• Design Objective:

\[
\begin{align*}
\min_{\text{vehicle parameters}} & \quad \int_{0}^{5} \text{roll angle}^2 \, dt \\
\max_{\text{maneuver parameters}} & \quad \text{Rollover Metric}
\end{align*}
\]

• Rollover Metric:

\[
\sqrt{\int_{0}^{5} \text{roll angle}^2 \, dt}
\]
Methodology for Robust Design

- Design Objective:

\[
\text{Max}_{\text{vehicle parameters}} \left( \frac{C - \text{Mean Rollover Metric}}{\text{Variance Rollover Metric}} \right)
\]

Vehicle

Maneuver (range)

ArcSim Surrogate

Rollover Metric (range)

Response Surface Model generated from ArcSim
Worst-Case Design Results

VEHICLE WORST-CASE DESIGN

EXTREME MANEUVER

Dev. from Nominal

-20% -15% -10% -5% 0% 5% 10% 15% 20%

Hitch height
Hitch roll stiffness
Dist. bw springs on Axle 1
Axle 2/3 Axle 4/5/6
Laden load for Axle 1
Axle 2/3 Axle 4/5/6
Spring stiffness Axle 1
Axle 2/3 Axle 4/5/6
Tire stiffness Axle 1
Axle 2/3 Axle 4/5/6
Steering start time
end time
level
Braking start time
end time
level
Worst-case rollover metric
Conclusions

• Both worst-case and robust design problems can be solved as optimization problems if design objectives (metrics) can be efficiently calculated (simulated).

• Simpler models would facilitate both design formulations by reducing simulation runtimes to:
  - evaluate worst-case rollover metric for worst-case design,
  - generate surrogate models used to evaluate mean and variance of rollover metric for robust design.

• Different design techniques can be integrated with ArcSim.
Conclusions

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Detailed Technical Presentations
Room 107 EPB - Wednesday 9:00-12:00 am

• Reduced Order Mobility Models
  - Loucas Louca and Polat Sendur

• Efficient Equation Formulation of the M916
  - Steve Riley

• Worst Case Rollover
  - Huei Peng

• Vehicle Response Predictions for Active Safety Systems
  - Huei Peng and Lee Han

• Proper Tire Models
  - Ian Darnell

ArcSim Demo: Reception at North Campus Holiday Inn