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Integration of Virtual Prototyping with Instrumented Testing of Vehicles

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ABSTRACT

The objective of this paper is to demonstrate the use of computer modeling and simulation as an effective analytical tool which can be integrated with representative data from user duty cycles to validate test data recorded from a vehicle. Computer modeling is an increasingly important design tool, but the necessity of real-world test data is often overlooked. This paper will present an example of the Logistics Vehicle System Replacment (LVSR), using real-world proving ground data as inputs to the vehicle model, as well as instrumented vehicle test data to validate outputs of the vehicle model.

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NATC

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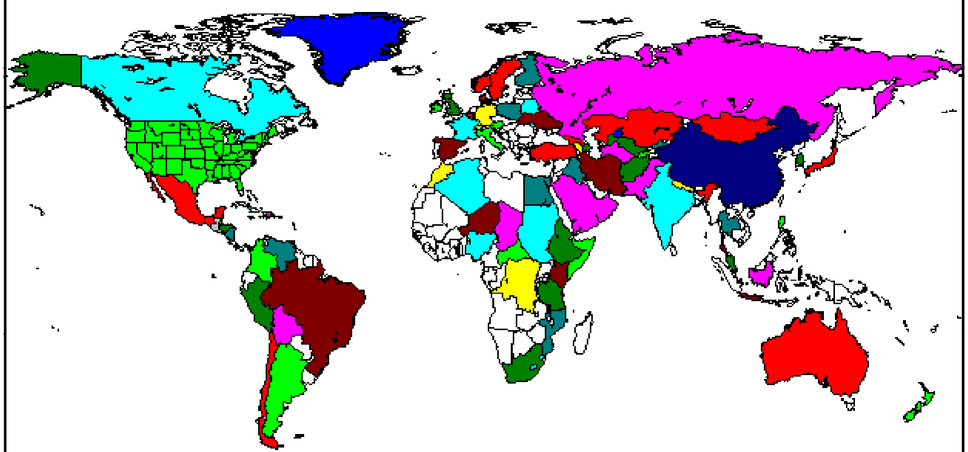
NEVADA AUTOMOTIVE TEST CENTER

NATC Overview

- Founded in 1957
- Internationally Recognized Proving Ground
- Engineering Services
- Duty Cycle Definition / Process Integration
- Prototype Fabrication
- Accelerated Durability and Environmental Testing
- Safety, Vehicle Dynamics and End-Limit Handling
- Instrumentation and Data Acquisition Services
- FEA and Dynamic Simulation Development
- Terrain Analysis / Asphalt Research
- Shock and Vibration Testing
- Certification Tests
- Weapons, Ordnance and Explosives Testing
- Development of Representative Requirements and Standards

A World of Difference

85 Percent of the Earth's Terrain Types Are Found Within a 150 Mile Radius of NATC



Colored Countries: NATC has been in country and developed duty cycle simulations

Advanced Technology Applications

- **Worldwide Road Network Development**
  - **Asphalt Research**
  - **Low Volume Road**
- **Anti-Lock Braking System**
- **Regenerative Power Systems**
- **Traction Control Systems**
- **Road Roughness Measurements**
- **Commensurate Share Determinations**
- **Intelligent Transportation Systems**
  - **Collision Avoidance**
  - **Vehicle Control Systems**
  - **GPS/Automatic Vehicle I.D.**
- **Semi-Active/Active Suspensions**
- **Extreme Vehicle Use - Center of Excellence**
- **Deformable Soils Modeling**
- **Vehicle Dynamics Modeling**
- **Vehicle Fabrication**
- **Accelerated Life Cycle/Warranty Prediction**
- **Driver in the Loop**
  - **Qualification and Simulation**
- **Hazardous Material Transportability**
- **Worldwide Transportation**
- **Driverless Vehicles**
- **Full Vehicle Environmental Test Chambers**

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LVSR Sponsors

NAVAL SEA SYSTEMS COMMAND

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CARDEROCK DIVISION

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LVS/LVSR

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Logistics Vehicle System Replacement

- **Primary Heavy Logistics Vehicle**
- **Current Fleet at 20 Years Service by 2005**
- **Greater On and Off-Road Capability**
- • **Cover More Terrain**
- • **Faster Speed**
- **Dual Rating (On/Off-Road)**
- **Technologically Capable Until 2020**
- **Integrate Representative Technology and Demonstrate Feasibility**
- **Stay Within Current Vehicle Footprint**

- **Priorities from MARCORSYSCOM:**
  - **Safety**
  - **Speed**
  - **RAM-D**
  - **Payload**
  - **Maneuverability**

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Highlights from LVSR ORD (DRAFT)

- Primary Mission - Provide heavy cargo transport with the Marine Air Ground Task Force
- Objectives
  - Payload objective is 16.5 tons cross-country, 22.5 tons highway
  - Speed 55 MPH on 2% grade with 22.5 tons cargo, 25 MPH cross-country with 16.5 tons
  - Profile 70% hard surface road, 30% off-road
  - MMBOMF 6,000 miles
  - Negotiate 18 inch wall
  - Turning diameter less than or equal to 3X vehicle length
  - Operate on JP-8
  - VCI less than or equal to 30
  - Anti-lock brakes
  - Central Tire Inflation System
  - Non directional radial tires with 10,000 mile capability at deflections up to 38%
  - -25 F to 125 F w/o kit
  - Meet all Federal Motor Vehicle Safety Standards (FMVSS)
  - 60% grade, 30% side slope
  - Increased Stability
  - Improved Ride Quality
  - Improved Mobility

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Define Mission Requirements in Engineering Terms

Identify Areas of Operation
Quantify Terrain Severity
Mission Profile

Helo Transportable
Payload
GVW

Wheel Travel
Braking System
Vehicle Mobility
Tire Size / CTIS
Powertrain Size / Type
Cooling
Frame / Structure

Required Operational Speed
MPH Highway
MPH Cross- Country

RAMD Requirement
Reliability, Availability
Maintainability,Dependability

LVSR - Tech Demo

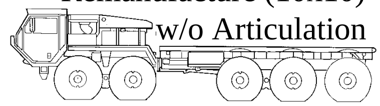
Technical Approach

- Multi-module straight frame truck
- Detroit Diesel, 600 Hp, in-line, 6-cylinder engine
- Twin Disc automatic transmission, 6 speed
- Oshkosh independent suspension
- Interoperability with Raydan, Hendrickson HHP, and existing RBU
- 10 x 10 vehicle configuration
- Multi-axle steering (4)
- Central tire inflation
- 16R20 tire
- ABS / ATS
- Integrated electronics-transmission based multiplex
- Dual voltage alternator, 14 / 28V
- Nylon heat exchanger
- High capacity air compressor
- Hydrostatic retarder
- Integrated hydraulic supply / transmission
- Extreme service brakes

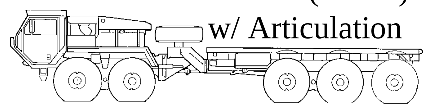
LVSR Tech Demo Approach

LVSR Tech Demos will provide information across the spectrum of alternatives

Remanufacture (10x10) w/o Articulation



Remanufacture (10x10) w/ Articulation

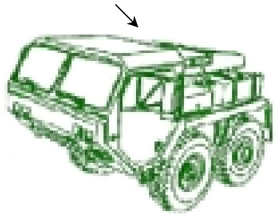


Rebuild (8x8)

Goals:
- Prove concept feasibility
- Demonstrate improved capabilities
- Performance Specifications

LVSR Tech Demo Evaluation Plan

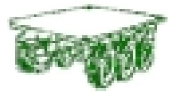
- Front Power Unit (FPU)
  - Oshkosh Independent Suspension #1, #2 axles



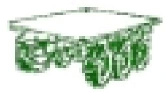
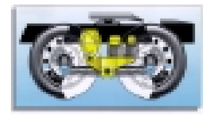
- Front Power Unit (FPU)
  - Raydan Air-Link Tandem Axle Suspension #1, #2 axles

LVSR Tech Demo Evaluation Plan

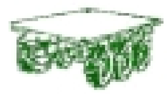
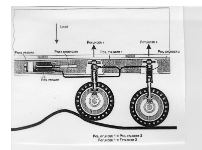
RBU #1
- 10 x 10 Configuration
- Oshkosh Independent Suspension #3, #4, #5 Axles



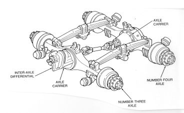

RBU #2
- 10 x 10 Configuration
- Raydan Air-Link Tandem Axle Suspension #4, #5 Axles
- Modified Hendrickson HT Trailing Arm Suspension #3 Axle

RBU #3
- 10 x 10 Configuration
- Hendrickson HHP (Heplex Hydro- Pneumatic) Suspension #3, #4, #5 Axles

RBU #4 (Base-Line)
- Standard LVS Three-Spring T-Rod Suspension (Current Vehicle)

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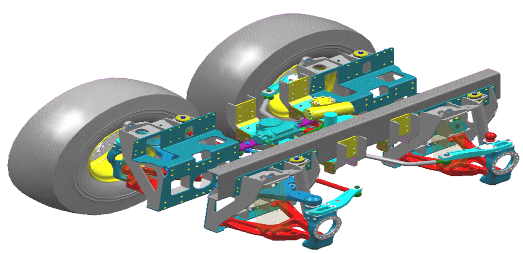
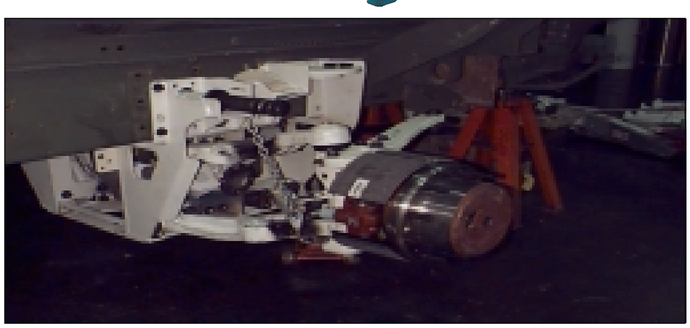
FPU Suspension





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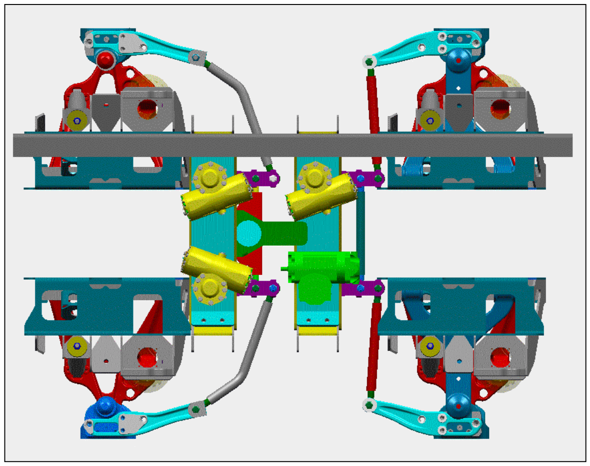
FPU Steering



Computer Simulation/Virtual Prototyping

- Modeling and simulation are valuable tools in vehicle development to optimize design and minimize program risk
- Commercially available modeling and simulation tools are utilized by vehicle manufacturers as design aids and decision tools
- Per DODD 5000.1 "Models and simulations shall be used to reduce the time… and risks of the acquisition process and to increase the quality of the systems acquired"

Modeling and Simulation for LVSR?

- Mission is well defined
  - 5 operational areas identified
    - Terrain severity measured and provided as input to the model
- Simulation developed concurrently with LVSR technology demonstration vehicle
- Pass / Fail criteria is defined
- Level of simulation accuracy has been defined
- Critical USMC mission events and vehicle events are known and can be simulated
- Decision for Template development made
- Training and hand off of model and simulation environment identified

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Modeling

- Objectives of Vehicle Modeling
  - Should be an inexpensive method to integrate operational duty cycle data into a computer model
  - Ability to take vehicle response data from instrumented analysis and compare to vehicle response data from the computer model
  - Help vehicle developer and manufacturer make effective design judgments relative to severity, user needs, and transient loads of operational duty cycle
  - **Develop a validated computer simulation environment used by developer, manufacturer and user**
  - **Validated template which allows design changes within an accurate simulation without need to rebuild model**
  - **Use template to ensure mission parameters are met within proven simulation environment**
  - **Allow validation of design changes with limited test**
  - **Allow accurate definition of component operating environment to reduce risk**
  - **Allow determination of impact of mission change on vehicle performance and ability to complete mission**

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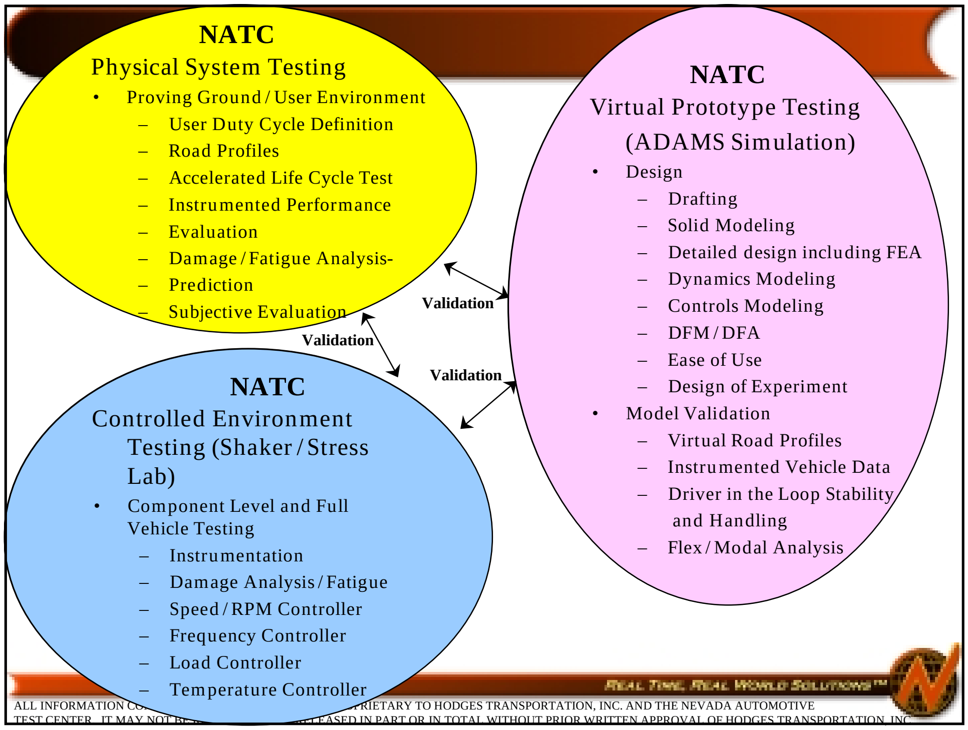

Computer Simulation Selection

- MDI / ADAMS selected
- Team approach established
  - MDI simulation expertise integrated with NATC vehicle, tire and terrain expertise
  - MDI personnel on site throughout the vehicle development process
  - NATC provides vehicle engineers to support model development

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NATC Modeling and Simulation

- Developed 5 operational mission scenarios in terms of mathematical representation of terrain roughness. This definition allows the mission environment to be introduced into the vehicle dynamics model.
- Developed validated 5-ton frame model to verify ability of 5-ton structure to support 8 ton payload for MTVR program.
- Historically has performed NRMM modeling analysis on wheeled and tracked vehicles ranging from HMMWV to AGS tracked vehicle.
- NATC has previously used DADS, SDRC I-DEAS, CATIA, AutoCAD, MSC / NASTRAN and MATLAB.

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NATC Modeling and Simulation

- Regularly performs modeling and simulation for vehicle applications from motorcycles to Class 8 trucks
- Generates RPC III drive files which are used to develop laboratory shaker inputs for vehicle component development.
- Developed critical failure criteria (tire blowout, steering failure, etc.) and has provided mathematical and input file relationships to vehicle driving simulators.
- Provided validation data for commercial driver simulators and road roughness based drive file inputs to dynamic shakers.

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LVSR Modeling

- Four models are planned for development:
  - Oshkosh Independent FPU / Oshkosh Independent RBU
  - Oshkosh Independent FPU / Raydan RBU (Hendrickson #3 Axle, Raydan #4 and #5 Axles)
  - Oshkosh Independent FPU / Heplex Hydraulic Suspension RBU
  - Stock LVS
- MDI / NATC are currently developing these models
- Validated computer models and templates provided to USMC
- Hand-off of validated templates to potential contractors at direction of USMC

International Duty Cycle

Duty Cycle Development

International Duty Cycle

Identify Customer Usage 80% / 95% / Vehicle Mix

Identify Environmental Conditions

Identify Competition

Final Duty Cycle

Establish Pass / Fail Criteria

Identify Current Infrastructure and Probable Infrastructure Growth

Identify Target Country / Markets / Customer

- Operate Vehicle Against Established Duty Cycle
- Establish Mode of Failure
- Perform Risk Assessment
- Review Duty Cycle based on In-Country Ride and Drive

Duty Cycle Definition

World-Wide Duty Cycle Information and Database

Demographic, Usage and Expectation Survey

Trip Reports from In-Country Duty Cycle Validation

Environmental Data

User Environment Miles ☐
Duty Cycle Test Miles ☐

Road Roughness	%	Speed
Paved	☐	☐
Degraded Paved	☐	☐
Gravel	☐	☐
Trails	☐	☐
Off-Road	☐	☐
Fixed Frequency	☐	☐
Infrastructure		
Domestic	☐	
International	☐	
Emerging Market	☐	
Specific Country	☐	
Environmental Loads		
High Temp	☐	
Low Temp	☐	
Humidity	☐	
Wet	☐	
Dry	☐	
Both	☐	
Payload		
Empty	☐	
Half	☐	
100%	☐	
>100%	☐	

Vehicle Design
Loads
Structure
Powertrain
Suspension

Accelerated Life Cycle Test Requirements and Roughness

Shaker Inputs

Kinematic Modeling and FEA Modeling

NVH, Ride Quality Requirements

Severity Com-parisons Against Known Cycles

Whole Vehicle

Component

PROPRIETARY

Warranty Prediction Based On Duty Cycle

- **Define User Duty Cycle**
  - **Measure Terrain Macro/Micro Profile**
  - **Identify Environmental Extremes**
  - **Determine Payload And Speed Cycles**
  - **Driver Experience/Abuse**
- **Develop Accelerated Life Cycle Test Scenario**
  - **10:1, 25:1, 50:1, Etc.**
- **Conduct Accelerated Test**
- **Perform Detailed Inspection**
- **Develop Prediction**
- **Run Accelerated Test And Long Life Vehicles**

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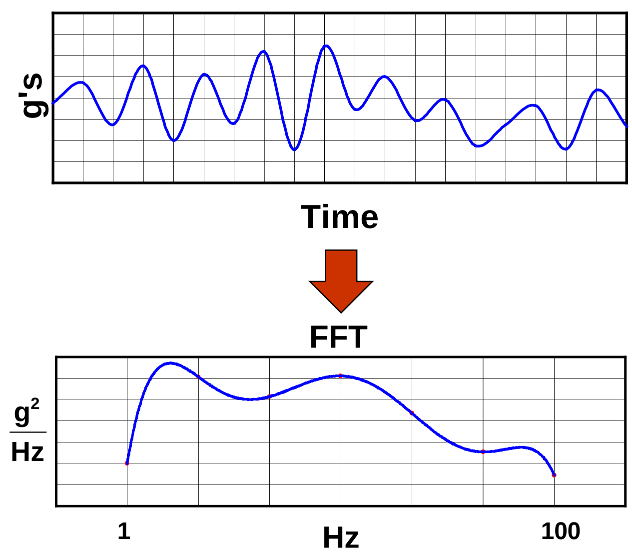
Vehicle Response



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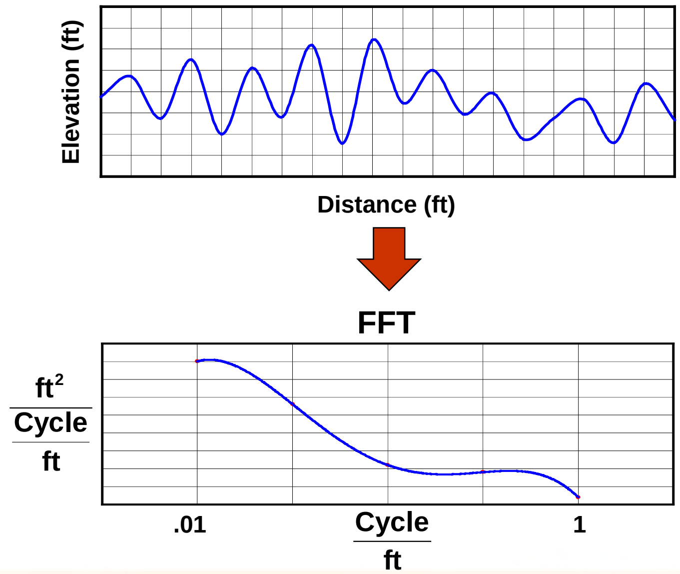
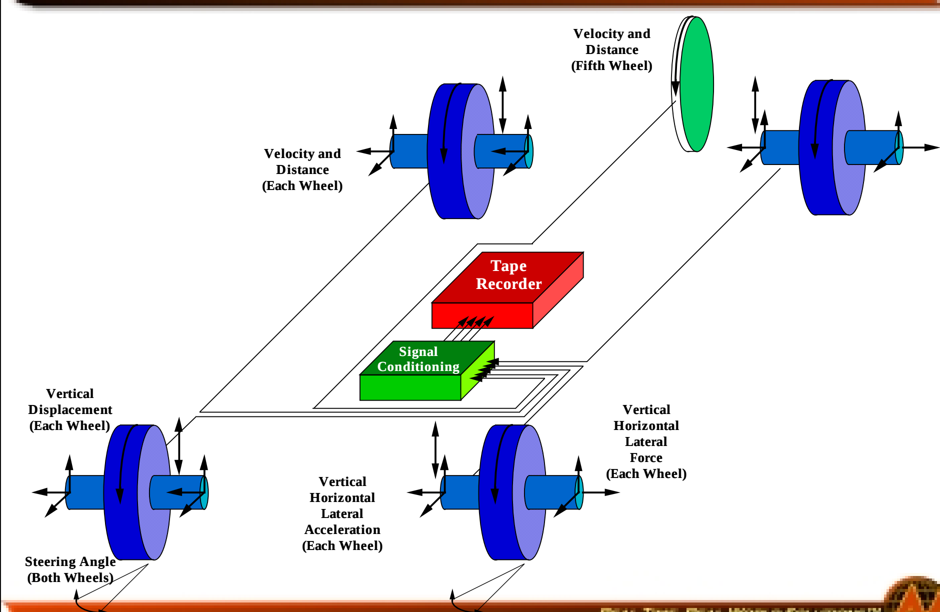
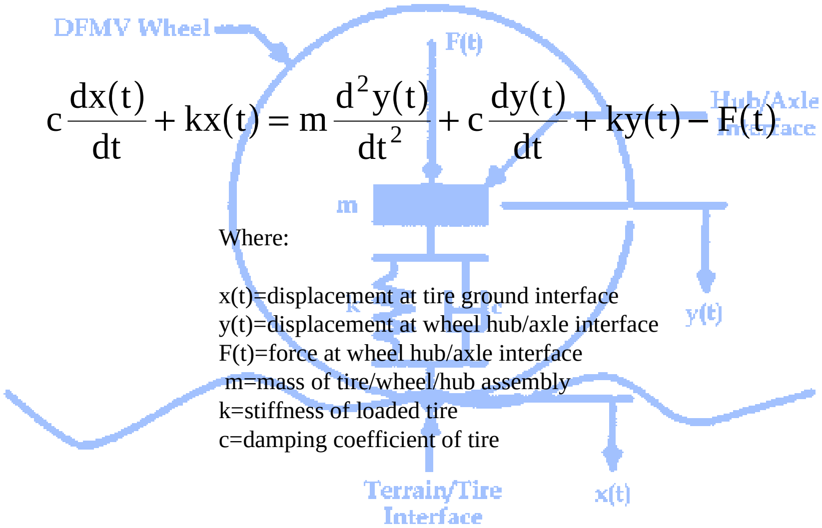
Road Roughness



Dynamic Force Measurement Vehicle (DFMV) (Continued)



Terrain Elevation Measurement Methodology

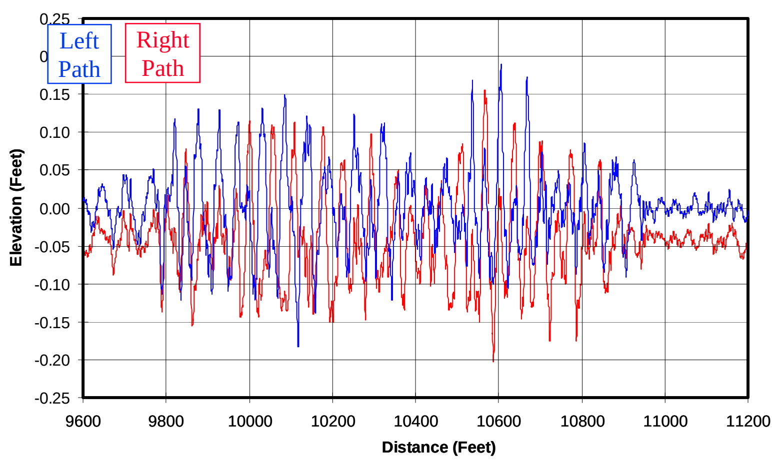


$$c\frac{dx(t)}{dt} + kx(t) = m\frac{d^2y(t)}{dt^2} + c\frac{dy(t)}{dt} + ky(t) - F(t)$$

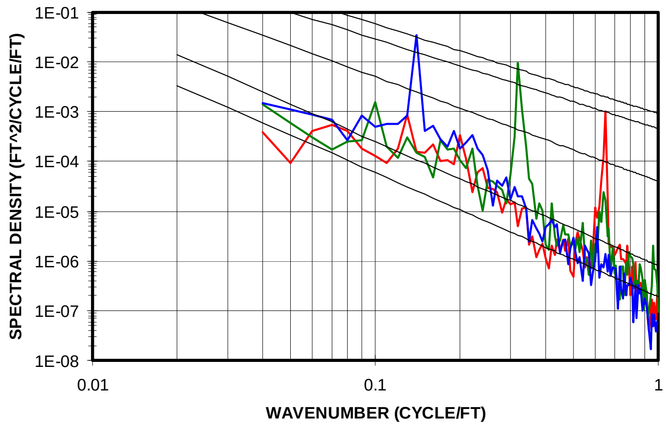
Where:

x(t)=displacement at tire ground interface
y(t)=displacement at wheel hub/axle interface
F(t)=force at wheel hub/axle interface
m=mass of tire/wheel/hub assembly
k=stiffness of loaded tire
c=damping coefficient of tire

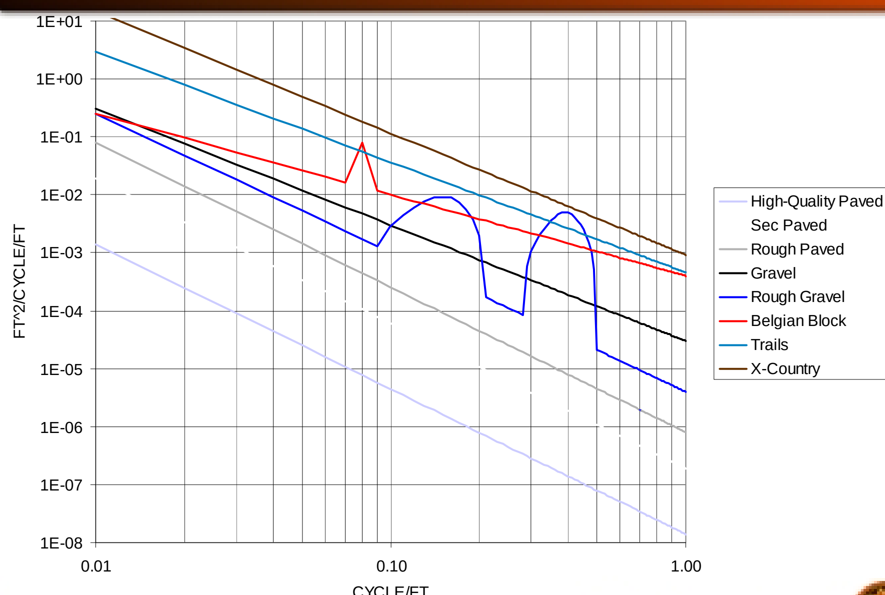
Body Twist - Left and Right Paths



7, 3 and 1.5 Sine Wave Course



Service Environment Example



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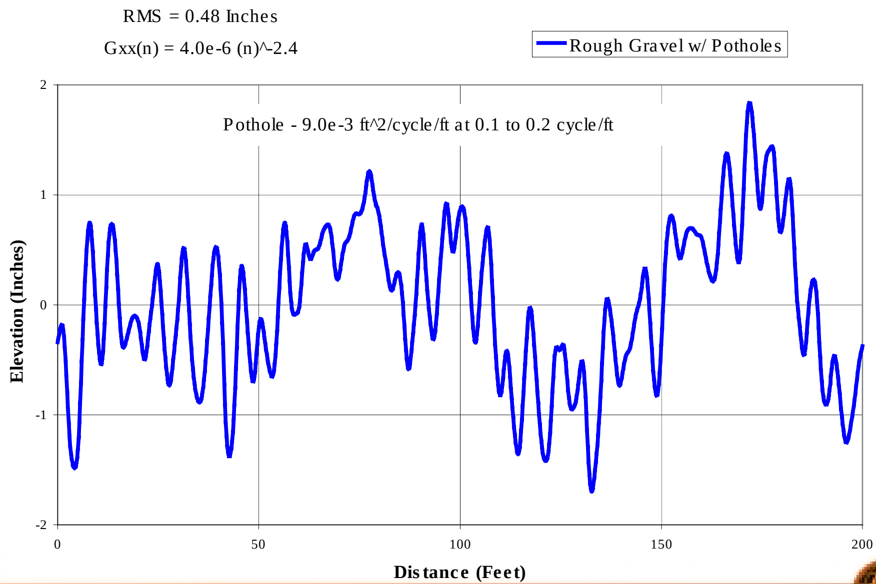
Rough Gravel with Potholes



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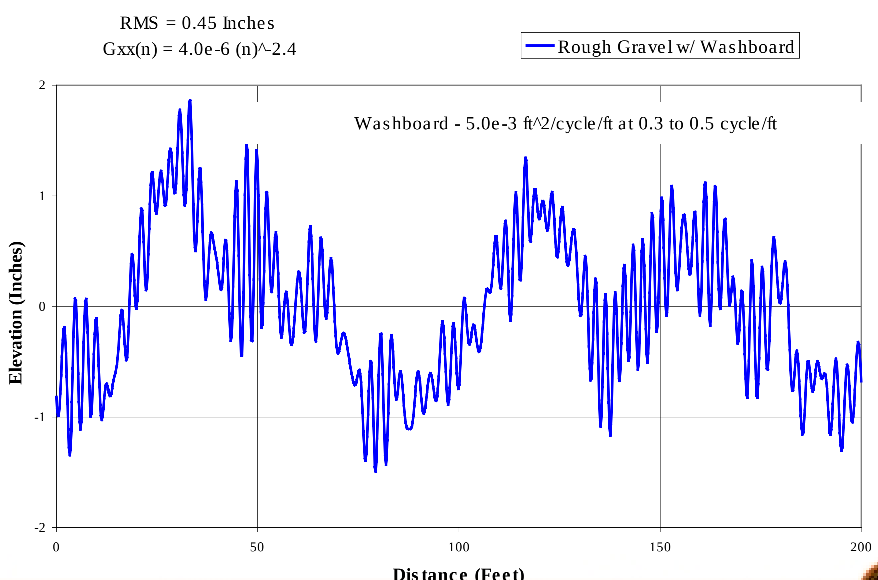
Rough Gravel with Washboard



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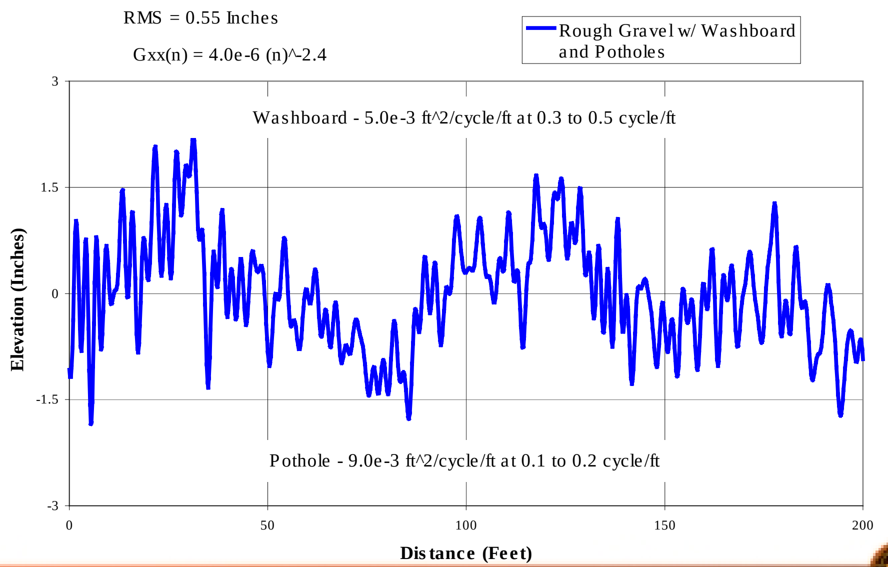
Rough Gravel with Washboard and Potholes



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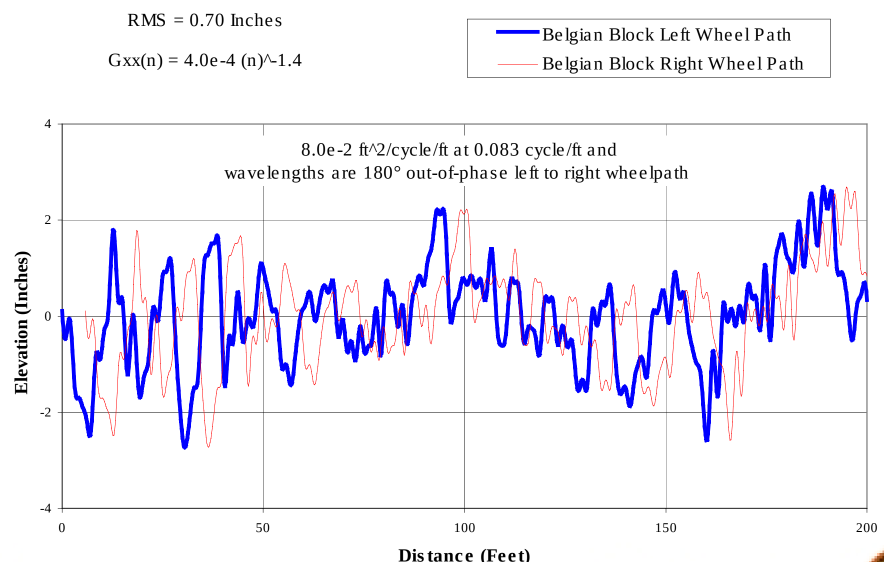
Belgian Block



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Mission Scenarios

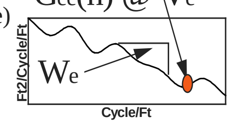
- Establish Baseline
  - On-Road / Off-Road Split
  - “Typical” Sortie Requirements
- Set Parameters for
  - Speed
  - Payload
- Logistics-Based

Accelerated Life Cycle Testing

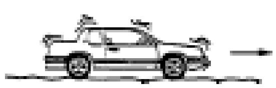
- 15 Years or 250,000 Miles in 16 Weeks and 30:1 Acceleration Factor (Depending on the Service Environment of the Vehicle)

Road Induced Dynamic Load Effects:

$G_{ee}(n)$ @ V_e

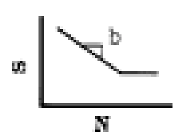


Roughness Profile of Service Environment



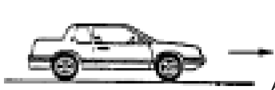
Velocity on Test Course

$$L_t = L_e \frac{V_t}{V_e} \left| \frac{V_t\, G_{ee}(n_{1e})}{V_e\, G_{tt}(n_{1t})} \right|^{\frac{b}{2}}$$



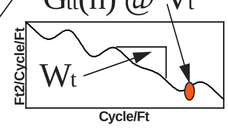
Slope of stress (S) vs number of cycles (N) for structural material (s) under test

Length of travel on the test course is a function of:

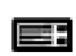


Velocity in Service Environment

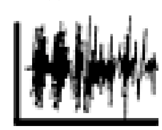
$G_{tt}(n)$ @ V_t



Roughness Profile of Test Environment



Strain Gage



Vehicle natural frequency via strain gage analysis

Vehicle Tests Performed by NATC

- Stability
  - Static Roll Threshold
  - Constant Radius Turning (High and Low Coefficient Surfaces
  - Severe Lane Change
  - Obstacles (Off-Road Stability)
  - Braking Panic, Braking in a Turn (High, Low and Split Coefficient Surfaces)
  - Side Slope Performance

Static Roll Threshold Evaluation

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Stability Testing

Vehicle Tests Performed by NATC (Continued)

- Durability
  - Performed to Duty Cycle (Domestic or International
  - Standard or Accelerated Life
  - Establish Mode of Failure Criteria and Develop Corrective Actions
  - Identify Vehicle System Limitations (Operation, Design)
  - Develop Predicted Reliability

Accelerated Durability Evaluation

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Accelerated Life Evaluation

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Vehicle Tests Performed by NATC (Continued)

- Ride Quality
  - Determine Input to Driver and Cargo While Traversing Various RMS, WNS and Half Round Courses
  - Determine Limits of the Vehicle As a Function of Terrain Type
  - Quantify Resonant Conditioning Which Could Impact System Reliability
  - Quantify Shock and Vibration As a Function of Vehicle Speed
  - Determine Safe Operational Speed
  - Identify Vehicle Parameters to Improve Ride Quality

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Vehicle Tests Performed by NATC (Continued)

- Ride Quality

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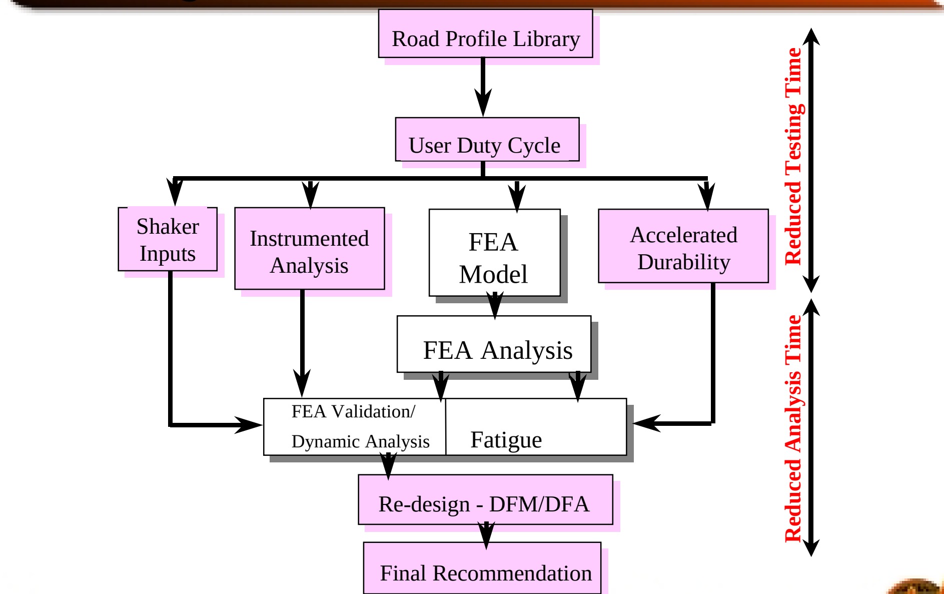
Vehicle Tests Performed by NATC (Continued)

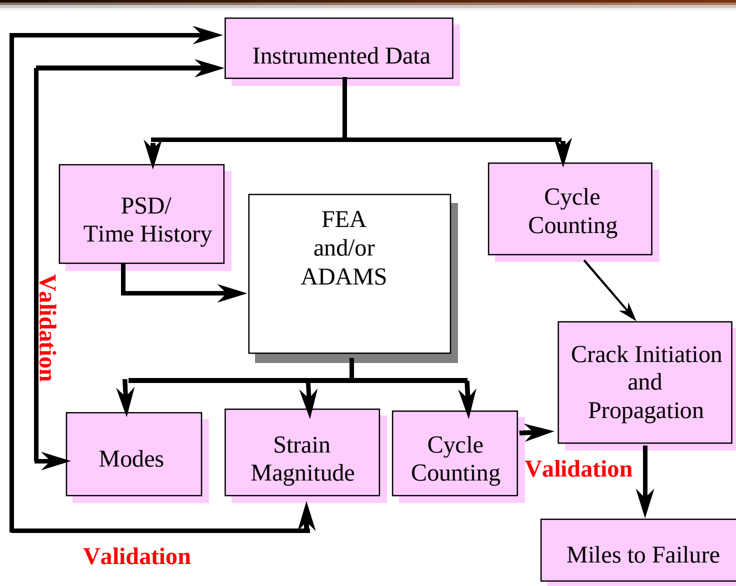
- Mobility

Durability/Mobility Evaluation

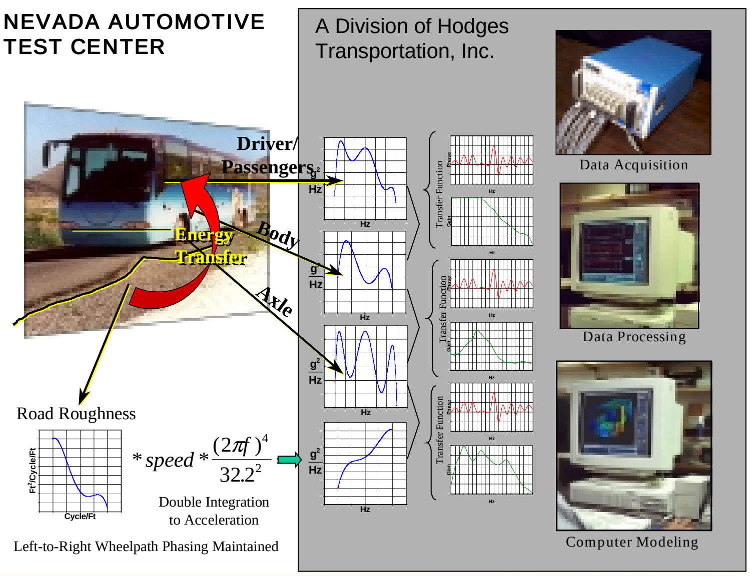
Modeling



Modeling

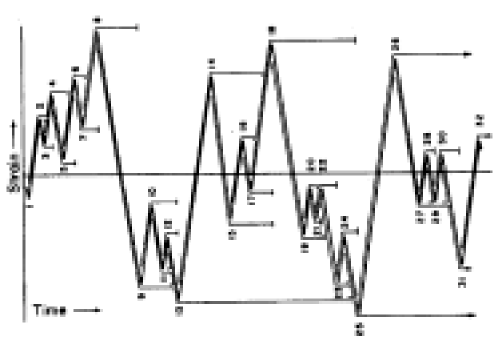


Modeling Integration



Modeling - Fatigue Analysis

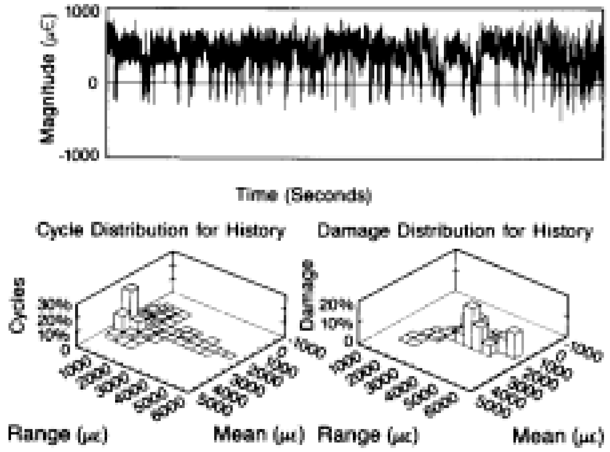
- Rainflow Cycle Counting Method
  - Rainflow Cycle Counting Rules:
    - Rainflow begins successively at the inside of each stress peak
    - Flow continues until it encounters a greater peak than where it initiated if it started at a maximum valued peak, or until it encounters a lesser peak than where it initiated if it started at a minimum value peak; the flow must stop preceding and opposite the new baseline peak
    - Rainflow must stop if it meets the rain from the roof above
  - Note that every part of the rainflow is counted once and only once



Reference: Fatigue Failure Predictions for Complicated Stress-Strain Histories, N.E. Dowling Journal of Materials, March 1972

Modeling - Fatigue Analysis

- Rainflow and Damage Matrices



For this strain-time history, note the difference between the cycles that constitute the majority of the signal and the cycles that constitute the majority of the damage.

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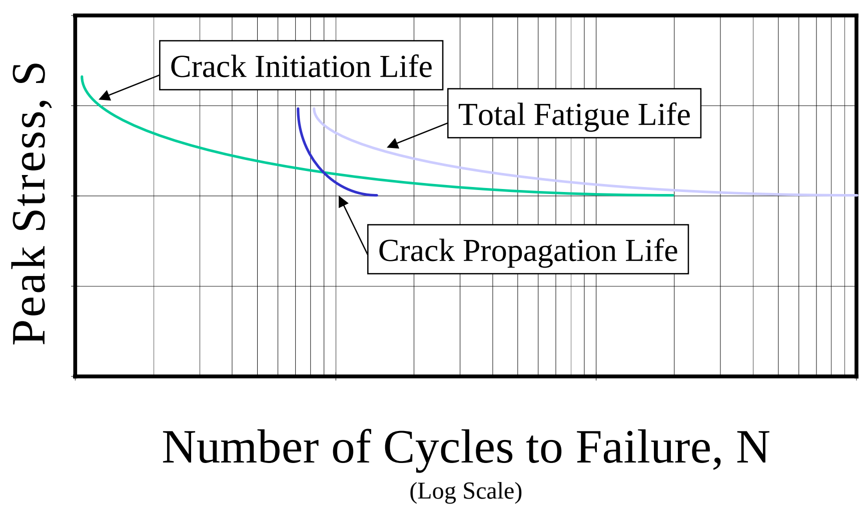
S/N Curves for Two Phases of Metal Fatigue Damage



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Fatigue Damage Principles Assuming Sinusoidal Loading

- Inverse Power Law for Material Fatigue:

$$N = c_1 S^{-b} \quad \text{or} \quad S = c_2 N^{-1/b} \quad \text{where}$$

S = peak value of cyclical stress (psi)
N = number of stress cycles to failure
c_1, c_2 = constants of proportionality
b = fatigue parameter

- The number of stress cycles for an accelerated test that will produce the same fatigue damage as the service environment is given by:

$$N_t = (S_e / S_t)^b N_e \quad \text{where}$$

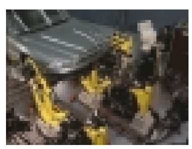
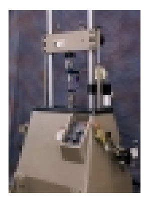
N_t, N_e = number of stress cycles during the test and service environment, respectively
S_t, S_e = peak stress level in the test and service environment, respectively (psi)
b = fatigue parameter

- If the sinusoidal loading in the test and the service environment are at exactly the same frequency f, then the number of stress cycles is proportional to time (N~T), and

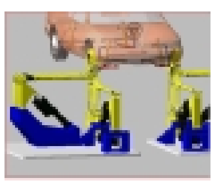
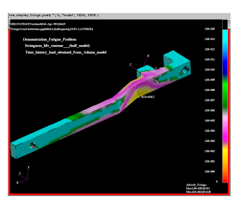
$$T_t = (S_e / S_t)^b T_e \quad \text{where}$$

T_t, T_e = time duration of the test and service environment, respectively (sec)

Modeling - Shaker Analysis

Environment → **Spindle Loads** → **Component Loads** → **Fatigue Life**

Modeling - Shaker Analysis

- Each course input and output parameters are individually modeled using any of the modeling tools
- The input data like the terrain data can be used as an input drive file to the shaker. All the courses are joined together to generate one operational mission drive file for the MTS shaker testing
- The load data at various points are also given as drive file for performing component / part shaker testing for the operational mission profile
- The shaker drive files are typically in RPC II or RPC III format

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Modeling - Dynamic Analysis

- Modeling Methodology - Dynamic Analysis
  - Deflection and Interference Analysis
  - Load and Stress Analysis
  - Fracture and Fatigue Analysis
  - Vehicle Dynamic Response at Operator / Crew Stations (Handling)
  - Provide Driver-in-the-Loop Simulation (Ride Quality, Shock and Vibration)

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Modeling - Dynamic Analysis

- Modeling Methodology - Dynamic Analysis
  - Deflection and interference analysis will be performed by using ADAMS
  - The CAD model will be translated to the dynamic model package
  - Degrees of freedom will be defined for the system
  - Equation of motion will be defined
  - Manufacturer’s standards data will be provided for quantities such as springs, dampers, bushings
  - Proper joint definitions will be given (translation, rotation)

Modeling - Dynamic Analysis

- Modeling Methodology - Dynamic Analysis
  - Proper force functions will be given
  - Terrain profiling data will be the input drive file to the model (operational data)
  - Proper transfer functions will be defined between the tire, the suspension, the other unsprung mass and the sprung mass, such as the frame
  - The model will be processed to obtain output in terms of part interference and part performance
  - Part performance can be quantified as the part deformation, part deflection or the whole vehicle performance

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Modeling - Dynamic Analysis

- Modeling Methodology - Dynamic Analysis
  - The output from this model is validated against the instrumented data
  - This dynamic model will be subjected to various terrain and speed conditions for model validation (for example at 10 MPH, 15 MPH over Perryman 3 or at different speeds for Lane Change Maneuvers)
  - Once the model is validated it can be used for further analysis

Modeling - Dynamic Analysis

Input Model

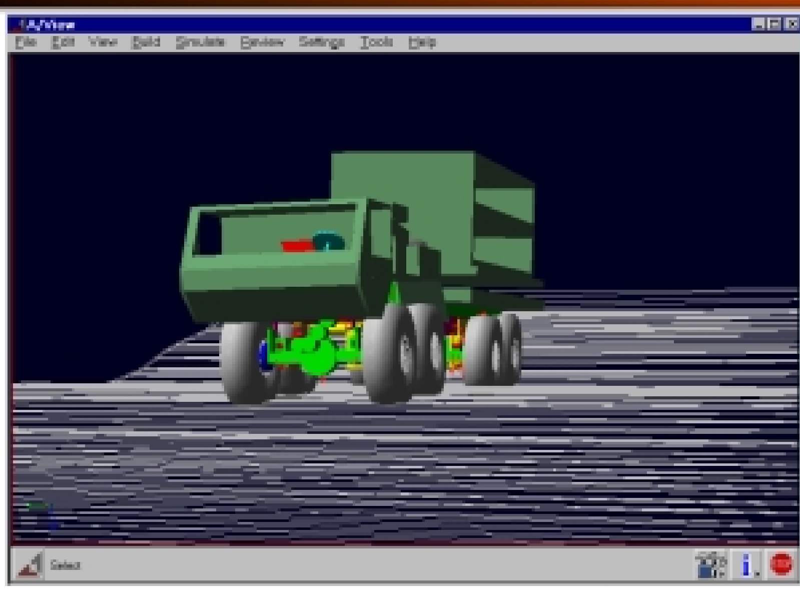
- Terrain modeling
- Tires
- Suspension modeling
  - Parts like tie rods, solid axle
  - Springs
  - Shocks
  - Bushing
  - Airbags
- Cab
- Payload

Modeling - Dynamic Analysis

Results

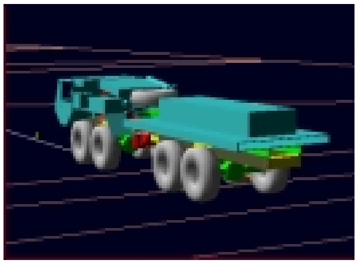
- Suspension optimization using ride quality and handling
- Structure
- Anti-Lock Brake System
- Traction Control System
- Steering Control System - Multi-Axle Steer
- Engine / Transmission Multiple Options (Mission Dependent)
- Results (Continued)
- Central Tire Inflation System
- Driver-in-the-Loop

Current LVS Model



LVS Double Lane Change Simulation at 19 MPH

Double-click on animation...



- Simulation Vs. Test data follows
  - Test data in blue
  - Simulation data in red

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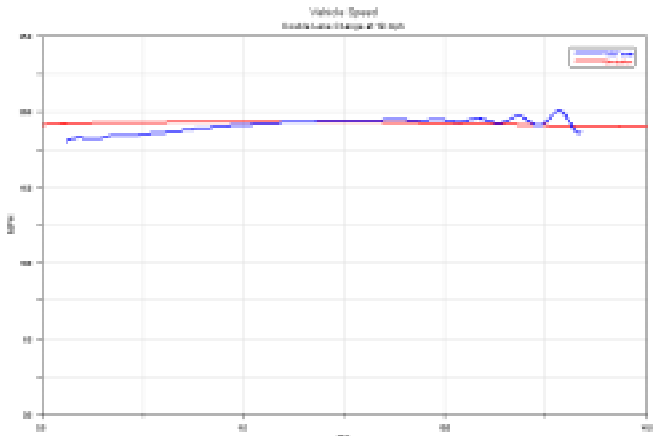
LVS Double Lane Change Simulation at 19 MPH



Vehicle Speed (mph)

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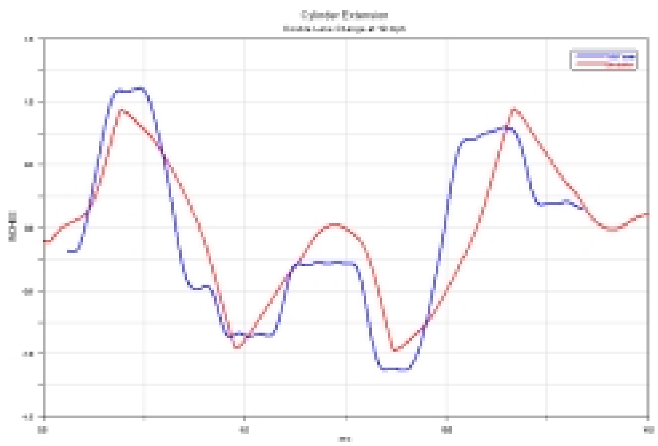
LVS Double Lane Change Simulation at 19 MPH



Articulation Cylinder Displacement (inches)

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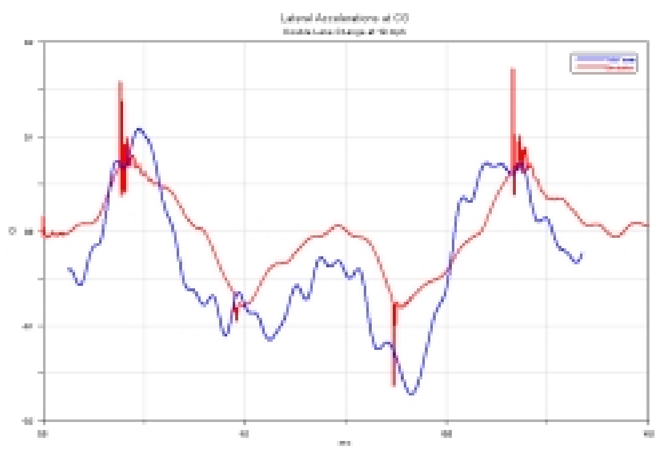
LVS Double Lane Change Simulation at 19 MPH



Lateral Acceleration at CG (g)

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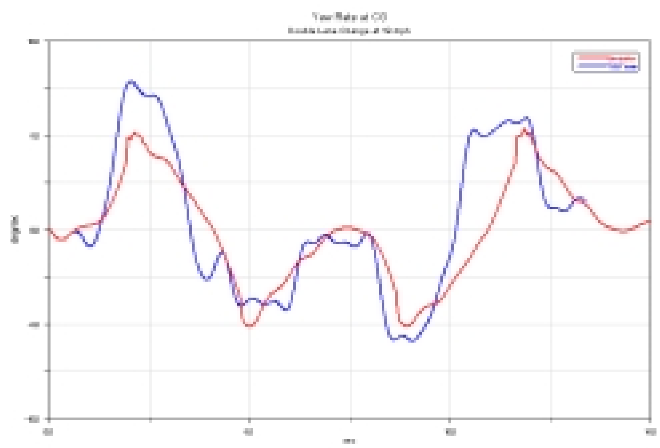
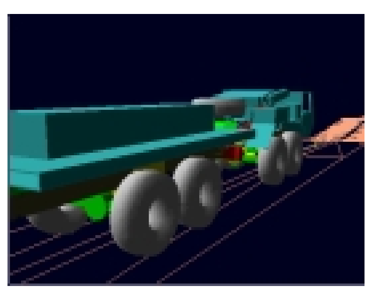
LVS Double Lane Change Simulation at 19 MPH



Yaw Rate at CG (deg/sec)

LVS Perryman III Simulation at 10 MPH



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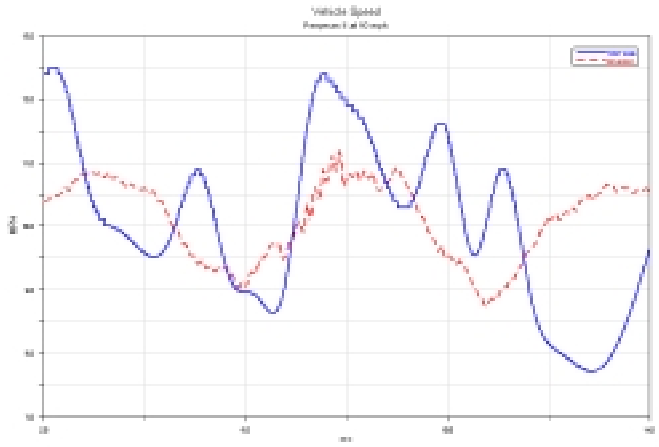
  - Test data in blue
  - Simulation data in red

LVS Perryman III Simulation at 10 MPH



Vehicle Speed (mph)

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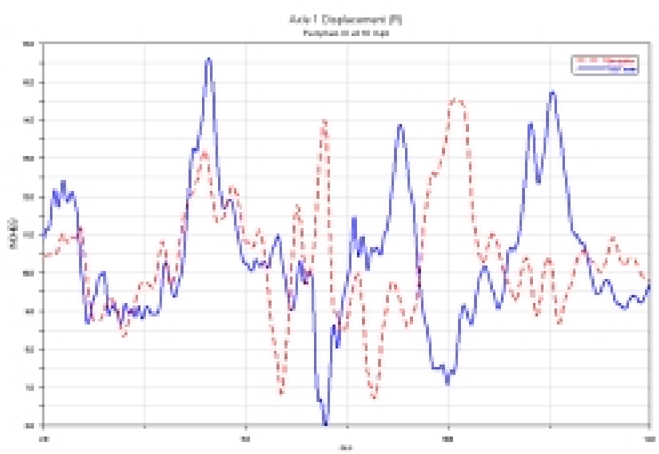
LVS Perryman III Simulation at 10 MPH



Axle 1 Displacement (inches)

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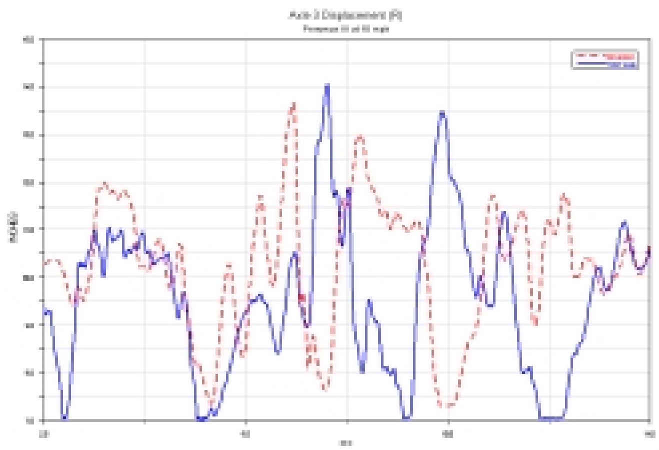
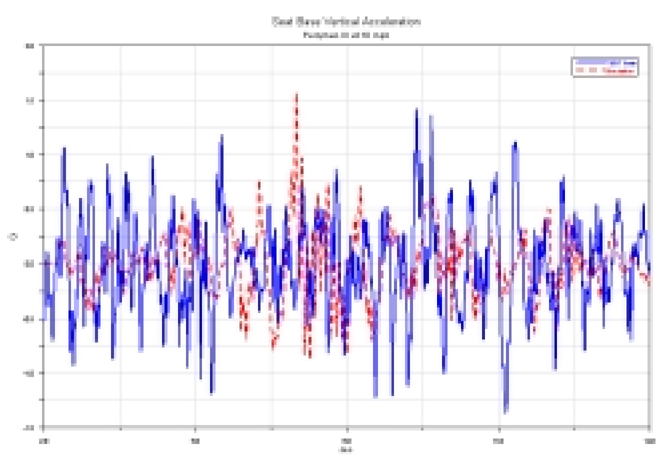
LVS Perryman III Simulation at 10 MPH



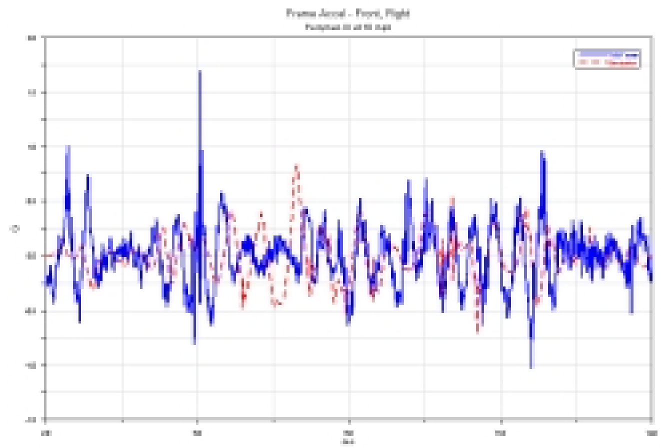
Axle 3 Displacement (inches)

LVS Perryman III Simulation at 10 MPH



Seat Base Vertical Acceleration (g)

LVS Perryman III Simulation at 10 MPH



Right Front Frame Vertical Acceleration (g)

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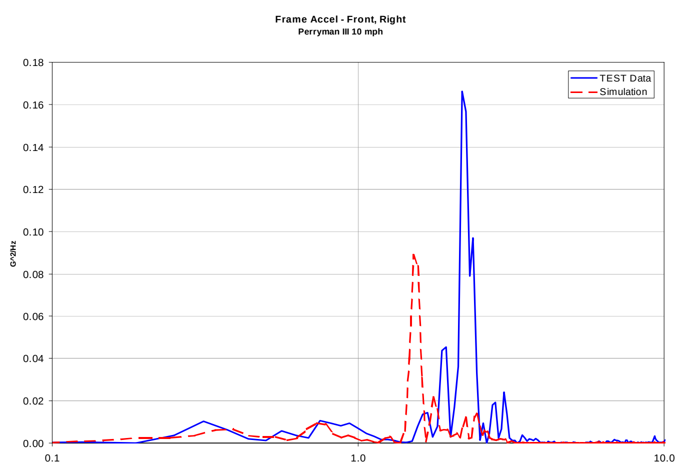
LVS Perryman III Simulation at 10 MPH



Right Front Frame Vertical Acceleration PSD (g^2/Hz)

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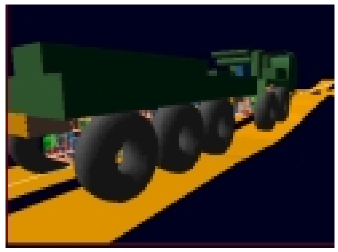
LVSR Perryman III Simulation at 16 MPH



LVSR Double Lane Change Simulation at 26 MPH

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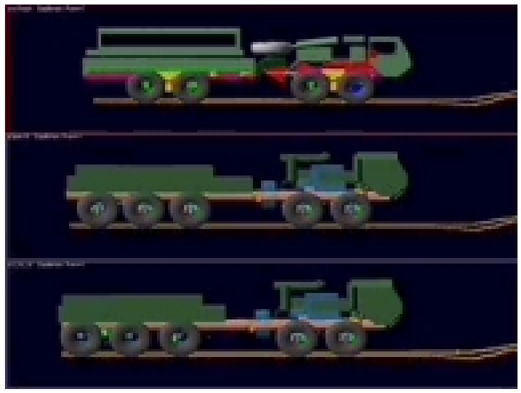
LVS vs. LVSR 1A & 1B Perryman III at 16 MPH



Modeling - Template Development

- Templates are parameterized descriptions of a model's topology. They enable the user to keep model topology and data separate.
- The templates are delivered as part of the toolkit. There will be a template developed for each of the suppliers that are participating in the program. All of the suppliers will have access to all of the templates.
- The data is stored in text files and can either be manipulated directly with a text-editor or thought the ADAMS/Pre GUI. Data will not be supplied as part of the toolkit. Suppliers will not have access to other suppliers' data.
- Rapid-simulation tool
  - ADAMS/Pre can be used to quickly run several simulations and design-of-experiments. Allows user to modify parameters to test different configurations
  - Each template has a series of easy-to-use dialog boxes, which provide access to the data. Offers reporting and plotting capabilities through ADAMS/View

Modeling - Template Events

- Events Based on Physical Tests
  - Tilt table
  - Constant 200' radius circle to 0.4 G lateral
  - Double lane change (ISO 3888)
  - 30% Side slope
  - RMS deformable
  - Gravel oval
  - 2" washboard course
  - Discrete bumps
  - Straight line stopping
  - Split coefficient stopping
  - 500' radius turn stopping
  - 60% grade climb
  - Extended descent
  - USMC Mission Scenarios

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Modeling - Post Technology Demonstration Support

- Capability resident at MARCORSYSCOM
- Training to all appropriate USMC support personnel
- Capability support at manufacturer location
- Quarterly “lessons learned” meetings
- Implementation across all USMC wheeled vehicle platforms

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Modeling - Keys to Success

- Understand the Duty Cycle
- Establish parametric criteria at the start
  - Insure that release engineers understand data requirements
  - Dial them into the process (what do i need)
  - Identify anticipated results (what does it look like)
  - Treat the vehicle as a system (avoid “not my chassis, your body in white”)

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Modeling - Keys to Success

- Establish the pass/fail criteria (what can never fail, how will I quantify this ?)
- Establish model expectations
- Understand the vehicle (avoid quick fix modeling solutions)
- Validate the model (physical test is necessary)
- Develop bounded applications for future iterations (templates, etc)

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