Integration of Virtual Prototyping with Instrumented Testing of Vehicles

Nevada Automotive Test Center

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 Replacement (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 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

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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
LVSR Sponsors

NAVAL SEA SYSTEMS COMMAND

Logistics Vehicle System Replacement

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

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
Define Mission Requirements in Engineering Terms

- Identify Areas of Operation
- Quantify Terrain Severity
- Mission Profile
- Wheel Travel
- Braking System
- Vehicle Mobility
- Tire Size/CTIS
- Powertrain Size/Type
- Cooling
- Frame/Structure

- Helo Transportable
- Payload
- GVW
- 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

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

LVSR Tech Demo Evaluation Plan

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

FPU Suspension
**FPU Steering**

![FPU Steering Diagram]

**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

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
Physical System Testing

- Proving Ground/User Environment
  - User Duty Cycle Definition
  - Road Profiles
  - Accelerated Life Cycle Test
  - Instrumented Performance
  - Evaluation
  - Damage/Fatigue Analysis
  - Prediction
  - Subjective Evaluation

Controlled Environment Testing (Shaker/Stress Lab)

- Component Level and Full Vehicle Testing
  - Instrumentation
  - Damage Analysis/Fatigue
  - Speed/RPM Controller
  - Frequency Controller
  - Load Controller
  - Temperature Controller

Virtual Prototype Testing (ADAMS Simulation)

- Design
  - Drafting
  - Solid Modeling
  - Detailed design including FEA
  - Dynamics Modeling
  - Controls Modeling
  - DFM/DFA
  - Ease of Use
  - Design of Experiment

- Model Validation
  - Virtual Road Profiles
  - Instrumented Vehicle Data
  - Driver in the Loop Stability and Handling
  - Flex/Modal Analysis

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
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.

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.
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
- Establish Pass/Fail Criteria
- Identify Target Country/Markets/Customer
- Identify Competition
- Identify Current Infrastructure and Probable Infrastructure Growth

**Final Duty Cycle**

- 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
    - 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 Comparisons 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

Vehicle Response

<table>
<thead>
<tr>
<th>g's</th>
<th>Hz</th>
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FFT

\[ g^2 \text{ Hz} \]

1 Hz 100 Hz
Road Roughness

Distance (ft)

Elevation (ft)

FFT

\( \text{ft}^2 \)

Cycle

\( \text{ft} \)

.01

Cycle

1

Velocity and Distance (Each Wheel)

Vertical Displacement (Each Wheel)

Stirng Angle (Both Wheels)

Velocity and Distance (Fifth Wheel)

Signal Conditioning

Tape Recorder

Vertical Horizontal Lateral Force (Each Wheel)

Dynamic Force Measurement Vehicle (DFMV) (Continued)
Terrain Elevation Measurement Methodology

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

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

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7, 3 and 1.5 Sine Wave Course

![Graph showing spectral density against wavenumber for 7, 3, and 1.5 sine wave courses.]

Service Environment Example

![Graph showing spectral density against wavenumber for different service environments including High-Quality Paved, Sec Paved, Rough Paved, Gravel, Rough Gravel, Belgian Block, Trails, and X-Country.]
Rough Gravel with Potholes

RMS = 0.48 Inches

\[ G_{xx}(n) = 4.0 \times 10^{-6} (n)^{-2.4} \]

Pothole - 9.0 \times 10^{-3} ft^2/cycle/ft at 0.1 to 0.2 cycle/ft

Rough Gravel with Washboard

RMS = 0.45 Inches

\[ G_{xx}(n) = 4.0 \times 10^{-6} (n)^{-2.4} \]

Washboard - 5.0 \times 10^{-3} ft^2/cycle/ft at 0.3 to 0.5 cycle/ft
Rough Gravel with Washboard and Potholes

RMS = 0.55 inches
Gxx(n) = 4.0e-6 (n)^-2.4

- Washboard: 5.0e-3 ft^2/cycle/ft at 0.3 to 0.5 cycle/ft
- Pothole: 9.0e-3 ft^2/cycle/ft at 0.1 to 0.2 cycle/ft

Belgian Block

RMS = 0.70 inches
Gxx(n) = 4.0e-4 (n)^-1.4

- Belgian Block Left Wheel Path: 8.0e-2 ft^2/cycle/ft at 0.083 cycle/ft and wavelengths are 180° out-of-phase left to right wheel path
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:

\[ L = L_t \left( \frac{V_t}{V_e} \right)^2 \frac{G_{ee}(n) \cdot V_e \cdot G_{n}(n)}{b} \]

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

- Velocity on Test Course
- Velocity in Service Environment
- Roughness Profile of Service Environment
- Slope of stress (S) vs number of cycles (N) for structural material (s) under test
- 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
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

Accelerated Life Evaluation
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
Vehicle Tests Performed by NATC (Continued)

• Mobility

Durability/Mobility Evaluation
Modeling

Road Profile Library

User Duty Cycle

Shaker Inputs

Instrumented Analysis

FEA Model

FEA Analysis

FEA Validation/ Dynamic Analysis

Fatigue

Re-design - DFM/DFA

Final Recommendation

Reduced Testing Time

Reduced Analysis Time

Instrumented Data

PSD/ Time History

FEA and/or ADAMS

Cycle Counting

Crack Initiation and Propagation

Validation

Validation

Modes

Strain Magnitude

Cycle Counting

Miles to Failure

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Modeling Integration

NEVADA AUTOMOTIVE TEST CENTER

Driver/ Passengers

Body

Axle

Road Roughness

\[ \text{speed} = \left(\frac{2\pi}{32}\right)^2 \]

Double Integration to Acceleration

Left-to-Right Wheelpath Phasing Maintained

A Division of Hodges Transportation, Inc.

Data Acquisition

Data Processing

Computer Modeling

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

**Modeling - Fatigue Analysis**

- Rainflow and Damage Matrices

![Graph of Rainflow and Damage Matrices](image1)

**S/N Curves for Two Phases of Metal Fatigue Damage**

- Crack Initiation Life
- Total Fatigue Life
- Crack Propagation Life

Number of Cycles to Failure, $N$

(Log Scale)

![S/N Curves Graph](image2)
**Fatigue Damage Principles Assuming Sinusoidal Loading**

- **Inverse Power Law for Material Fatigue:**
  \[ N = c_1 S^{-b} \quad \text{or} \quad S = c_2 N^{1/b} \]
  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:
  \[ N_t = (S_t / S_e)^b N_e \]
  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 (\( N \sim T \)), and
  \[ T_t = (S_t / S_e)^b T_e \]
  where \( T_t, T_e \) = time duration of the test and service environment, respectively (sec).

**Modeling - Shaker Analysis**

Environment \( \rightarrow \) Spindle Loads \( \rightarrow \) Component Loads \( \rightarrow \) 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.

**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)
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)

- 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
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

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

Vehicle Speed (mph)
LVS Double Lane Change Simulation at 19 MPH

Articulation Cylinder Displacement (inches)

LVS Double Lane Change Simulation at 19 MPH

Lateral Acceleration at CG (g)
LVS Double Lane Change Simulation at 19 MPH

Yaw Rate at CG (deg/sec)

LVS Perryman III Simulation at 10 MPH

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

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

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
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”)

- 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)