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SIMULATION OF GROUND VEHICLE MOBILITY EVALUATION WITH MERCURY

Jacob Brendle, Jacob Woten, Sara Boyle, Jeremy Mange, PhD, and Thomas Skorupa

CCDC GVSC – Analytics, Warren, MI

ABSTRACT

Mobility is a crucial vehicle requirement for the Army, as it needs to ensure that soldiers to not become immobilized in conflict. The Army currently pays thousands of dollars annually in order to obtain licenses for commercial software to analyze vehicle mobility. The High Performance Computing Modernization Program (HPCMP) Computational Research and Engineering Acquisition Tools and Environments for Ground Vehicles (CREATE™-GV) Mercury attempts to provide the Army with a high-fidelity tool that can analyze mobility at the same level as commercial software, while being owned and developed by the government. By providing a government owned mobility software, Mercury eliminates licensing fees and allows development of the software to be focused on military applications and what the Army needs. Mercury can continuously evolve to meet the Army's future goals and requirements.

Mercury currently is capable of modeling many vehicle subsystems in order to provide very robust vehicle models. These vehicle models can then be run through an assortment of mobility tests that the Army runs its vehicles through in the physical world. By modeling high-fidelity vehicles within Mercury first, the Army can easily test new concepts for vehicles before spending funds on building a physical prototype. This study will provide an overview of Mercury as well as an example of a vehicle modelled and ran through Mercury.

1. INTRODUCTION

Multi-body dynamics simulation is critical to the US Army's mission. It allows engineers to analyze one of the main "-ilities" of the Army: mobility. Currently, there are several multi-body dynamic software packages that satisfy this need, however, they cost the army thousands of dollars every year in licenses. The HPCMP CREATE™-GV looks to fill this gap by developing a government owned multi-body dynamics software called Mercury. Mercury is a high-fidelity co-simulation tool that brings together detailed vehicle, terrain, and powertrain models. It uses a defined simulation procedure, extensive logging and metric calculations, and a flexible architecture. Mercury uses a synchronized execution of multiple context-specific simulations, which allows for the use of "specialized" systems within the larger framework.

Mercury has been written to perform many of the standard mobility tests used within the Army, such as NATO Double Lane Change and Static Rollover. All of Mercury's capabilities will be discussed at length in this paper. Mercury runs all of these tests on the high performance computing system Onyx, allowing for large batches of tests to be run in a short amount of time. Utilizing the extensive logging done by Mercury, a large number of vehicle aspects can be tracked for validation purposes. For example, with the NATO Double Lane Change test, not only does Mercury track a pass/fail metric, but the roll of the vehicle and steering information as it completes the maneuver. With the Ride Quality test, Mercury tracks the metrics of 6-Watt speed and absorbed power, along with orientation angles of the vehicle. Both the desired metric and time series data of the vehicle are very important to mobility analysis. The output can be used to verify that we are calculating the metrics appropriately in order to match test operating procedures developed by the Army. The time series data can be used to verify that the vehicle is behaving in a way that mimics the physical world.

This report takes a deep look at the procedures and results of Mercury simulations compared against both real life test data and commercial software. To do this, we will be conducting a validation and verification study of Mercury with a wheeled vehicle. This study will validate that Mercury is running its mobility simulations in a way that is realistic and useful to its users, while also verifying that the results coming out of Mercury are mimicking the behavior that is observed in real life vehicles. Performing this comparison will provide greater insight to a powerful, government owned tool being developed by HPCMP CREATE^{TM}-GV. By providing this insight, it is desired to get this tool into the hands of more mobility and dynamics subject matter experts for their use. In the future, as more experts are using the software, it will continue to grow to cover even more aspects of mobility, as well as other "-ilities" that are important to the Army's mission.

2. MERCURY OVERVIEW

Mercury is a co-simulation software framework that has three main components:

1. Modules – an implementation of a specific vehicle sub-system with inputs and outputs for each timestep of the co-simulation
2. Simulation – a combination of two or more Modules run in a time-stepped vehicle simulation
3. Tests – instances of specific mobility tests with specific predefined terrain and maneuver information, that report mobility metrics

The main Modules in Mercury include vehicle dynamics, vehicle-terrain interaction, powertrain, driver models, and vehicle control system modules.

The vehicle dynamics module models many of the different vehicle sub-systems, including the chassis, driveline, and suspension systems. The vehicle dynamics modules uses the forces and torques at the wheel hub generated by the vehicle-terrain interaction module to calculate the state of the rigid bodies comprising the chassis, steering, and suspension systems. Mercury uses Chrono [1], an open source multi-physics simulation engine, for the vehicle dynamics module. Of particular interest is the Chrono::Vehicle API, which is a C++ middle-ware library designed for modeling and simulation of wheeled and tracked vehicles. The Chrono::Vehicle API supports a JavaScript Object Notation (JSON) template-based approach to build the many sub-systems for both wheeled and tracked vehicles.

The powertrain module models the engine and transmission of a ground vehicle and calculates the torque applied to the vehicle drive-shaft. Depending on the details of the powertrain simulation being implemented, it may make use of the vehicle state, driver state, and wheel state information to perform the calculations. There are several different powertrain models available through Chrono::Vehicle, including a simple powertrain, maps powertrain, and shafts powertrain. The simple powertrain model requires only maximum engine speed, maximum engine torque, and single gear ratio. The maps powertrain model is a more realistic powertrain simulation module based around the definition of several different engine maps, such as an engine speed / torque map, shift point maps, and a transmission losses map. The shafts powertrain model is a more realistic powertrain simulation module based around different engine and transmission information, such as motor and crankshaft inertias, torque map, torque converter, and transmission gear ratios. The Powertrain Analysis Computational Environment (PACE) [2] is a more advanced powertrain modeling capability that is being incorporated into the Mercury codebase as well.

The Vehicle-Terrain Interaction (VTI) calculates the forces and torques generated by contact of the tire or track with the terrain and updates the forces and torques on either the wheel hub or the various track bodies. The tires/tracks and terrain are a tightly coupled system and are therefore treated as a single sub-system in the Mercury simulation. The Chrono::Vehicle API supports several different tire modeling capabilities, including Fiala [3], Tmeasy [4], Pacejka [5], and Finite Element Modeling (FEM) [6] tire models. The Chrono::Vehicle API also supports tracked modeling capabilities, including single-pin, double-pin, and band track models. The Ground Contact Element (GCE) [7] model, a coupled tire/soil model that focuses on soft soil interactions, is also incorporated into Mercury.

The driver module determines the throttle, brake, and steering settings for the Mercury simulation. The driver module has controllers to set the speed and to also perform specific driving maneuvers by using path planning. In addition to this there are many advanced features that can be used for specific test cases, such as steering and throttle rate limiters.

There are also vehicle control system modules for anti-lock braking system and electronic stability control implemented in Mercury. These control systems are only available for use with wheeled vehicle models and they introduce control by applying braking commands dependent on different characteristics of the vehicle simulation.

Mercury also has the capability of modeling more complex vehicle assemblies that include towing a trailer or a vehicle. There are several different types of connections that can be used for attaching the trailer or towed vehicle to the main vehicle, including cylindrical, hook, spherical, and fifth wheel connections.

A test rig capability is currently being implemented as well to test sub-system models before using them in the full Mercury simulation. The vehicle test rigs will support testing individual wheel, suspension, or track assembly components with a variety of input and scenario options.

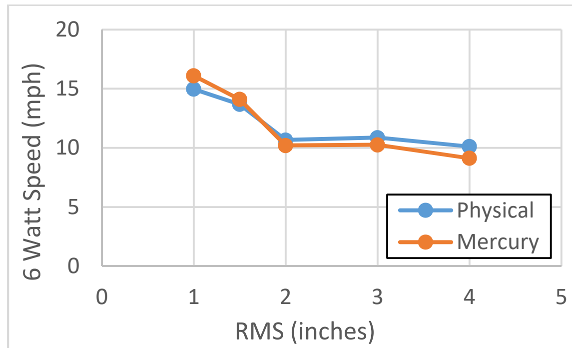
3. RESULTS OF MERCURY RUNS

For this study, a vehicle was ran through various test scenarios for which there was physical test data available to validate results against. The vehicle is 13,000 pounds and has two axles with a double wishbone suspension at each axle. All simulations for this study were run on the HPC Onyx, as that is the HPC that is currently available for users of Mercury to launch their jobs. By partnering Mercury with Onyx, the users gain the ability to run massive numbers of jobs without straining their personal work stations. This allows for faster run times and eliminates the need for users to make sure that their personal computer will not be undergoing maintenance during run times.

3.1. Ride Quality

The first simulation scenario will be looking at the vehicle performing a series of ride quality tests. The purpose of this simulation is to evaluate the vehicle's ride dynamics to ensure the safety of the driver and crew of the vehicle across rough terrains. In Mercury, the vehicle is run over 36 terrain profiles of varying RMS values. These RMS values range from 1 inch to 5 inches. For the general user experience, the vehicle is run over each course multiple times at different speeds, the results of which are used by the solver to calculate the true 6 Watt speed. Once Mercury has found the 6 Watt speed for each terrain, it then plots the 6 Watt speeds versus the corresponding terrain RMS value. In this situation, the 6 Watt speeds for the vehicle was known, so the vehicle was ran at a range of speeds around that speed. Figure 1 shows the Mercury ride quality test results and physical test results for the vehicles.

Figure 1: Ride Quality Curve



The test results in Figure 1 show a very close correlation between Mercury simulation and physical test data.

3.2. Shock

The next simulation scenario takes a look at the vehicle performing a series of shock absorber tests. The purpose of this test is to introduce an obstacle to the vehicle traveling at a certain speed. This test records the acceleration produced by the jounce that happens when the vehicle hits these half rounds. The maximum amount of acceleration a vehicle is allowed to experience in these scenarios is 2.5g. In Mercury, the vehicle is run over 7 different half rounds with radiuses measuring 4, 6, 8, 10, 12, 14, and 16 inches. For the general user experience, the vehicle is run over each half round multiple times at different speeds, the results of which are used to calculate the true 2.5g speed. Once again, for this analysis, the 2.5g speeds were already known from physical test data for the 10 inch half round, so the vehicle was ran at a range of speeds around that speed. Chart 1 shows the Mercury shock test results and physical test results for the vehicle going over a 10 inch half round.

Chart 1: 10 Inch Half Round Results

	2.5g Speed (mph)
Physical Test	16
Mercury Simulation	17.04

The test results shown in Chart 1 show a close correlation between Mercury simulation and physical test data.

3.3. NATO Double Lane Change

Another simulation scenario that was run was the vehicle going through the NATO double lane change, or obstacle avoidance, test. The purpose of this test is to test a vehicle's maneuverability when suddenly faced with an obstacle. To set up this scenario both in real life and within Mercury, a course of cones is set up with dimensions based on the vehicle's overall length and width. Once the course is established, the vehicle makes many runs through the course while increasing speed after each successful run until the vehicle fails the test. The test is considered a fail if the vehicle hits any of the cones or if a tire is lifted off of the ground. Mercury detects tire lift off by watching each tire and ending the simulation if it no longer detects a normal force between the ground and any of the tires. During this test, the lateral acceleration, roll angle, and yaw rate of the vehicle are also recorded in order for inspection of the dynamics of the vehicle during the test. The figures below show these parameters versus time from the Mercury simulation as well as physical testing for the vehicle while completing the double lane change at 40 mph.

Figure 2: Lateral Acceleration vs. Time

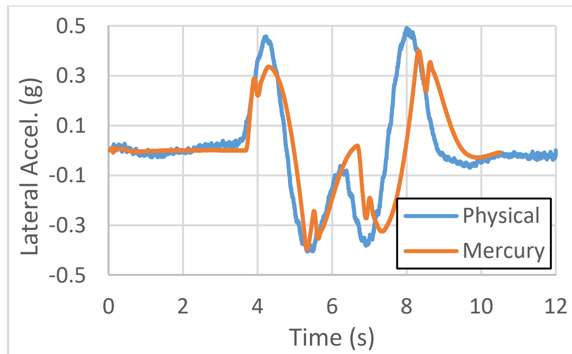


Figure 3: Roll Angle vs. Time

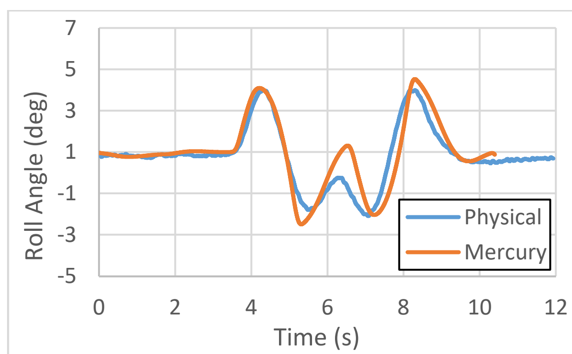
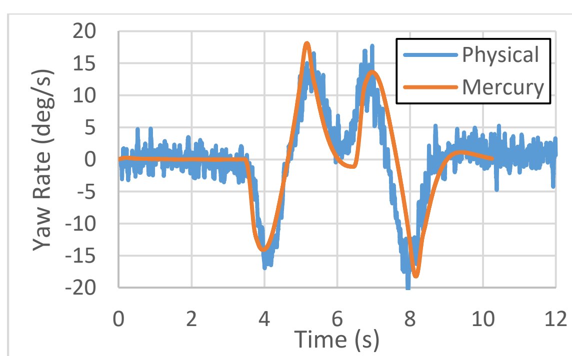


Figure 4: Yaw Rate vs. Time



For this vehicle, the physical test team unfortunately did not run the double lane change until fail. Instead, they made several runs at three different speeds. The figures above show some of the main data points that are observed for this test while running at 40 mph. While the data matches well, it is important to note that it can be very difficult to mimic the mindset of a human driver in a simulation. This can cause slight variations in the shapes of the curves that are generated, causing them to be jagged and less smooth. This is because the simulated driver's response time and input to the steering can be much quicker than a real human driver. Differences in the dynamics of the vehicle between physical and test data can be attributed to the driver as well as differences in suspension stiffnesses.

3.4. Braking

The next simulation scenario that was run was the vehicle performing a braking test. For this test, the vehicle is driven up to a specific speed and then full braking is applied. The distance travelled during the braking period is recorded. This test is useful to see how long it takes a vehicle to stop from specific speeds, as well as observing how the vehicle performs dynamically under full brakes. The figures below show some of the parameters that may be observed during this test. Chart 2 compares the maximum braking distance that was required for the vehicle to stop.

Chart 2: Braking Test Metrics

	Distance (ft) from 20 mph start	Distance (ft) from 40 mph
Physical Test	23.0	89.9
Mercury Simulation	19.5	78.1

While the straight line braking test results are similar, it should be noted that this particular Mercury vehicle model is using a simple brake model. The simple brake model simply applies a maximum braking torque to the wheel. It does not account for varying brake temperatures, control systems, brake wear, or any other factors at play.

3.5. Steady-State Cornering

The final simulation scenario for this study was running the vehicle through the steady-state cornering test. This test is performed by allowing the vehicles to drive in a circle of a constant radius while slowly increasing speed until fail. The test is considered a fail when the vehicle fails to maintain the circle or tire lift off is detected. The purpose of this test is to record the vehicle's lateral acceleration, roll angle, and yaw rate. The understeer or oversteer gradient of the vehicle can also be measured from this test. Chart 3 compares some of the metrics from this test between Mercury and the test data.

Chart 3: Steady State Cornering Metrics

	Max Speed (mph)	Max Lat. Accel. (g)
Physical Test	27	0.55
Mercury Simulation	29.5	0.65

4. FUTURE WORK

Goals and future work of Mercury are always evolving as the atmosphere of needed analysis changes with the need of soldiers. Mercury 3.0 has provided a number of new vehicle component types and major capability tests, but much is still planned for Mercury 4.0 and later releases. The following are major capabilities being implemented for version 4.0:

1. Soft soil mobility of tracked vehicles – Focus on a Ground Contact Element or discrete element method (DEM) approaches for tracked vehicles (single-pin, double-pin, and band tracks)
2. Tow-like vehicles tests – Variety of tests involving towing a vehicle of the size category
3. Integration of sensors and autonomous vehicles – Development of a module or bridge to allow users to connect autonomous intelligence to Mercury for evaluation
4. PACE – Further integration of a new modular approach to the Powertrain Analysis and Computational Environment

4.1. Sensors for Autonomous Unmanned Vehicle Simulations

As the theater changes and operational needs evolve, autonomous vehicles are moving to the foreground. Mercury recognizes the need for a high fidelity testing of autonomous systems. What Mercury would provide that normal testing software does not is the vehicle dynamics that can have adverse effects on a system, along with the mobility evaluation of autonomous vehicles. A number of solutions are being pursued for implementation for this. ERDC's Virtual Autonomous Navigation Environment is being looked at, as well as Robotic Operating System and the Unreal game engine. Mercury would allow for a black box intelligence to provide inputs, such as throttle, braking, and steering, that could control the Mercury vehicle. The black box intelligence itself would need the capability to create, sense, and traverse a scene (from VANE or another virtual environment). The major effort on the Mercury development will be finding a common ground among the different sensor/intelligence packages to provide a way to drive the simulation.

4.2. Updates to the Verification and Validation Tool Sets

As Mercury grow, more work becomes involved with V&V process for it. New tools are being developed, as well as current tools being updated, to keep up with the demand. The main focus of these tools are automation of processes that currently involve human input. Automation of HPC job submission, graph generation with data overlay, and vehicle-level report generation are areas of focus.

4.3. Vehicles for Validation

The number of vehicles that Mercury uses for vehicle validation is ever growing. Focus on vehicles with a greater variety of vehicle sub-systems and characteristics will greatly increase the ability to test new features that users may request.

5. CONCLUSION

CREATE™-GV Mercury is a high-fidelity, multi-body dynamics tool that satisfies many of the Army's needs for evaluating vehicle mobility. The use of HPC systems with the high-fidelity code-base allows for users to easily run a great number of simulations in a short amount of time. As the software continues to grow and shape itself based on the Army's needs, it will continue to provide users with mobility analysis for ground vehicles.

6. REFERENCES

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