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ADDRESSING THE SOFT SOIL TOWING CAPABILITY OF A NOTIONAL RECOVERY VEHICLE USING NEXT GENERATION M&S TOOLS

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ABSTRACT

Sustaining readiness is a core component of the Army Modernization Strategy and the fleet of ground vehicles must be capable and available to fight when called to action even as additional requirements such as additional armor and electrical loads are imposed on such systems. In support of this principle, Combat Capabilities Development Command Ground Vehicle Systems Center (CCDC GVSC) provided Program Executive Office Ground Combat Systems with modeling and simulation (M&S) expertise to analyze soft soil towing capability of a notional recovery vehicle. The analysis involved simulating a notional recovery vehicle and disabled towed main battle tank up a slope and developing design changes to improve soft soil towing performance.

1. INTRODUCTION

Operational demands on Army ground vehicles continue to increase, especially as vehicle platforms align their capabilities with the Army Modernization Strategy. Despite growing weights and electrical loads, the ground vehicle fleet, including recovery vehicles, must be ready and capable to accomplish the mission. One use case is towing a main battle tank up a terrain of a specified slope, including the consideration of soft soils. Several experimental design studies have been conducted to improve soft soil towing performance, but limited success has been achieved. An alternate approach is to use high-fidelity modeling and simulation to help identify effective design solutions to achieve the increased mobility requirement.

Engineers at the CCDC GVSC had previously developed dynamic full vehicle models for both notional recovery and main battle tank vehicles and had simulated these vehicles traversing rigid terrain. However, a simulation of the vehicle operating on soft soils was needed for the current evaluation. Thus, a process to model and simulate the tracked vehicle combination while taking into account track-to-soft soil interactions was developed and implemented in this study.

The prediction of vehicle behavior on soft soils is extremely difficult because many factors influence the behavior of the soil when interacting with tracks

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or tires, and those factors are constantly varying in most example terrains. Consequently, the “worst case” soil properties that reasonably match previously obtained soil samples and test cases from proving grounds were used. Likewise, the “worst case” soil parameters were used to conservatively predict the behavior of the vehicles with hardware modifications. In a climbing maneuver the key aspect of the soil modeling is to determine the shear breakout force, since slip is the limiting factor to climbing.

2. OBJECTIVE

The objective of this project was to develop the methodology to evaluate with high fidelity the towing ability of a notional recovery vehicle with regards to pulling a main battle tank up target soft soil grades. This is done by developing a high-fidelity dynamics model of the recovery vehicle that includes detailed depictions of the track assemblies with individual track links and the vehicle suspension. The individual links interact with a detailed soil model for a climbing event in the target soil, such that the individual normal, lateral, and longitudinal forces are considered with the track/soil interaction. Validation testing was conducted to build confidence in the closed loop simulation before analyzing several design configurations to improve soft soil towing performance.

Note that any ground condition that is not pavement may be referred to as a soft soil. In this case the target obstacle is a hill that has a thin layer of soil covering a base of gravel. The result of simulations done in the gravel-based soil may be significantly different than the result of a climbing event in a loam soil or sand. For example, ground pressure is not an issue for a climbing event in a gravel soil, but it could be a significant factor in other soils. Consequently, the best vehicle configuration for the climbing event while towing may not be the best vehicle configuration for other mobility events.

3. APPROACH

The modeling and simulation approach consisted of four high-level steps as summarized in the eight blocks of Figure 1. The first step involved analyzing test data to determine the pintle force experienced during main battle tank towing operations on the soft soil slope as shown in blocks 1 and 2. Representing the main battle tank in simulation as a force vector on the pintle rather than a full fidelity vehicle model with track to soil interaction simplified the modeling process and decreased computation time significantly. A set of proving ground test data that included historical recovery vehicle pintle force measurements versus time for towing operations up the soft soil slope of interest was analyzed. Twelve time series measurements were averaged to determine a representative force exerted by the disabled main battle tank on the recovery vehicle. In order to provide a margin of safety and to account for variability in the soil and vehicle performance, the pintle force extracted from test data was scaled by 110% before being used in the simulations.

The second step, as shown in blocks 3 and 4, was to use a complex physics-based Discrete Element Method (DEM) soil modeling approach [1] to best capture the behavior of the recovery vehicle track-

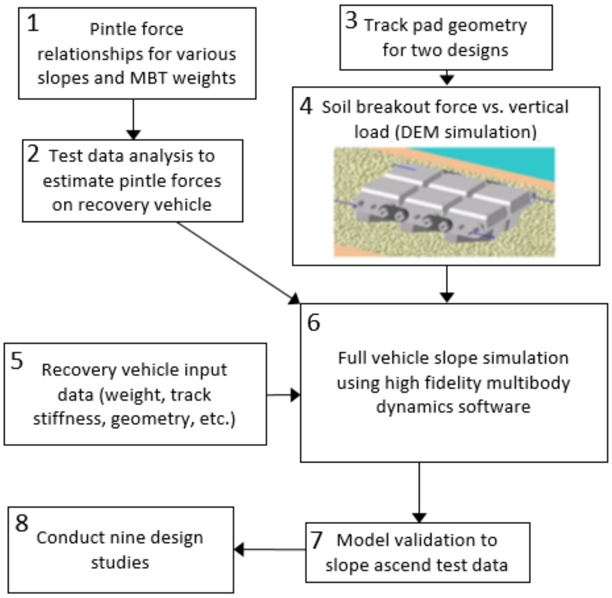

Figure 1: Modeling and Simulation Approach.

to-terrain interaction. This process is described in detail in Section 4.

The third step was to run multibody dynamics simulations [2] of the full vehicle and validate the system with available physical test data. This step is summarized by blocks 5-7. The details of this step are given in Section 5.

The fourth step, as shown in block 8, was to perform design studies and determine a vehicle definition that would attain the desired performance. This is described in detail in Section 6.

4. SOIL CHARACTERIZATION

Particle-based methods are computationally expensive such that it would be prohibitive to model the entire soft soil slope as particles interacting with the entire vehicle in one simulation. Instead, the problem was broken into its constituent components. Three track shoes and a DEM particle-based soil bin simulation were used to develop traction curves used by the recovery vehicle to simulate operating in soft soil terrain. Nonlinear relationships for track pad traction as a function of normal force, sinkage, and track slip were generated and imported as a subroutine into a multibody dynamics simulation. The subroutine was appropriately applied to all track shoe's in contact with the soil to capture the behavior of a high-fidelity soil model without an excessive amount of computational time during the vehicle simulation.

Discrete element modeling (DEM) can be an effective technique for modeling soils in higher fidelity than past approaches that represent the interaction between a tire (or track) with soil using a small set of equations. Extensive research has been conducted for a variety of applications from earth-moving studies [3] to vehicle mobility analyses, including both wheeled [4] and tracked vehicles [5]. In this project the EDEM software from DEM Solutions of Edinburgh, Scotland was used.

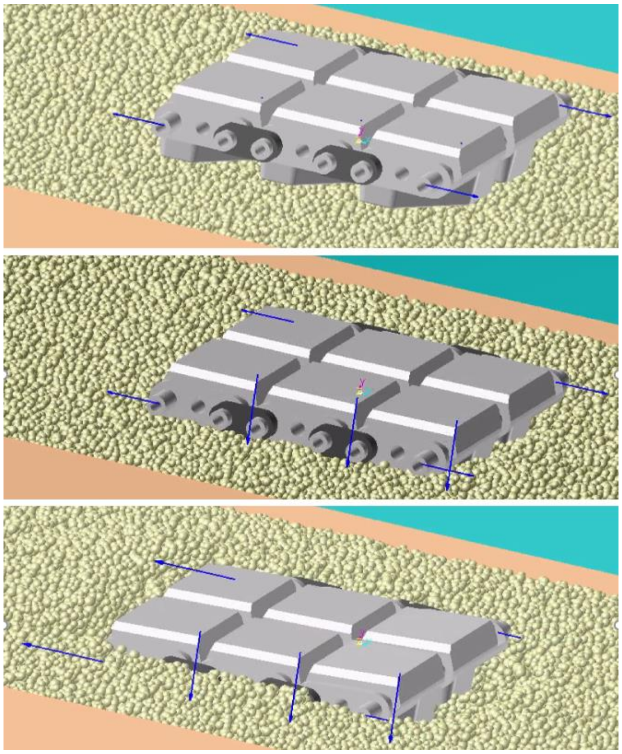

Figure 2: Track Link Soil Engagement.

Figure 2 shows an initial simulation of the interaction of a set of three track links with the DEM-based soil. In this model there are 87,000 particles, each one made up of three spheres. The total number of spheres is more than ¼ million. Three track links are used because the outer two track links provide the proper boundary conditions for the middle track link. Output data is only retrieved from the middle track link.

In this example the soil is too soft (the cohesion is too low). The top frame is the starting position of the track links. In the middle frame a set of vertical forces have been applied to the track links, representing the vertical forces caused by the weight of the vehicle as applied through the road wheels. The middle track link has the highest load because it is assumed that a road wheel is resting on it. Because the soil representation is too soft, in the middle frame it can be observed that the track link has sunk into the particles down to the connecting links. Then, as the track tension (horizontal) becomes imbalanced to represent the effect of

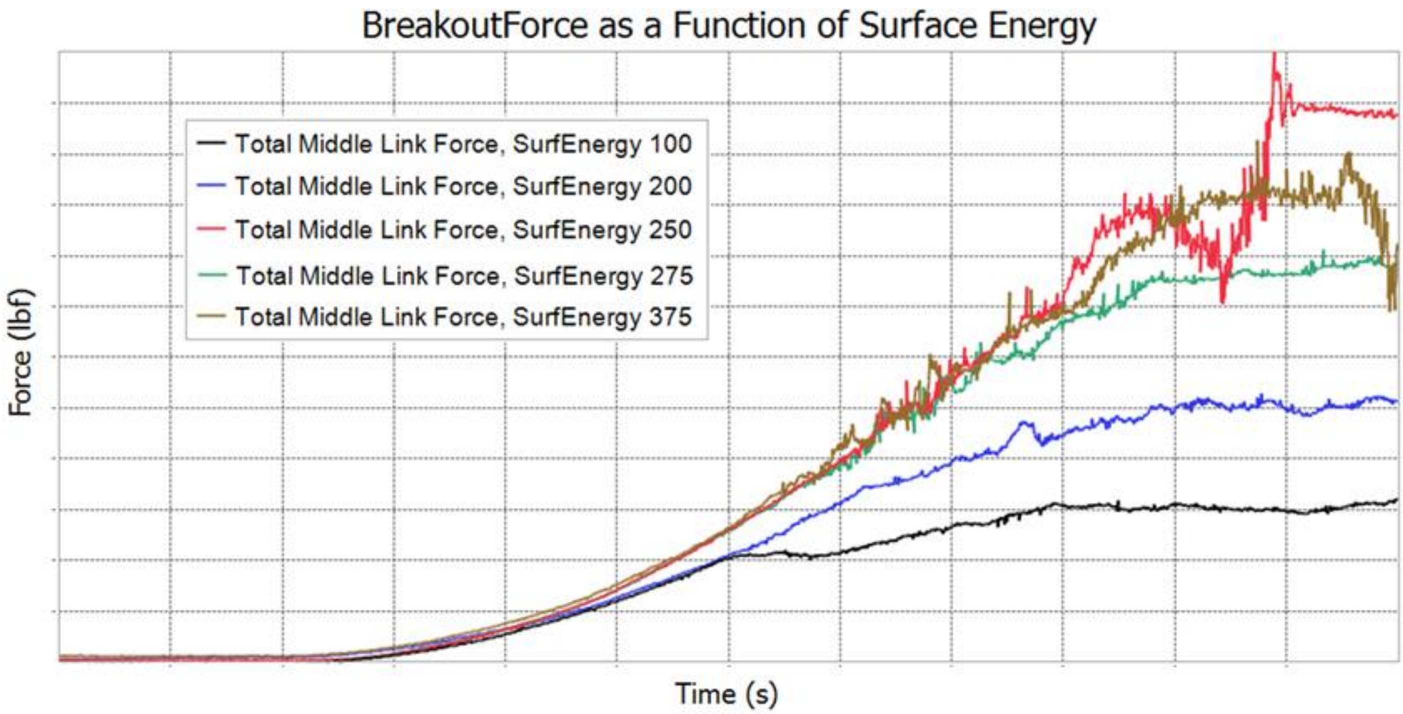

Figure 3: Breakout Force as a Function of DEM Surface Energy Parameter

engine torque, the track links break through the soil and sink.

The soil was tuned by increasing the soil cohesion (increasing the Surface Energy parameter in the EDEM soil). The soil was made more cohesive until the longitudinal (or breakout) force was as large as the normal (vertical) forces on the track links. A family of curves of the breakout force as a function of time, for various values of surface energy, is shown in Figure 3.

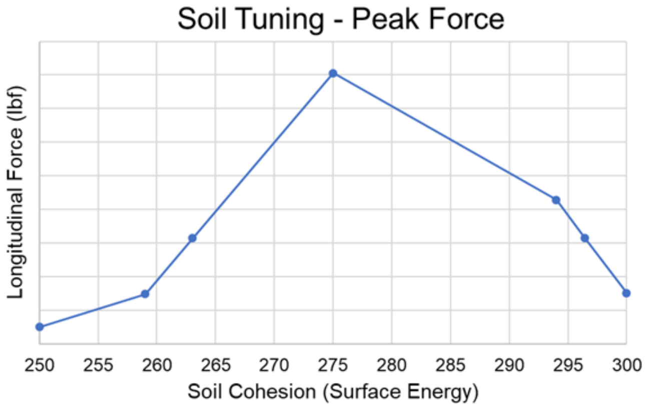

Figure 4: Selection of Surface Energy Value

Plotting the maximum longitudinal force for the various levels of cohesion results in the interesting curve shown in Figure 4. The maximum longitudinal force reaches a peak and then decreases. This behavior may explain why tractive effort was sometimes observed to increase with

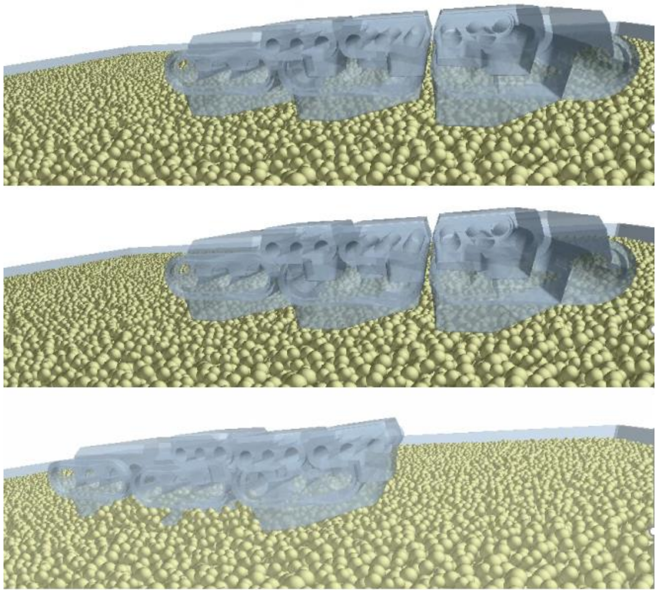

Figure 5: Track Engagement with Tuned Soil

greater moisture content in the physical testing. If we were pounding a stake into the soil then we would always expect the resistive force to increase as the soil cohesion increased. However, with track links there is a trade-off between sinkage and soil stiffness. If the soil cohesion is too high then the track links don't sink in the soil enough for the pad geometry to engage fully with the soil. Therefore, it is logical that a soil cohesion that is too high results in a decrease in longitudinal resistance. The curve was used to select a value of soil cohesion that best matched physical test results. Figure 5 depicts the behavior of the track with the tuned soil. The top frame shows the initial position of the track links in contact with the soil. The middle frame shows the slight sinkage of the track links as the nominal vertical force is applied. The bottom frame shows the soil that is gathered up between the track pads as the track links start to slip. As the track links slip, they better engage with the soil. These effects are observed more clearly when viewing the actual animation of these virtual tests, as compared to a few still images.

Many virtual tests were run with various levels of normal (vertical) force on the track links. The longitudinal force results for the DEM soil modeling is shown in Figure 6. Other families of curves that were calculated for various operating conditions include:

1. The distance that the track links slide (translate) in the soil while they are still building up resistance to the motion. After that point the track links break loose and the longitudinal force is much reduced.
2. The sliding velocity of the track links during the simulation. Once the velocities exceed a limit then the track links break free.

The maximum longitudinal forces for the various values of normal force were plotted as a single curve, and a smoothed version of the curve was created to define a spline entity in RecurDyn that is used in the user subroutine.

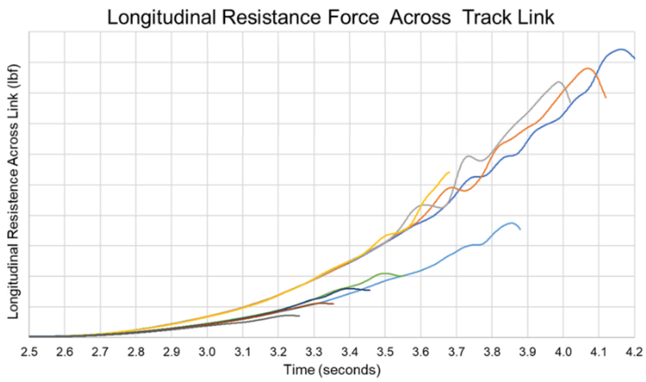

Figure 6: Longitudinal Resistance for Various Normal Forces

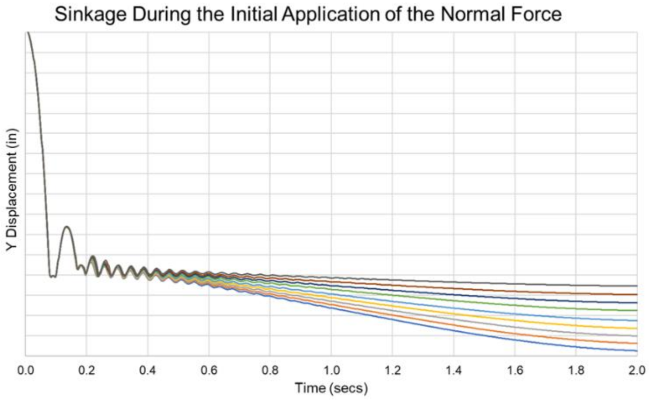

Figure 7: Initial Sinkage for Various Normal Forces

The sinkage of the track links as a function of the normal (vertical) force is shown as a family of curves in Figure 7. The maximum sinkage values from the initial stage of the simulation are used to create a second data spline for the RecurDyn soil subroutine. The third data spline contains information about the amount of longitudinal resistance as a function of the slipping velocity of the track links.

While it takes over five hours to run the three links in the DEM soil using EDEM, the full vehicle simulation up the slope can be done in 40 minutes in RecurDyn. These statistics demonstrate the efficiency of characterizing the nonlinear behavior of the soil and then inputting those relationships into the soil subroutine.

5. MODEL VALIDATION

Simulations of proving ground runs were conducted using the RecurDyn multibody dynamics software and the results compared to test data to validate the vehicle and soil model combination as summarized in Table 1. A predefined tracked vehicle module and prior experience using the multibody dynamics software with a complex tracked vehicle [6-9] reduced the technical risk of this step. The second column describes the recovery vehicle weight (RV WT). The third column indicated the battle tank weight (BT WT). Two track designs and three slopes were considered. The validation tests consisted of driving the recovery vehicle up various grades of soft soil slopes while towing the main battle tank at various weights. In place of the tank, various pintle forces were used across twelve simulations for validation. For each of the twelve cases, the recovery vehicle would ascend a slope with the pintle force starting at zero and ramping up to the representative force for a given main battle tank configuration. Depending on whether the notional recovery vehicle ascended the slope or failed to ascend the slope, a pass or fail rating was recorded for that run. The simulation results were compared to previously collected test data for the same combination of recovery vehicle weight, recovery vehicle track, main battle tank weight, and grade of slope. The soft soil model was tuned using two of the twelve validation cases. That is, soil model properties were adjusted until towing performance for VL4 and VL6 was at the cusp of not ascending the slope successfully. After tuning, the remaining ten simulation run results matched the performance of the physical vehicle in the proving ground data without requiring further modification of the soil model. This process built confidence that the soil model and tracked vehicle combination were predicting performance with sufficient accuracy for this study.

Table 1: Validation Cases

#	RV WT	BT WT	Track	Slope	Test	Simulation
VL1	Low	Low	1	High	Failed	Failed
VL2	Low	Low	1	Low	Passed	Passed
VL3	Low	Med	1	Low	Passed	Passed
VL4	Low	High	1	Low	Marginal	Tuning
VL5	Low	High	1	High	Failed	Failed
VL6	Low	Low	2	High	Marginal	Tuning
VL7	Low	Med	2	High	Failed	Failed
VL8	Low	High	2	High	Failed	Failed
VL9	Low	High	2	Low	Passed	Passed
VL10	Med	High	2	High	Failed	Failed
VL11	High	High	2	High	Failed	Failed
VL12	Med	High	2	High	Failed	Failed

6. RESULTS

After validation, nine different design configurations of the recovery vehicle were analyzed that showed potential to increase the tractive force for better towing performance (Figure 8). The configurations included changes to different subsystems of the vehicle, although the details are intentionally excluded from this report due to the sensitive nature of the topic. Results showed that some design configurations would significantly increase the towing capability of the recovery vehicle. For the greatest performance increase, a combination of these design configurations allows the recovery vehicle to achieve the towing capacity required to consistently perform a single vehicle recovery of the main battle tank up a soft soil slope with margin to account for soil property and vehicle performance variability (Figure 9). Other design changes that had no or minimal impact were recorded but not deemed feasible options. The results of this analysis were used to inform the customer about towing capability for the notional recovery vehicle with a disabled main battle tank on soft soil slopes.

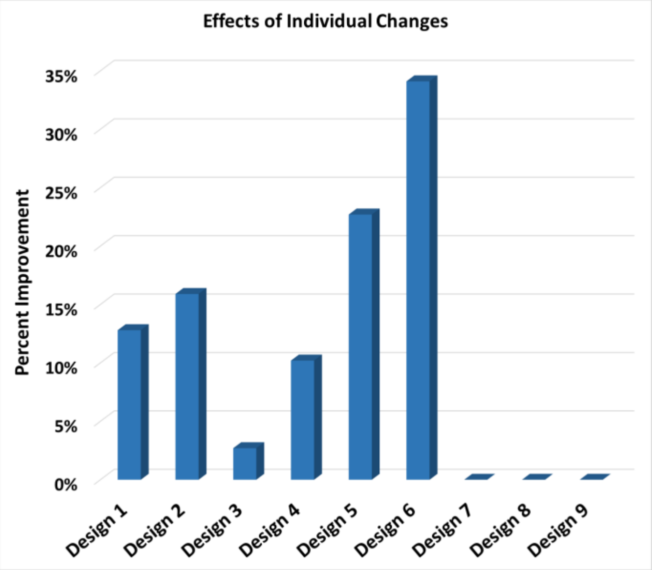

Figure 8: Percent Towing Improvement for Different Design Configurations Tested

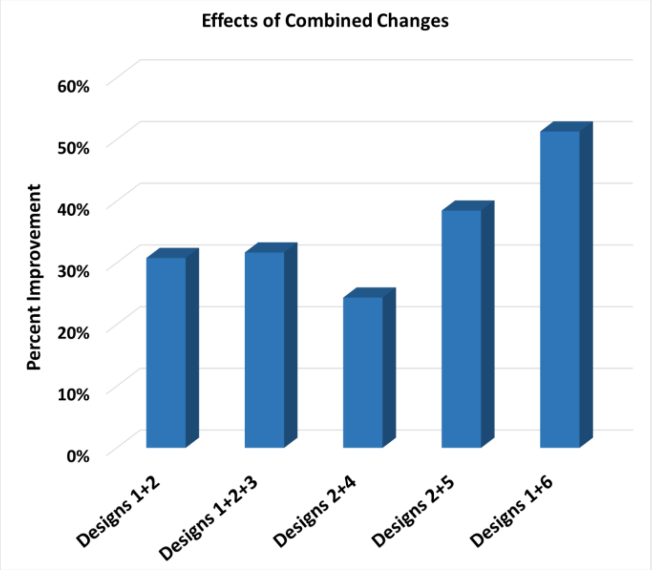

Figure 9: Effects of Combined Design Changes to Towing Performance.

7. SUMMARY

The combination of high-fidelity simulation of track-soil interaction by using DEM software and multibody dynamics software resulted in the ability to predict vehicle performance that matched physical testing for a wide variety of cases. Useful design guidance was generated that could help guide the design of a notional recovery vehicle. These same tools could be used to perform high-fidelity simulation for other tracked vehicles in other operational scenarios, given minimal soil information and physical test results for basic tuning.

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