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CO-SIMULATION OF MBD MODELS WITH DEM CODE TO PREDICT MOBILITY ON SOFT SOIL

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ABSTRACT

Simulating the behavior of tracked and wheeled vehicles over soft soil terrains requires modeling the individual behavior of both the vehicle and the soil, as well as the dynamic interaction between the vehicle and the terrain. Various shortcomings with traditional methodologies have limited the ability to fully model the mobility and performance of vehicles on deformable terrain. This paper chronicles the process for taking validated MultiBody Dynamics (MBD) full-vehicle models in Adams and integrating them with 3D Discrete Element Models (DEM) of soft soil particles in EDEM. Both wheeled and tracked vehicles are simulated with various vehicle events and the results are analyzed. A discussion of the relationship between the Bekker-Wong parameters and the DEM characterization is presented, along with an example of a testing procedure for calibrating the DEM particles against their Bekker-Wong equivalent.

INTRODUCTION

MultiBody Dynamics (MBD) models of wheeled and tracked vehicles can be validated and used to predict behavior on hard surfaces for a wide variety of events. However, when the vehicle is simulated over a deformable terrain, no current methodology can fully represent the dynamic interactions of the vehicle and the soft soil. When designing a vehicle, engineers will often resort to using their past experience with physical testing to predict how the vehicle will behave once it leaves the hard road surface. Only when the vehicle is built and tested, can they obtain the actual data for how the vehicle performs over soft soils. And for many low-rate or expensive vehicles, the prototype may actually be the end product as well, requiring major modifications to the physical vehicle once off-road testing is performed. Accurately modeling the terramechanics is key to understanding the mobility characteristics of off-road vehicles, and understanding how changes to the vehicle and terrain will impact the dynamic behavior.

Modeling the behavior of soft-soil can be accomplished via different methods. Bekker-Wong parameters can define the interaction between the vehicle and the soil based on sinkage and shear characterization at the vehicle-soil interface. Most of these parameters can be directly obtained through physical testing. Traditional Bekker modeling is based on static relationships, but modifications can be made to account for dynamic effects. Given adequate physical testing, the analytical nature of the Bekker-Wong equations allows for rapid solving of the resultant forces between the soil particles and the vehicle. However, lateral bulldozing cannot be represented, and non-flat surfaces such as hills or berms can be difficult to model.

Finite Element (FE) Models can also be used to represent the deformable terrain. The soil can be defined using simple 2-D or complex 3-D FE models, each of which assumes the soil is a continuum as well as homogeneous. If there is limited cohesion between particles or variation in sizing, the FE method may not be appropriate. Particle breakage or separation cannot be modeled using the FE approach.

Discrete Element Models (DEM) represent the soil as individual particles, with complete free body motion between other particles as well as any physical objects they encounter. DEM is a particle-scale numerical method for modeling the bulk behavior of granular materials and many geomaterials, including coal, ores, soil, rocks, aggregates, pellets, tablets and powders. The particles can be represented in a variety of shapes, from combinations of spheres to more complex non-convex shapes. These particles generate forces and torques at each time step, and have physical attributes as well as interactions defining cohesion, friction, and others.

DEM allows for particles to break down or separate from the material bed, and can easily represent particles of varying size and shape. Different particle types may be mixed together to obtain a non-homogenous material, or layered on top of each other as needed. Since the particles dynamically act in 3-D, lateral bulldozing effects, soil accumulation on wheels or tracks, as well as vertical surface features like hills can be easily represented by the soil model. Additionally, the particles may be compacted once or multiple times to provide a variety of soil conditions.

A limitation of DEM is that the discrete particle forces are calculated at each time step, often requiring large amounts of computer memory and CPU time for simulations with a high number of particles. Recent improvements in DEM modeling, such as a dynamic moving domain and boundary sharing, have made significant improvements for these limitations.

CO-SIMULATION REQUIREMENTS

In order to simultaneously solve an existing MBD vehicle model with a separate DEM soil model, co-simulation is required to allow each solver to accurately calculate the dynamic behavior of the vehicle-soil interactions. The forces and displacements of the MBD/DEM objects must be shared between each program, via a structured interface that connects and manages the communication.

Integration of MBD and DEM models

An MBD model of a vehicle must define the contact between the vehicle and the ground surface. For wheeled vehicles on a hard surface, the tire forces and moments are calculated based on equations formulated to characterize the tire-road interaction based on the tire's properties and the road surface location. For tracked vehicles on a hard surface, individual contact forces are defined between the road and each vehicle element that may contact the road, based on the physical properties of the road and the vehicle's contact geometries.

When integrating an MBD model with a soft-soil DEM model, these existing vehicle-road forces are replaced with corresponding forces between the vehicle and the soil particles. One approach would be to define separate forces between every object in the MBD model, and every particle in the DEM model. This would be prohibitive from a computational aspect, as well as requiring very complicated model definitions. An alternative approach is for the DEM model to calculate a single resultant force from all particles in contact with any particular vehicle geometry, and then communicate this force to the MBD model which will apply that composite force to the corresponding vehicle part.

This "composite force" approach, which is a combination of force and moments from the particles on a geometry center of mass, is implemented for the use of this paper. The MBD model supplies geometry locations at each integration step, and the DEM model then calculates the particle forces based on the discrete particle model employed. The resultant force on each geometry is then communicated back to the MBD model, which uses the forces during the subsequent dynamic time step.

Process for co-simulating an Adams MBD vehicle model with an EDEM soil model

The first step towards integrating an MBD model with a DEM soil model is to validate each model within its own domain. By isolating this initial verification phase, each model can be tested independently to ensure the behavior meets the desired specifications. The MBD model can be simulated on a hard surface with various maneuvers performed; these tests can be the same as those normally performed during the standard model verification phase. Likewise, the DEM soil model can be calibrated, changing the parameters until the particle behavior matches that obtained from physical testing. The DEM model can be validated in a simple test environment, without regard for any future use-case when integrated with the MBD model. For the purposes of this paper, the Adams MBD software from MSC.Software was selected to model the multi-body dynamics of the vehicle [1], and the EDEM DEM software from DEM Solutions was chosen to model the bulk dynamics of the soil particles [2].

After the Adams MBD model is validated, the next step is to determine which geometries will potentially come into contact with the soft soil. For a wheeled vehicle, this might be as simple as the four tires. In contrast, a tracked vehicle will require many more contact geometries, including the track segments, connectors, wheels, and hull. For each of the Adams parts containing the corresponding geometry, a GFORCE element is created which will hold the force value calculated by the EDEM soil model. These GFORCE's must be created at the center of mass of the Adams part, and an Adams MARKER is referenced by the GFORCE at the center of mass location.

For each Adams part with a GFORCE, the corresponding contact geometry must be exported for use by the EDEM model. This geometry may or may not completely represent the part's center of mass location, as Adams allows for part mass properties to be defined independent of any geometry. When the geometry is imported into EDEM, the corresponding center of mass for the Adams part can be entered into the EDEM properties to ensure alignment between the MBD and DEM models. Various geometry formats are supported, including parasolid, iges, and stl.

The EDEM soft-soil particles must be configured to represent the desired MBD-EDEM testing scenario. For instance, if a flat terrain is desired, then the appropriate dimension of particles needs to be determined. The width should be enough to ensure that any lateral particle displacement does not build up against the side boundaries, and the length should be long enough to perform the vehicle maneuver. Likewise, particle depth should reflect the desired behavior; if the vehicle will sink while traversing the bed, then care should be taken to provide a deep enough bed so that the vehicle will not sink to the bottom. The soil particles are then populated into the test bed, at which point the particles may also be prepared by compressing with a vertical force or pressure to obtain any desired conditions corresponding to physical test properties.

Once the EDEM particles are prepared, the vehicle geometries exported from the Adams model are then imported into EDEM. The geometries are imported such that a single EDEM geometry is created for each corresponding Adams part. After import, all center of mass properties are verified against those values in the Adams model, and any EDEM geometries needing updates can be manually modified with the correct Adams locations. Scripts were created to help automate this process, in anticipation that the software would provide similar functionality in future releases.

With the Adams and EDEM models ready for simulation, the final step is to define a communication protocol for the integration of the models. The Adams ACSI (Adams Co-Simulation Interface) is a framework that provides the topological interface between Adams and other software via a configuration script and corresponding glue code. The ACSI controls the co-simulation, allowing for asynchronous communication and various interpolation and extrapolation algorithms. The ACSI references a configuration file that defines the Adams and EDEM objects that will communicate with each other during co-simulation. Each Adams part that had a GFORCE created must be included as a block entry, along with a block entry for the corresponding EDEM geometry object.

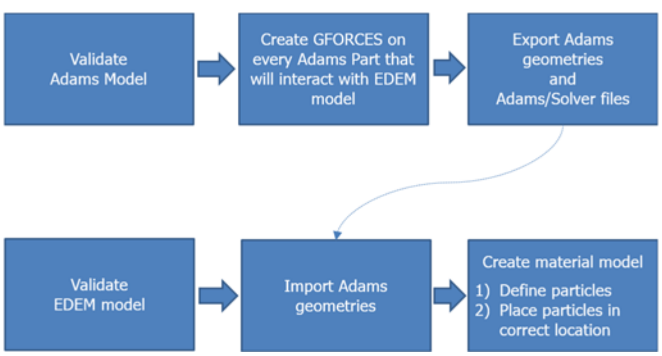

Figure 1. Adams - EDEM setup workflow

An Adams block from a sample configuration file is shown below:

```
interaction {
   name       = adams_handling_tire_rear_geometry_whl_wheel
   connection = edem_handling_tire_rear_geometry_whl_wheel
   gforce_id  = 4
}
```

The corresponding block for the EDEM geometry is shown below:

```
interaction {
   name          = edem_handling_tire_rear_geometry_whl_wheel
   connection    = adams_handling_tire_rear_geometry_whl_wheel
   geometry_name = handling_tire_rear_geometry_whl_wheel
}
```

These two blocks together define the interaction between the Adams and EDEM models for this Adams part and the corresponding EDEM geometry. Each block is assigned a unique identifier through the "name" field, and each block is paired with another block via the "connection" field. The Adams block is named "adams_handling_tire_rear_geometry_whl_wheel", and connects to the EDEM block named "edem_handling_tire_rear_geometry_whl_wheel". The EDEM block has a similar connection scheme. The Adams block also contains a "gforce_id" reference to the specific GFORCE element in the Adams model, and the EDEM block contains a "geometry_name" entry that identifies the EDEM geometry.

When the ACSI interface is started, the configuration file supplied will define how the Adams and EDEM models share data at each communication step. The Adams model will provide the location of each GFORCE, and the EDEM model will take assign that location to the corresponding EDEM geometry. Based on this geometry displacement, the EDEM solver will calculate the bulk behavior of the soil particles, and determine the composite particle force and moment on each EDEM geometry object. This force is then communicated back through the ACSI which assigns the values to the corresponding GFORCE elements. These forces are then included in the next dynamic time step the Adams solver takes.

MODEL DEFINITIONS

Two separate Adams vehicle models were defined for this paper: a wheeled vehicle, and a tracked vehicle. One EDEM particle model was developed and used for all the different co-simulations. Considerations for creating different particle models are presented at the end of the paper.

For all Adams models, the coordinate system definition is X rearward, Y vehicle right, and Z up.

Adams Wheeled Vehicle Model

An Adams model of a HMMWV (Humvee) was used for development and validation. This HMMWV Adams model had been previously used for hard surface simulations, and the behavior verified using various test maneuvers. The tires used were of size 37x12.50R16, tested at an inflation pressure of 35 psi. An overall vehicle mass of around 2700 kg was specified, with corresponding inertial properties. The rates for the various bushings, springs, stops, and dampers were all specified based on typical values for a standard HMMWV.

Figure 2. Adams model of HMMWV

The initial integration with the EDEM particle model included only the four tires as contact objects with the terrain; subsequently, the body and certain exposed suspension elements were also exported for use during co-simulation.

While the behavior of tires on hard surfaces is well defined by various tire models, the interaction of tires and deformable terrain is more problematic. Historically, tires have been represented by rigid geometries when simulating with soft soil, as first proposed by Bekker [3]. Recent developments have included soft soil characteristics in tire models, although these have limitations, ranging from lack of bulldozing effects, to inability to handle non-flat terrains, and particle separation not permitted.

The bulk particle behavior modeled by EDEM currently does not support any deformable tire patch from a tire geometry object, as vehicles moving through soft soil is a relatively new area for DEM codes. Thus for this paper, the tires were represented as rigid objects in EDEM. This required a relatively accurate tire geometry file, as the tread depth and pattern directly impacts how the EDEM particles will respond to the tire movement. The limitation of non-deformable tires for wheeled vehicles is a notable shortcoming, especially as tires are generally run at low pressures across soft-soil terrains. Active development is ongoing to characterize the contact surface interface between flexible tires and bulk particles.

An additional complication for a rigid tire representation in EDEM, is that the model particles are scaled to a different size than the actual particles. As DEM is modeling bulk particle behavior, the behavior of any single particle is not as important as the overall bulk behavior of the particles together. This scaling allows for large material beds to be simulated, since the reduction in the quantity of particles will not exceed memory or runtime requirements. However, these scaled particles will have a different behavior with the tire tread than actual-sized particles; depending on the particle scaling and the tire geometry, individual particles may be too large to fit into the tread pattern. To approximate the tire-soil interaction, calibration of the particle definition is required to model the appropriate interaction of tread and soil. In the future, an ideal solution would be a soil model that allows for bulk behavior at the macro scale, but also localized contact areas where smaller-sized particles are used to appropriately capture effects like tread-soil interactions.

Adams Tracked Vehicle Model

An Adams model of a medium-sized tank was used for the tracked-vehicle use-case. This tank was an existing Adams model that had been developed and tested on hard road surfaces. As the tank was expected to sink into the soft terrain and generate lateral bulldozing forces, almost all the Adams part geometries were exported for use in the EDEM model; these included the track segments, track connectors, track wheels, support rollers, idler arms, tensioners, hull, and shelf.

Figure 3. Adams model of tracked vehicle

The overall dimensions of the tank were 3.7m long by 1.5m wide by 1.3m tall (excluding any weapons, mounts, etc). The width of each track was 0.3m, with a distance of 1.2m between the center point of the left and right tracks. On each side of the tank, 5 road wheels were specified, along with an idler wheel, idler arm, 2 support rollers, and track tensioner. Each track contained 84 track segments and connectors.

The tank was able to operate in two modes, driven either by a motion or torque input. The motion-driven model allowed for separate velocities to be defined for the left and right tracks, and could be defined via any standard Adams function allowing for complex behavior. The torque-driven model also included controllers for the velocity and steering. The velocity controller had separate settings for the left and right tracks, and could be set as a constant value, or using an Adams function definition. The steering controller had an input target path that the vehicle followed during the maneuver.

EDEM Particle Model

Extensive testing and correlation has been performed by EDEM users to define particles that match the behavior of the desired physical soil. To aid users in obtaining particle models that behave as desired, EDEM provides the GEMM Material Database, where users can lookup pre-defined materials based on three inputs: the scale of the application; the angle of repose; and the bulk density of the material. Finally, the EDEM Soil Starter Pack provides eight sample out-of-the-box materials with different ranges of compressibility and stickiness.

As no correlation was intended as part of this project, DEM Solutions provided a material definition of particles that were non-compressible with medium stickiness. This particle definition was used for all the Adams-EDEM co-simulations to provide a constant basis for comparison. The particle model is equivalent to a loose sand that would be found in dunes or similar environments.

The properties of the EDEM particle model are as follows:

Poisson's Ratio: 0.25
Solids Density: 2600 kg/m^3
Shear Modulus: 1.0E+07 Pa

The Particle-to-Particle Interaction is defined by:

Coefficient of Restitution: 0.5
Coefficient of Static Friction: 1.0
Coefficient or Rolling Friction: 0.15

The Particle-to-Geometry Interaction is defined by:

Coefficient of Restitution: 0.75
Coefficient of Static Friction: 0.44
Coefficient or Rolling Friction: 0.20

Once this EDEM particle model was established, various test bed configurations were required to be built using these particles.

Adams Road to EDEM Particle transition

For each of the Adams-EDEM co-simulations performed, the vehicle started on the Adams hard road surface, and then transitioned onto the EDEM particles. While on the Adams road, the ADAMS GFORCE elements do not contain any force values since the particles are not in contact with the vehicle, and the normal Adams vehicle-ground forces are in play (either through the tires or the track contacts). As the vehicle transitions onto the EDEM particles, the GFORCEs begin to supply the contact force between the vehicle and ground, with the Adams contact forces going to zero once the hard surface is left behind.

The EDEM particles can either be placed inside a geometry container, or can be allowed to naturally create a particle formation based on the particle properties.

Figure 4 shows a sample particle bed that was used for flat terrain co-simulations. The particles are set inside a container geometry which in this case matches the corresponding Adams road profile. In reality, there is no need for the Adams road to continue underneath the particle bed; once the vehicle leaves the Adams road and enters the soft soil region, the particles will provide the contact forces and the Adams road becomes irrelevant. Only if the test maneuver should have the vehicle exit the bed onto the hard surface, will the Adams road be required to extend beneath the particle surface.

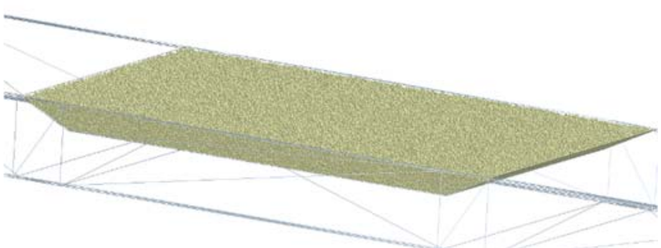

Figure 4. Flat particle bed in EDEM

Figure 5 shows a double hill terrain configuration used for both the HMMWV and Tank Adams models. To create this test case, the Adams road surface was imported into EDEM, and then a fixed quantity of particles were dropped onto the road, with the particles forming a natural rounded hill based on the material properties. The same amount of particles was then dropped onto the road at a fixed offset location, creating the second rounded hill in the background, which has a slightly higher peak than the first hill.

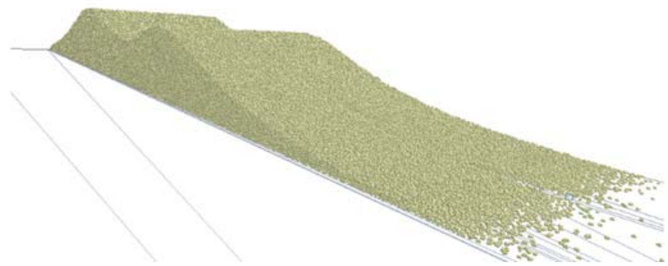

Figure 5. Double hill terrain in EDEM

To create the grade climb and side slope terrains, a flat particle bed of correct dimension was first created. The particle container was then rotated inside EDEM to achieve the appropriate slope. This rotation was performed at a very slow rate, approaching a quasi-static effect, to minimize particle shifting. This approach proved to generate the desired terrains without much difficulty.

The EDEM software has a new “Bed Generation Tool” that was also investigated. This capability allows users to create large beds quickly by copying small blocks of material. Equivalent test beds were created for the grade climb and side slope using the Bed Generation. It is expected that the Bed Generation would prove more useful in future projects, based on the long simulation time required to slowly rotate the entire flat bed. However due to time constraints, no comparison was made between the two approaches in terms of ease of use, or amount of time required.

SIMULATION RESULTS

Each of the Adams models was run for a variety of different maneuvers. These included straight-line on a flat terrain; single and double hill climbs; grade climbs; traversing a side slope; pivot steer; drawbar pull; and multi-pass runs.

Adams Wheeled Vehicle Simulations

The Adams HMMWV model was simulated over a variety of soft-soil terrains, using the same EDEM particle model in each case. The first maneuver is the HMMWV traversing a flat particle bed as shown in **Figure 6**. This event allowed for the debugging of various issues arising from the co-simulation of Adams MBD and EDEM DEM models, as well as certain specific issues with the vehicle controller inside the Adams model.

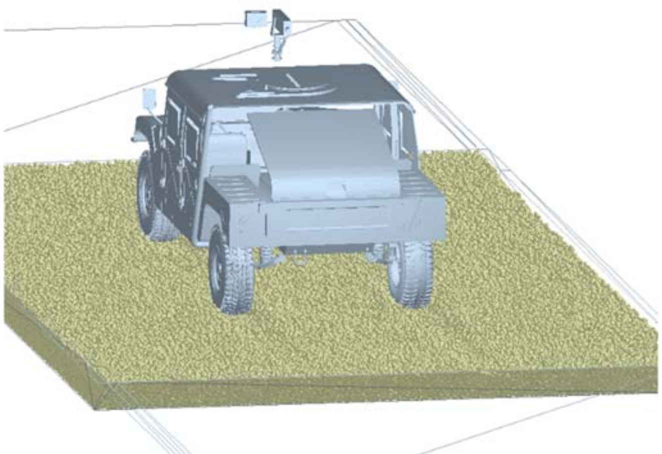

Figure 6. HMMWV on flat terrain at 20kph

The HMMWV was then run over a single hill at various speeds to investigate the ability to traverse the obstacle, as well as the power required during the event. **Figure 7** shows the HMMWV at 20kph trying to climb the hill, and getting the front wheels stuck in the soft soil.

Figure 7. HMMWV on single hill at 20kph

At a high speed, the HMMWV becomes airborne as it crests the hill. Based off this behavior, the HMMWV was run over the double hill at various speeds, with the vehicle impacting the ground at different points based on the velocity. When running at 60kph as shown in **Figure 8**, the HMMWV lands just before the crest of the second hill, with the impact "splashing" the soil particles.

Figure 8. HMMWV on double hill at 60kph

In order to run the HMMWV on a side-slope, the vehicle starts out on a level hard road surface, which then gradually rotates until it reaches the desired slope gradient. At this point the hard surface ends and the soft soil begins. The steering controller in the Adams model is set to try and maintain a straight-line while on the side-slope. **Figure 9** demonstrates the vehicle behavior as it leaves the hard surface and enters the material bed. The vehicle initially slides down the slope as the steering reacts to the lessened traction available, and compensates until the vehicle begins to recover towards the desired straight-line path.

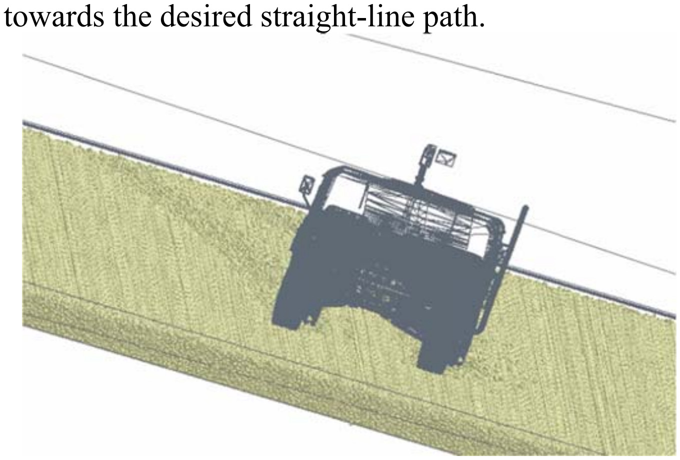

Figure 9. HMMWV on 30 percent side slope at 25kph

Adams Tracked Vehicle Simulations

The Adams tank model was likewise simulated over a number of soft-soil terrains, using the same EDEM particle model as the HMMWV simulation runs.

The first maneuver is the tank traversing a flat material bed, which is shown in **Figure 10**. The track "footprint" can be seen where the track has passed, and the track is visibly sunk into the soil particles producing a lateral bulldozing effect. As EDEM utilizes bulk-particle-scaling, care must be taken to maintain the correct sizing ratio between the scaled soil particles and the vehicle geometries. A rule of thumb suggested by DEM Solutions for initial particle modeling (before any calibration), is to have at least a 20:1 ratio of track/wheel width to particle diameter. Anything above this may begin to produce localized effects of individual particles, impacting the bulk particle modeling. The figure shows that the soil particles are indeed small enough compared to the tank tracks, to retain the desired bulk particle behavior.

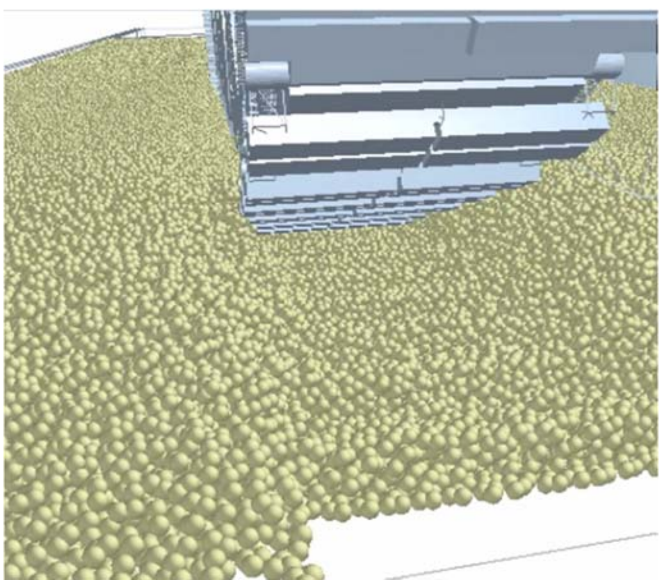

Figure 10. Closeup of Tank on flat terrain at 5kph

The tank model was run over the same single hill terrain as the HMMWV (see **Figure 7**). Based on the soil properties defined in the EDEM model, along with the tank characteristics such as weight, ground clearance, track tension, and track sizing, running at different speeds produced both successful and failed simulations. When running at 7kph as shown in **Figure 11**, the tank sinks into the soil and cannot fully traverse the hill. The figure shows the point at which the tracks begin to dig deep into the soil, creating a yaw effect as the tracks try to gain enough traction to move forward. Due to sinkage the tank hull is also pressing into the soil, producing friction forces that further reduce mobility. Even the motion-driven tank model, which theoretically has unlimited torque capacity, was unable to move the tank over the hill with the target speed of 7kph.

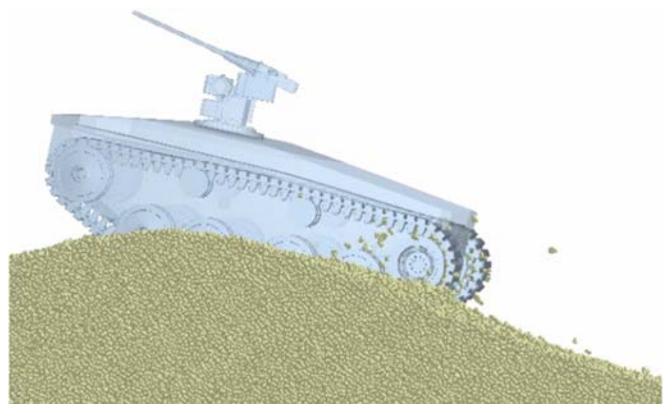

Figure 11. Tank at 7kph becoming stuck on hill

However, increasing the vehicle speed by just 2kph proved sufficient to crest the hill. **Figure 12** captures the tank as it crests the second hill of the "double hill" profile at 9kph, having already successfully passed over the first hill which was impassable at 7kph. Information from simulations such as this would aid in preparing unskilled drivers for traversing obstacles without sinking or stalling.

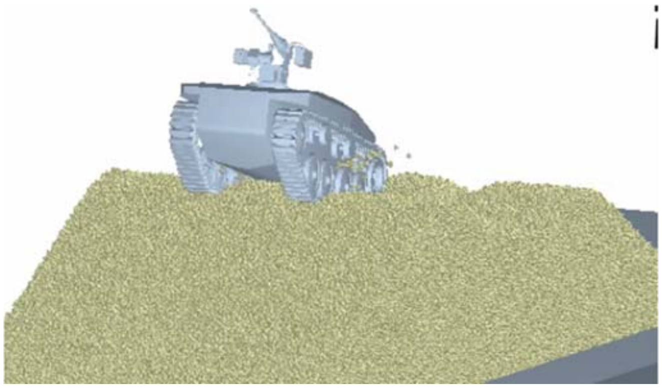

Figure 12. Tank cresting second hill at 9kph

The tank was simulated on a number of different grade climbs. For each specific grade simulation, the same Adams road was used, along with a corresponding EDEM particle bed rotated to the appropriate longitudinal slope. The tank began the simulation on the hard surface, and when it encountered the EDEM material, the soil particles began exerting their contact force and the tank would then begin climbing the particle bed. In **Figure 13**, the tank has slowly rolled onto the soft soil at 3kph. Once the tank is completely on the particles, the throttle is increased to 100% and the tank accelerates up the grade.

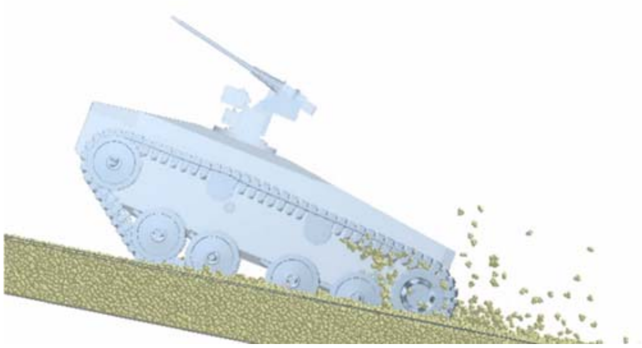

Figure 13. Tank on 20pct grade climb, full throttle

A variation of the flat terrain EDEM model was used for testing the tank during a pivot steer event. The width of the particle bed was increased by a factor of 150%, to provide enough area for the particles to displace as the tank spun around. A close look at **Figure 14** shows that as the tank is performing the pivot steer, the tracks have created a bowl-shaped depression in the soft soil. To perform the pivot steer maneuver, the tank was rolled slowly onto the soil particles and allowed to come to rest. At this point, the track motion controller initiated left/right track speeds of 3kph in opposite directions. As the tank began to spin, the tracks and wheels began to churn the particles with a lateral bulldozing force, pushing them up and away.

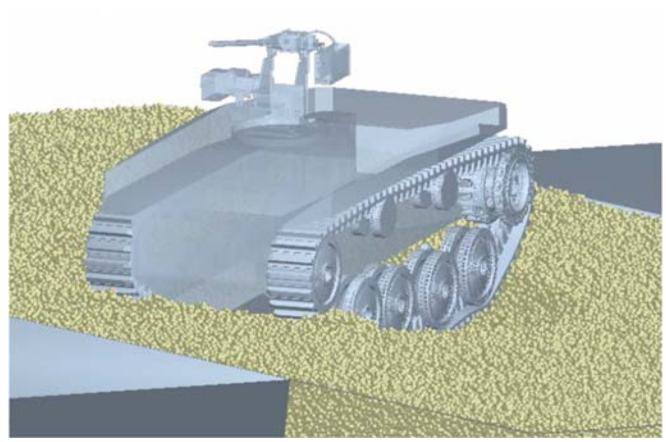

Figure 14. Tank pivot-steer at 3kph, with opposite left/right track speeds

The tank drawbar pull simulation required a modification to the Adams tank model. A drawbar part was created, and attached via joints to the tank and an immovable ground object. The drawbar was allowed to extend a certain distance, after which an Adams BISTOP function was enabled that forced the drawbar to remain at that fixed distance. **Figure 15** shows the tank after it has rolled onto the soil particles and come to rest, and the throttle then increased to 100%. For each variation of this test, the tank invariably became stuck in the particles, with the tracks unable to free themselves and continue rotating. Further study would be required to determine if the predominant factor in this behavior was the particle sizing, or the lack of cohesion in the particle model.

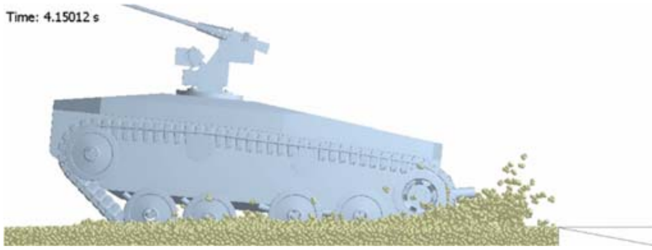

Figure 15. Tank drawbar pull

The final simulation performed was a multi-pass test. A common metric for characterizing trafficability of wheeled and tracked vehicles over deformable terrain is the VCI (Vehicle Cone Index), first proposed by Rula and Nuttal [4]. The VCI is commonly given for both a single pass, as well as a 50-pass requirement. An advantage of using the DEM terrain modeling, is that multi-pass events can account for lateral soil movement, as well as non-flat terrain. In **Figure 16**, the tank has already traversed the flat soil bed one time, and is running along the same path a second time. The particle coloring indicates the Z (vertical) depth of individual particles. As the tank moves along the path the second time, the tank continues to sink deeper. The soil particles under the track after the second pass are displayed as dark red, indicating the particles are at a lower Z (vertical) height. This particular test has the vehicle moving at a slow speed (3kph); when the vehicle moves at a faster speed, slightly less sinkage occurs during each pass.

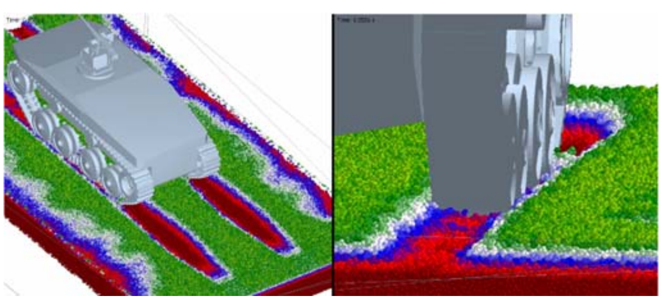

Figure 16. Tank performing second pass over terrain

CO-SIMULATION RESULTS

Simulation Metrics

While multiple factors impact the co-simulation performance, a general pattern emerged of around 1 hour runtime per 1 second of simulation time. The co-simulations with large test beds were run with a 20 CPU setup on a server machine, with 192 GB of memory. For smaller-sized particle beds, a laptop with 8 CPU's and 16 GB memory would perform at a similar runtime/simtime rate.

The EDEM software package also supports a GPU solution, with users finding anywhere from 2x to 10x speed improvements for their computationally expensive simulations. As no GPU cards were available for testing with EDEM, no results were generated for this use-case.

To achieve maximum performance, the EDEM "Dynamic Domain" was implemented in each model. This capability provides a moving bounding box that prevents the EDEM solver from calculating particle behavior outside a specified area. The materials outside the active region are frozen, allowing for large particle beds to be used in a far more efficient manner. The Dynamic Domain region was defined as a bounding box around the HMMWV or Tank geometries, with enough buffer space to allow for particle bulldozing or separation to occur.

HMMWV Results

Two of the simulation results for the HMMWV model are discussed below. First, for the vehicle traveling across the flat terrain; second, when the HMMWV is traversing the 30% side slope.

One important validation step was to compare the tire forces when the vehicle is on the hard surface, against the forces when it is crossing the soft soil. **Figure 17** shows the forces between the left rear tire and ground during the entirety of the simulation. Up until around time=1sec, the HMMWV is on the hard surface, and the tire forces are calculated through the standard Adams Tire routines (shown in red). As the vehicle transitions onto the soft soil, the Adams Tire forces go to zero, and the EDEM particle forces (shown in blue) begin to carry the load. After an initial transient phase, the vehicle stabilizes and the contact forces calculated by the EDEM particles are equivalent to the tire forces on the hard surface.

As the HMMWV exits the material bed, there is a spike in the EDEM particle force, due to a localized particle effect at the transition from soft soil to hard surface (a scaled soil particle which was pushed onto the hard surface is traversed). Once the vehicle returns to the hard surface, the tire forces again are calculated by the Adams Tire method.

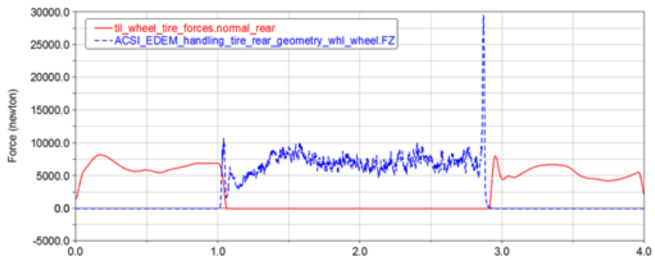

Figure 17. HMMWV tire and particle forces

The HMMWV side slope maneuver (slope downward from right-to-left) provided an opportunity to investigate the behavior of the vehicle as it transitioned onto the soft soil, and the vehicle's ability to maintain a straight-line course once on the EDEM particles.

The simulation begins with the HMMWV on a flat, hard road surface, at a constant speed of 25kph. At time 3.75 seconds, the hard surface begins to gradually roll, until at about a time of 5.5 seconds the 30% side slope is achieved. The vehicle continues on the hard side slope road until around time 7.6 seconds, at which point the hard surface ends and the soft soil begins. The EDEM particle bed was positioned to match the slope of the hard surface to the soft soil; however, as seen in **Figure 18** there is a transient response as the vehicle enters the deformable terrain.

As the front wheels of the HMMWV enter the particle bed, the vehicle initially yaws to the left while the rear wheels are still on the hard surface. Once the entire vehicle is on the soft soil, it begins to drift down the slope, and the steering controller increases the angle to return to a straight line course, causing the vehicle to yaw in the opposite direction. At the end of the simulation, the yaw has stabilized and the steering angle is maintained at about 50 degrees to travel in a straight direction.

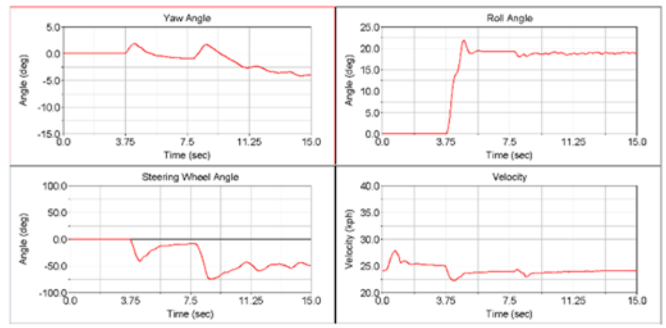

Figure 18. HMMWV on 30% side slope

Tank Results

Two simulations with the tank model will now be discussed. The first is shown in **Figure 19**, where the tank is run up at 20% grade at a maximum 50% throttle. The tank begins on a flat, hard surface, at an initial velocity of 3kph, with the throttle going from zero to 50% over the course of the first second. After about 0.9 seconds of runtime, it encounters the angled EDEM particle bed, and begins to climb the 20% slope.

Initially the tank accelerates up the slope, with the front of the tank raising up a bit. However, once the entire tank is on the soft soil (at around 1.5 seconds), the tank begins to decelerate. At this point the tracks sink further into the material bed, eventually becoming stuck and unable to continue turning. So when using 50% of the throttle, there is not enough available torque to climb the 20% slope.

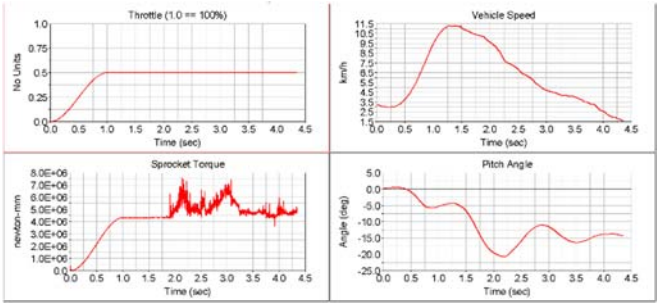

Figure 19. Tank on 20% grade at 50% throttle

The final simulation discussed is the tank performing a pivot steer. The tank begins on the hard surface, and rolls to a stop once it is fully on the EDEM terrain. As shown in **Figure 20**, the tank sinks about 150 mm into the soil particles before it comes to rest.

After stabilizing, at time 5.5 seconds the tracks are sped up to 3kph over the course of one second, with each track rotating in opposite direction. As the tank begins to pivot, the tracks dig into the soil and begin to push the particles off to the side. This has the effect of 'digging' the tank deeper below the surface, as it continues to displace more particles as it spins around. After a second of spinning, the tank has sunk about another 100mm lower.

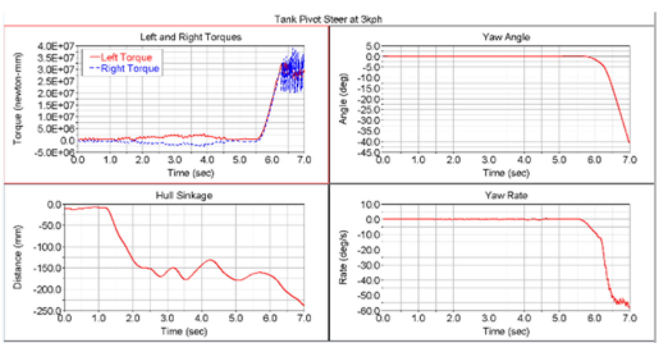

Figure 20. Tank Pivot Steer at 3kph

FUTURE CONSIDERATIONS:

Substantial work has been done with mapping the traditional Bekker-Wong parameters to DEM models. Smith et. al. [5] described a method to use a DEM soil model to produce most of the parameters normally obtained via physical testing. Two aspects of soil characterization are important for validating the Adams-EDEM vehicle-ground interaction approach.

Correlation of Adams-EDEM Soil Properties with Bekker-Wong Parameters

The process of co-simulating the Adams MBD vehicle model alongside the EDEM DEM soil model, introduces a new dimension to the established procedure for verifying DEM soil properties. When the entire solution is performed inside a DEM environment, the force/displacement interactions are all internally computed. With the Adams-EDEM co-simulation, each software solves its own equations, communicating the displacements and forces at the established communication intervals.

Additionally, the dynamics of the vehicle can generate rapidly changing displacements and force values between the vehicle and soil particles.

A testing procedure is proposed for validating the Adams-EDEM implementation. It is based on the same process described in [5], which itself is a replication of the physical field testing. However, the testrig will be created inside an Adams MBD model, with the pressure/force also being defined in Adams. The testrig geometry will be exported from Adams and imported into EDEM, and then filled with the desired soil particles (see **Figure 21**).

The Adams-EDEM co-simulation will then run, applying the specified force or pressure to the plate, with the Adams simulation results post-processed to generate the corresponding Bekker-Wong parameters.

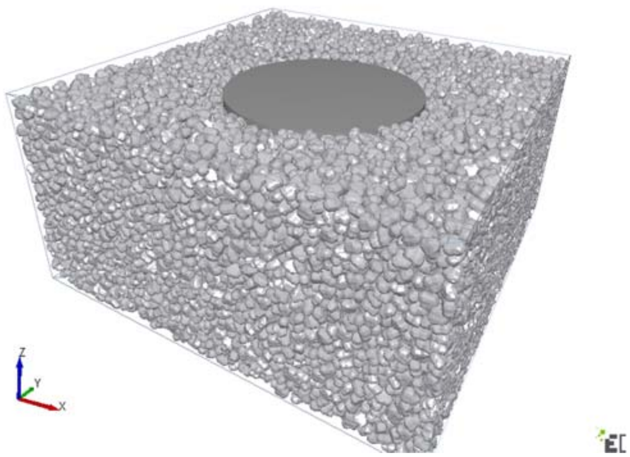

Figure 21. Adams-EDEM testrig for soil parameter characterization

Catalog of EDEM Soils

A considerable amount of testing has been performed throughout the world on different soils, with the results being converted into the corresponding Bekker-Wong parameters for future reference. This testing has generated a wide range of available soils that can be referenced by models utilizing the Bekker-Wong formulation.

Currently, the EDEM GEMM Database provides a catalog of soils based on physical attributes. However, there is no mapping between the EDEM parameters and Bekker-Wong parameters.

Once the Adams-EDEM testrig is generating Bekker-Wong parameters, steps can be taken to create a library of EDEM soils that correspond to existing Bekker-Wong soil definitions. If EDEM users are able to reference an EDEM soil particle that has been validated as equivalent to a published Bekker-Wong material, comparisons can then be made between the results obtained using EDEM and those obtained via traditional Bekker-Wong methods.

Another outcome of this cataloguing would be a set of "named" soils available inside EDEM. Many soft-soil Bekker-Wong based implementations (the soft-soil model inside the Adams ATV toolkit for example), have a set of sample soils such as "dry sand", "heavy clay", "sandy loam", etc. While these soils may not be representative of the exact terrain a specific vehicle is intended to run on, the existence of sample soils would allow for initial vehicle design and testing to be performed using representative terrain properties. Additionally, many times physical testing of a desired terrain may not occur early in a design process, or perhaps may be unfeasible. Having an EDEM library of named soils would allow vehicles to be simulated over terrains similar to the environment where the physical vehicle will run.

ACKNOWLEDGEMENTS

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References

[1] "Adams, The Multibody Dynamics Simulation Solution," MSC.Software, [Online]. Available: http://www.mscsoftware.com/product/adams.

[2] "EDEM, Discrete Element Modeling Software," DEM Solutions, [Online]. Available: https://www.edemsimulation.com/.

[3] M. G. Bekker, Off-the-road locomotion, Ann Arbor, Michigan: The University of Michigan Press, 1960.

[4] A. A. Rula and J. Nuttall, "An Analysis of Ground Mobility Models (ANAMOB)," 1971.

[5] W. Smith, D. Melanz, C. Senatore, K. Iagnemma and H. Peng, "Comparison of DEM and Traditional Modeling Methods for Simulating Steady-State Wheel-Terrain Interactions for Small Vehicles," in *7th Americas Conference of the ISTVS*, Tampa, Florida, 2013.