NG-NRMM Phase II Benchmarking:
Chrono Wheeled Vehicle Platform Simulation Results Summary

Asher Elmquist, Rainer Gericke, Radu Serban, Dan Negrut
Simulation Based Engineering Lab
University of Wisconsin – Madison

December 11, 2017
Contents

1 Brief Overview of Chrono 2

2 WVP Model Overview and Assumptions 2
   2.1 Model Setup and Assumptions 2
   2.2 Flat, Rigid Terrain 4
   2.3 Deformable Terrain Model 4
   2.4 Granular Terrain Model 4

3 Simulation Results 5
   3.1 Settling Configuration 5
   3.2 Acceleration Performance 5
   3.3 Steering Performance 7
      3.3.1 Wall to Wall Turn Radius 7
   3.4 Steady State Turning 8
      3.4.1 200 ft. Radius Steady State Cornering 8
   3.5 Double Lane Change 10
      3.5.1 Paved Double Lane Change with Open Loop Controller 10
      3.5.2 Paved Double Lane Change with Closed Loop Controller 17
      3.5.3 Gravel Double Lane Change with Open Loop Controller 28
      3.5.4 Gravel Double Lane Change with Open Loop Controller 35
   3.6 Side Slope Performance 45
      3.6.1 30% Side Slope Slalom 45
   3.7 Sand Slope Gradeability 53
      3.7.1 Sand Slope Maximum Gradeability based on Bekker Soil Mechanics 53
   3.8 Ride Quality 56
   3.9 Sand Traction 65
      3.9.1 Sand Traction based on Bekker Soil Mechanics 65
      3.9.2 Traction Test based on Granular Dynamics Soil 68
1 Brief Overview of Chrono

Chrono [1–3] is an open source multi-physics engine whose development is led by teams at the University of Wisconsin – Madison and the University of Parma, Italy. It supports the simulation of systems of rigid bodies, flexible bodies, and fluids interacting through traditional multi-body constraints, friction, and contact. To lower the learning curve for new users, several toolkits are currently under development or have already been developed. The most relevant of these is Chrono::Vehicle [4] which supports the simulation of both wheeled and track vehicles through a template interface.

2 WVP Model Overview and Assumptions

Assumptions built into the Chrono WVP model can be found below. These assumptions were made when a lack of data or Chrono simulation assumptions required additional information or simplifications. Assumptions for specific tests can be found in the results section with a description of the test itself.

2.1 Model Setup and Assumptions

Vehicle coordinate system: For the WVP Chrono model, the coordinate system was setup with the origin located in the same place as the WVP model data, namely between the front two wheels centered on the axle. A few adjustments were made to the axis directions for simplicity. In this model, the positive X axis point to the front of the vehicle, the position Y axis point to the left side of the vehicle, and the positive Z axis is up. This change between the model data and the Chrono model was made to be consistent with the Chrono::Vehicle simulation module. Any data given in non-SI units were converted as units in Chrono are required to be SI for consistency.

Overall vehicle: The target center of mass for the vehicle was based off the X and Y locations from the weight distribution as tested. The Z location was taken from the estimated location as the vertical component cannot be obtained from the weight distribution. All masses that were modeled, were modeled using the masses given in the model data. As the struts in Chrono are not modeled with mass, the 80 kg per strut was split half with the lower control arm and half to the chassis per the strut connection locations. In the steering, only the center link and pitman arm are given mass in this model. All mass associated with the wheel and tire was considered to be part of the wheel. Mass for the engine was included in the chassis. Any mass not specifically included in the subcomponents, was included in the chassis mass in order to achieve a correct overall mass. This chassis mass was moved around accordingly to achieve the vehicle center of mass at settled configuration as mentioned above. Where no inertial products were given yet required to fully describe the inertial properties, inertial products of 0 were included.

Chassis: The chassis is assumed to be a rigid body with mass as determined from above, and with the total inertia given for the vehicle.
**Suspension:** The suspension is modeled as a full double wishbone with all connecting components. The hard points and center of masses were located to match the data given at design configuration. The spring rate is linear, and is modeled as such through a lookup table based on spring deflection from length at settled configuration as given (779 mm for front struts, 831 mm for rear struts). The roll stabilization curve was added and per an NRMM WVP meeting suggestion, the points were shifted up and to the right to achieve a non-symmetric curve through the origin. These points were linearly interpolated through a lookup table based on strut length from the ride configuration. The bump stop positions were provided based on wheel travel. These locations were translated to strut travel using a 3 dimensional kinematic model built from the hard points. The forces were accordingly added to the spring force. The jounce stop was assumed to be linear past the data provided, as suggested by the NRMM committee. The damping was implemented as a two dimensional lookup table with linear interpolation between all points. An extra column was added to enforce 0 damping force at 0 velocity. With all of the spring-damper-bump stop data included in the spring and all masses accounted for, the vehicle was found to sit low on its suspension. As offset force was then added to the strut force curves (different for front and rear) until the desired settled configuration was achieved.

**Steering mechanism:** In Chrono::Vehicle, the steering mechanism includes the steering link, pitman arm, and tie rods as bodies with the idle arm modeled as a combination joint. All steering column components are ignored and the pitman arm is controlled directly. In order to perform any open loop tests, a steering factor was included that would transfer the steering wheel angle given into a steering value (-1 to 1) that corresponds to full left and full right steer. This factor was assumed to be -.001282 which related 4 and 1/3 turns on the steering wheel to the -1 to 1 value of steering that Chrono::Vehicle requires. The pitman arm is also limited by a maximum steering angle. This was determined to be 41.25 degrees at the pitman arm which results in an inside wheel maximum steering angle of 35 degrees to match the model data.

**Drivetrain and engine:** The engine torque speed curve has been adjusted to account for auxiliary power consumption listed in the model data. Since power consumption of the additional units is given, the ratio has been assumed to be constant for all motor speeds. The motor torque available is assumed to be the fraction of motor torque not taken up by the auxiliary modules and also takes into account all transmission and gear efficiencies provided. The engine data in linearly interpolated between the points provided. Since Chrono does not model clutch characteristics, values for low engine speed were assumed to be roughly 90 percent of the motor torque at 1000 rpm, with a positive slope. The transmission is assumed to be able to instantaneously and perfectly shift gears at ideal shift points provided in an NRMM WVP conference call. The motor speed is smoothed using an exponentially weighted moving average in order to prevent false positive shifts due to engine speed spikes.

**Tires and wheel:** The connection of the wheel to the spindle is assumed to be at the center of the wheel as no other parameters are given for Y value of this location. The tires for the WVP are modeled using the Pacejka89 tire forumula with the parameters provided. The deflection curve is linearly interpolated as a lookup table and has been extrapolated
linearly based off the final two points in the curve. The rolling resistance is assumed to be 1.5 percent from suggestion by the NRMM WVP committee. This tire is used for all rigid terrain tests including the ride quality test. For the deformable terrain tests, a rigid tire is used as the Pacejka model is not well defined for deformable terrain.

2.2 Flat, Rigid Terrain

For all tests conducted on flat rigid terrain (i.e. double lane change, steady state turn, acceleration, etc), the terrain was assumed to be a plane with constant and uniform coefficient of friction. The coefficient of restitution was assumed to be 0.01.

2.3 Deformable Terrain Model

While Chrono provides full support for Discrete Element Method (DEM) granular dynamics and coupled vehicle – granular terrain simulations, due to time and resource limitations, for the purpose of these tests we opted to use a more expeditious model for deformable terrain, based on the Soil Contact Model (SCM) [5]. The Chrono implementation provides several extensions to the original SCM; e.g. non-uniform and adaptive gridding and ability to load terrain profiles from height field or mesh data. Due to lack of data for the soil in the WVP benchmark, LETE sand from the M113 benchmark was used [6].

2.4 Granular Terrain Model

As a demonstration of capability, we conducted limited tests using the Chrono DEM capabilities for a traction test. Chrono supports two computational approaches for DEM: penalty-based (also known as a compliant-body approach; denoted here by DEM-P) and complementarity-based (also known as a rigid-body approach; denoted here by DEM-C). Here, we use the DEM-C method, which requires the solution of a large Differential Variational Inequality (DVI) problem. Tractive effort tests require relatively long simulations which can become prohibitively expensive due to the sheer number of required soil particles that must be taken into account. To address this issue, we employ a recently implemented feature in Chrono::Vehicle based on a "moving patch" approach, wherein particles are continuously relocated (from behind the vehicle) to maintain the patch of granular material underneath the vehicle. Note that appropriate contact material properties for the DEM-C problem are not available and these would have to be obtained from a separate calibration process. In the tests conducted here, we used estimated parameters.
3 Simulation Results

3.1 Settling Configuration

The settling configuration was determined based on a test with low friction terrain and vehicle dropped from 0.5 m above the ground. Strut force was offset from the initial data to insure accurate strut lengths and ride height. The goal of this test was to calibrate the vehicle model to locate the center of mass and strut lengths. Through an iterative process of moving the chassis COM and pre-load on the struts, we were able to match the data provided. The vehicle roll and pitch are provided to give additional settled configuration data to compare with the WVP.

Total Vehicle Mass: 8935.76 kg

vehicle COM: (-1.934 m, 0.013 m, 0.496 m)

Vehicle Orientation: -0.001 rad roll 0.026 rad pitch

<table>
<thead>
<tr>
<th>Strut Location</th>
<th>Strut Length at Settled Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Left</td>
<td>0.781 m</td>
</tr>
<tr>
<td>Front Right</td>
<td>0.782 m</td>
</tr>
<tr>
<td>Rear Left</td>
<td>0.832 m</td>
</tr>
<tr>
<td>Rear Right</td>
<td>0.832 m</td>
</tr>
</tbody>
</table>

3.2 Acceleration Performance

Paved (μ=0.8) Straight Line Acceleration test was performed at full throttle with open differentials. The vehicle response including throttle, speed, engine torque, wheel angular velocities, wheel torques, and vehicle longitudinal acceleration are plotted below for the duration of the acceleration. For the WVP, the engine torque is measured as the available torque at the engine output after all power required by axillary power takeoffs as well as all gear efficiencies have been accounted for.

The throttle value as created to represent the given data in the plots provided in the event list document. After one second (t=1 second), the throttle is pressed and the vehicle takes until t=2 seconds to reach full throttle (figure 1). An exponential curve was used to mimic a realistic step response matching the sample data given. The gear change is assumed to be instantaneous and shifts at the optimal shift points provided in the WVP Benchmark June 27, 2017 Conference Call Agenda.

In the gear time history, plotted in figure 2, we can see the effect of perfect and instantaneous shifting in the lower gears. Visible in figure 8 is the clutch effect. For the WVP, the engine minimum velocity should be around 1000 rpm (105 rad/s). Without a clutch, we assume that the vehicle engine can start at 0 velocity. This is a reasonable assumption as the vehicle reaches normal operation very quickly and the effect can only be seen in this test as other tests will start at a steady state speed.
Figure 1: Straight Line Acceleration throttle time history.

Figure 2: Straight Line Acceleration selected gear time history.

Figure 3: Straight Line Acceleration vehicle speed.

Figure 4: Straight Line Acceleration torque at the output of the engine.
3.3 Steering Performance

3.3.1 Wall to Wall Turn Radius

Paved (μ=0.8) surface wall to wall turn radius as measured by the smallest bounding circle that encompasses the vehicle at all heights was found to be 9.444 m for a counterclockwise turn and 9.425 m for a clockwise turn. Plotted in the figure below is the outermost point on the chassis. For counterclockwise turn, this is the front right point of the chassis, and front left point on the chassis for the clockwise turn. To carry out this event, the vehicle was set to turn at one extreme for the entire simulation and target a constant speed of 5 mph.
Then, by looking at the path of the chassis outermost corner (figure 9), the bounding circle was be calculated.

![Figure 9: Wall to Wall turn radius. Radius of counterclockwise radius calculated as 9.444 m. Bounding radius of clockwise turn found to be 9.425 m.](image)

**3.4 Steady State Turning**

**3.4.1 200 ft. Radius Steady State Cornering**

The demanded method reflects the procedure for a real world steady state cornering test, where the result curves must be constructed point by point. The speed of the vehicle must be increased by steps. After the new state is stationary we get one point of result curves. By using a vehicle simulation software in the time domain the speed of the vehicle can also be increased continuously from Ackermann speed to the driving limit. The speed sweep phase should take at least 120 s. The instationary states can then approximately be taken as stationary states.

Both the path controller and the speed controllers were in closed loop mode. For the path controller a PI controller was used. The I gain was 10 percent of the P gain. That led to a very low path deviation, smaller than a cm. This controller did only work sufficiently with a look ahead point 5 m in front of the vehicle. This is clearly a deviation from the demands, where no look ahead distance is wanted. The complete absence of controller overshoots is a great advantage yet. Controller behavior does not influence the driving limits any more. The result curves are usually presented as functions of lateral acceleration, which is measured correctly.

The maximal speed for steady state cornering can be limited for example by tipping, sliding, lack of engine power. In the vehicle dynamics literature also the vehicle slip angle
is mentioned. This method has been employed here. The limit for the vehicle slip angle is -5 deg. At begin of the acceleration phase the angle starts at ca. 2 deg and goes down continuously with increasing speed.

![Figure 10: Steering wheel angle vs lateral acceleration during 200 ft constant radius turn.](image10.png)  
![Figure 11: Vehicle roll angle vs vehicle speed during 200 ft constant radius turn.](image11.png)

The steering wheel gradient in figure 10 shows the most important results of the test. The vehicle is understeering. This is an appropriate design for road vehicles driven by an average human driver.

![Figure 12: Steering wheel angle vs vehicle speed during 200 ft constant radius turn.](image12.png)  
![Figure 13: Vehicle slip angle vs vehicle speed during 200 ft constant radius turn.](image13.png)
3.5 Double Lane Change

For all of the double lane change tests, the vehicle was driven through the course in a right then left lane change configuration as well as a left then right pass. The paved surfaces for these tests used a friction coefficient of 0.8 and the gravel lane change equivalent of 0.5.

As expected due to numerous assumptions and simplifications, the open loop controller double lane changes were not able to stay near the lane, so closed loop double lane change tests were also performed. Both the open and closed loop tests are plotted for comparison. All the lane change tests used the same proportional controller to maintain the target velocity before starting the course. For steering, the closed loop controllers used a proportional controller to follow a predetermined path that followed the center of the course. For the open loop steering, the data given was fed into the model with no smoothing. For this input data, all lag, steering, and driver effects are assumed to be incorporated.

The purpose of the double lane change tests is to determine the maximum speed at which the vehicle can drive through the course without exceeding the course limits and without loss of control. In order to determine this, the vehicle was setup to drive at incremental speeds starting at 10 mph until loss of control or lane exceedance.

3.5.1 Paved Double Lane Change with Open Loop Controller

For all of the following open loop tests for the paved double lane change, the vehicle was unable to successfully advance through the course as demonstrated by plot of wheel locations in figures 14, 15, 26, and 27. The tire forces still show some interesting results, namely between the 35 mph test and 48 mph tests, there is some rear wheel lift shown as 0 vertical tire force in figures 24 and 25.

![Figure 14: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.](image)

![Figure 15: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.](image)
Figure 16: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.

Figure 17: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.

Figure 18: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.

Figure 19: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.
Figure 20: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.

Figure 21: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.

Figure 22: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.

Figure 23: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.
Figure 24: Paved Double Lane Change with open loop controller - Left then Right at 35 mph.

Figure 25: Paved Double Lane Change with open loop controller - Left then Right at 48 mph.
Figure 26: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 27: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.

Figure 28: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 29: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.
Figure 30: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 31: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.

Figure 32: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 33: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.
Figure 34: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 35: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.
3.5.2 Paved Double Lane Change with Closed Loop Controller

Since even small errors in model data have resulted in major differences in an open loop controller, the double lane change tests were also performed using a closed loop path controller which we argue more accurately tests the capabilities of the vehicle within simulation platform. These path controllers were designed to follow a specific path that would carry the vehicle between the cones with reasonably low curvature. The results for the double lane change with open loop controller at different speeds are shown in Figures 36 and 37.

Figure 36: Paved Double Lane Change with open loop controller - Right then Left at 35 mph.

Figure 37: Paved Double Lane Change with open loop controller - Right then Left at 48 mph.
change for varying vehicle speeds are shown below in Figures 38 through 43 for left then right turn double lane change and Figures 44 through 49 for the right then left double lane change on paved surface \((\mu=0.8)\).

For the paved closed loop double lane change, the tests were performed at 5 mph increments for both left-then-right and right-then-left runs. For clarity, only the tests at 35 mph and 45 mph are compared in detail due to the large increase in wheel lift and lateral slip of the vehicle between these tests. As indicated here, 35 mph was the observed test limit as the fastest speed with no significant wheel lift which can be seen in figure 59. The test limit was confirmed in the left-then-right case.

Figure 38: Paved Double Lane Change with closed loop controller - Left then Right at 20 mph.

Figure 39: Paved Double Lane Change with closed loop controller - Left then Right at 30 mph.
Figure 40: Paved Double Lane
Change with closed loop controller -
Left then Right at 35 mph.

Figure 41: Paved Double Lane
Change with closed loop controller -
Left then Right at 40 mph.

Figure 42: Paved Double Lane
Change with closed loop controller -
Left then Right at 45 mph.

Figure 43: Paved Double Lane
Change with closed loop controller -
Left then Right at 50 mph.
Figure 44: Paved Double Lane Change with closed loop controller - Right then Left at 20 mph.

Figure 45: Paved Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 46: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 47: Paved Double Lane Change with closed loop controller - Right then Left at 40 mph.
Figure 48: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.

Figure 49: Paved Double Lane Change with closed loop controller - Right then Left at 50 mph.

Figure 50: Paved Double Lane Change with closed loop controller - Left then Right at 35 mph.

Figure 51: Paved Double Lane Change with closed loop controller - Left then Right at 45 mph.
Figure 52: Paved Double Lane Change with closed loop controller - Left then Right at 35 mph.

Figure 53: Paved Double Lane Change with closed loop controller - Left then Right at 45 mph.

Figure 54: Paved Double Lane Change with closed loop controller - Left then Right at 35 mph.

Figure 55: Paved Double Lane Change with closed loop controller - Left then Right at 45 mph.
Figure 56: Paved Double Lane Change with closed loop controller - Left then Right at 35 mph.

Figure 57: Paved Double Lane Change with closed loop controller - Left then Right at 45 mph.
Figure 58: Paved Double Lane Change with closed loop controller - Left then Right at 35 mph.

Figure 59: Paved Double Lane Change with closed loop controller - Left then Right at 45 mph.
Figure 60: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 61: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.

Figure 62: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 63: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.
Figure 64: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 65: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.

Figure 66: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 67: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.
Figure 68: Paved Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 69: Paved Double Lane Change with closed loop controller - Right then Left at 45 mph.
3.5.3 Gravel Double Lane Change with Open Loop Controller

For all of the following open loop tests for the gravel double lane change, the vehicle was unable to successfully advance through the course as demonstrated by plots of wheel locations in figures 70, 71, 82, and 83. Key differences between these tests can be seen in the tire forces as there is some rear wheel lift shown as 0 vertical tire force in figures 81 and 93 and no wheel lift in figures 80 and 92.

Figure 70: Gravel Double Lane Change with open loop controller - Left then Right at 31 mph.

Figure 71: Gravel Double Lane Change with open loop controller - Left then Right at 36 mph.

Figure 72: Gravel Double Lane Change with open loop controller - Left then Right at 31 mph.

Figure 73: Gravel Double Lane Change with open loop controller - Left then Right at 36 mph.
Figure 74: Gravel Double Lane Change with open loop controller - Left then Right at 31 mph.

Figure 75: Gravel Double Lane Change with open loop controller - Left then Right at 36 mph.

Figure 76: Gravel Double Lane Change with open loop controller - Left then Right at 31 mph.

Figure 77: Gravel Double Lane Change with open loop controller - Left then Right at 36 mph.
Figure 78: Gravel Double Lane Change with open loop controller - Left then Right at 31 mph.

Figure 79: Gravel Double Lane Change with open loop controller - Left then Right at 36 mph.
Figure 80: Gravel Double Lane Change with open loop controller
- Left then Right at 31 mph.

Figure 81: Gravel Double Lane Change with open loop controller
- Left then Right at 36 mph.
Figure 82: Gravel Double Lane Change with open loop controller - Right then Left at 31 mph.

Figure 83: Gravel Double Lane Change with open loop controller - Right then Left at 38 mph.

Figure 84: Gravel Double Lane Change with open loop controller - Right then Left at 31 mph.

Figure 85: Gravel Double Lane Change with open loop controller - Right then Left at 38 mph.
Figure 86: Gravel Double Lane Change with open loop controller - Right then Left at 31 mph.

Figure 87: Gravel Double Lane Change with open loop controller - Right then Left at 38 mph.

Figure 88: Gravel Double Lane Change with open loop controller - Right then Left at 31 mph.

Figure 89: Gravel Double Lane Change with open loop controller - Right then Left at 38 mph.
Figure 90: Gravel Double Lane Change with open loop controller - Right then Left at 31 mph.

Figure 91: Gravel Double Lane Change with open loop controller - Right then Left at 38 mph.
3.5.4 Gravel Double Lane Change with Open Loop Controller

For the gravel (\(\mu=0.5\)) closed loop double lane change, the tests were performed at 5 mph increments for both left-then-right and right-then-left runs. For clarity, only the tests at 35 mph and 45 mph are compared in detail due to the large increase in wheel lift and lateral slip of the vehicle between these tests. The path for tests between 20 mph and 50 mph can be seen in figures 94 through 105. As indicated here, 30 mph was the observed test limit as
the fastest speed with no wheel lift which can be seen clearly on both rear wheels in figure 115. The test limit was confirmed in the left-then-right case.

Figure 94: Gravel Double Lane Change with closed loop controller - Left then Right at 20 mph.

Figure 95: Gravel Double Lane Change with closed loop controller - Left then Right at 25 mph.

Figure 96: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 97: Gravel Double Lane Change with closed loop controller - Left then Right at 35 mph.
Figure 98: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.

Figure 99: Gravel Double Lane Change with closed loop controller - Left then Right at 50 mph.

Figure 100: Gravel Double Lane Change with closed loop controller - Right then Left at 20 mph.

Figure 101: Gravel Double Lane Change with closed loop controller - Right then Left at 25 mph.
Figure 102: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 103: Gravel Double Lane Change with closed loop controller - Right then Left at 35 mph.

Figure 104: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.

Figure 105: Gravel Double Lane Change with closed loop controller - Right then Left at 50 mph.
Figure 106: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 107: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.

Figure 108: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 109: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.
Figure 110: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 111: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.

Figure 112: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 113: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.
Figure 114: Gravel Double Lane Change with closed loop controller - Left then Right at 30 mph.

Figure 115: Gravel Double Lane Change with closed loop controller - Left then Right at 40 mph.
Figure 116: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 117: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.

Figure 118: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 119: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.
Figure 120: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 121: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.

Figure 122: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 123: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.
Figure 124: Gravel Double Lane Change with closed loop controller - Right then Left at 30 mph.

Figure 125: Gravel Double Lane Change with closed loop controller - Right then Left at 40 mph.
3.6 Side Slope Performance

3.6.1 30% Side Slope Slalom

For the 30% side slope slalom test, an open loop controller was used. The vehicle was brought up to steady state speed using a proportional straight line path follower and speed controller. After 20 seconds for the vehicle to reach steady state, the path follower was replaced by input data in the form of time and steering values provided by the NRMM WVP committee. All results vs time history are shown only for the portion of the test conducted with the open loop controller. For data that did not start at 0 steering angle, the data was padded with ramped values matching the rate of steering angle change during the following portion of the data. As mentioned previously, the steering value is shown between -1 and 1 corresponding to full right and full left steer. The input data was processed with a steering wheel to maximum steer ratio to match the simulation software required inputs.

The steering input for the critical runs can be seen below in figures 126 and 127 for the tests with left side down and figures 140 and 141 for the tests with right side down. The test was performed at speeds starting at 5 mph. Each successive test was conducted at a higher speed to determine the maximum controllable speed. A non-controllable test was determined to be one with vehicle slip, roll, or loss of control.

For the left side down test, the maximum controllable speed was 22.5 mph with the test of 25 mph showing vehicle slip. This was observed in the form of chatter in the tire forces in figure 139 indicating wheel slippage. This chatter is more evident on the right front and right rear wheels. While the tire forces in figure 138 show the beginning of chatter, this was not enough to indicate slippage.

The path at fastest successful run can be seen in figure 128. The vehicle appears to get steering data bias toward the right, explaining the vehicle travel up the slope. When compared to a path at higher speed as in figure 129, the vehicle tends to slip down the slope at higher velocities in accordance with the observed slippage.
Figure 126: 30% Side Slope - Steering input for left side down at 22.5 mph.

Figure 127: 30% Side Slope - Steering input for left side down at 25 mph.

Figure 128: 30% Side Slope - Path of fastest successful run for left side down - 22.5 mph.

Figure 129: 30% Side Slope - Path of slowing unsuccessful run for left side down - 25 mph.
Figure 130: 30% Side Slope - Speed history for left side down at 22.5 mph.

Figure 131: 30% Side Slope - Speed history for left side down at 25 mph.

Figure 132: 30% Side Slope - Lateral acceleration for left side down at 22.5 mph.

Figure 133: 30% Side Slope - Lateral acceleration for left side down at 25 mph.
Figure 134: 30% Side Slope - Vehicle rotation for left side down at 22.5 mph.

Figure 135: 30% Side Slope - Vehicle rotation for left side down at 25 mph.

Figure 136: 30% Side Slope - Vehicle rotation rates for left side down at 22.5 mph.

Figure 137: 30% Side Slope - Vehicle rotation rates for left side down at 25 mph.
For the right side down test, the maximum controllable speed was 12.5 mph with the test of 15 mph showing vehicle slip. This was observed in the form of chatter and even wheel lift in the tire forces in figure 139 indicating wheel slippage. This chatter is more evident on the left front and right rear wheels with wheel lift seen on the left rear wheel.

The path at fastest successful run can be seen in figure 128. The vehicle is again bias toward the right, but this time with the slope. When compared to a path at higher speed...
as in figure 129, the vehicle tends to slip down the slope at higher velocities in accordance with the observed slippage.

Figure 140: 30% Side Slope - Steering input for right side down at 12.5 mph.

Figure 141: 30% Side Slope - Steering input for right side down at 15 mph.

Figure 142: 30% Side Slope - Path of fastest successful run for right side down - 12.5 mph.

Figure 143: 30% Side Slope - Path of slowing unsuccessful run for right side down - 15 mph.
Figure 144: 30% Side Slope - Speed history for right side down at 12.5 mph.

Figure 145: 30% Side Slope - Speed history for right side down at 15 mph.

Figure 146: 30% Side Slope - Lateral acceleration for right side down at 12.5 mph.

Figure 147: 30% Side Slope - Lateral acceleration for right side down at 15 mph.
Figure 148: 30% Side Slope - Vehicle rotation for right side down at 12.5 mph.

Figure 149: 30% Side Slope - Vehicle rotation for right side down at 15 mph.

Figure 150: 30% Side Slope - Vehicle rotation rates for right side down at 12.5 mph.

Figure 151: 30% Side Slope - Vehicle rotation rates for right side down at 15 mph.
Figure 152: 30% Side Slope - Tire forces for right side down at 12.5 mph.

Figure 153: 30% Side Slope - Tire forces for right side down at 15 mph.

3.7 Sand Slope Gradeability

3.7.1 Sand Slope Maximum Gradeability based on Bekker Soil Mechanics

The task was to determine the maximum slope the vehicle can negotiate on soft soil. The vehicle should drive on sandy soil given by data from NATC. We did not find a way to transform these data into soil parameters we needed for our simulation. We decided to
take the soil parameters form LETE sand provided by Dr. Wong for the tracked vehicle benchmark tests before. The soil model we used is based on the theory of M. G. Bekker with enhancements of Janosi and Hanamoto. The vehicle was configured with open differentials and closed loop speed and path controllers. A rigid tire model with appropriate geometry was chosen.

Every simulation run is composed of three sequential phases - the dynamic equilibrium phase, the grade sweep phase and the hold phase. Each phase takes 10 secs of time. Figure 154 shows the development of the slope angle vs time. The vehicle should maintain a constant speed of 5 mph. In figure 155 we can clearly see the driving limit on LETE sand. The demanded speed of 5 mph can only be maintained up to 25 percent slope. At 26 percent slope the speed goes down to zero. Since there is no torque converter in the drive train the wheel speeds go down as well. We did not see flying wheels. That means also that we do not need to repeat the tests with locked differentials. In figure 158 we can see some spikes of the average slip value. In the very beginning of the first the vehicle is dropped from a height with no wheel soil contact. It takes some seconds to establish a dynamic equilibrium, In the first phase high slip values do not have any influence on the vehicle tractive effort. In the last phase, if the speed goes down to zero a singularity effect of the slope calculation can occur. These effects can also be ignore as long they do not cause free spinning of wheels.

![Figure 154: Slope angle vs time during soil gradeability test.](image1)

![Figure 155: Vehicle speed vs time during soil gradeability test.](image2)
Figure 156: Motor speed vs time during soil gradeability test.

Figure 157: Motor torque vs time during soil gradeability test.

Figure 158: Average slip vs time during soil gradeability test.

Figure 159: Left front wheel speed vs time during soil gradeability test.
3.8 Ride Quality

3D representations for four uneven road profiles are given. There are small differences between left and right road side, which lead to a 3-dimensional wheel excitation and therefore to a vibrational load on the driver’s seat. The Absorbed Power Method is to be used to estimate the driver’s capability to stand the oscillations. The widely accepted limit for an average driver is 6 W Absorbed Power. The Absorbed Power can be calculated by means of different algorithm in the time or frequency domain. Often only the vertical component of the oscillation signal is used. Here we calculated the 3-axial value. The 3-axial algorithm is based on the TARADCOM Technical Report Nr. 12415 from Dec 1978. It works in the time...
domain with discrete signals. The originally analog filter coefficients were converted into the Z-domain via the bilinear transform (Tustin Method). The algorithm has been validated against analog and discrete MATLAB based solutions.

For the tests a standard vehicle setup was used. Speed- and path-controllers were closed loop to allow a constant speed and centering the vehicle on the road. The four road files are different in the unevenness of their height profiles measured in RMS (inch). Beginning with a constant speed of 5 km/h the road was passed and the accumulated Absorbed Power Value was reported. If this value was lower than 6 W, the simulation was repeated with velocity increased by a step of 5 km/h, until the Absorbed Power Limit was reached or exceeded. If the last result was above the limit the result was determined by linear interpolation.

![Graphs showing vehicle speed vs Surface Roughness and Absorbed power vs vehicle speed for each random course.](image)

**Figure 163**: Vehicle speed at 6 Watt vs Surface Roughness.  
**Figure 164**: Absorbed power vs vehicle speed for each random course.

Figure 163 shows the final result. The 6-Watt-speed normally decreases with the surface roughness. In this special case the results for surface roughness 2.4 in and 3.6 in are nearly identical. On the other side there is a big difference in the 6-Watt-speeds between the courses 1.0 in and 1.2 in roughness. Figure 164 presents the individual dependency of Absorbed Power vs average vehicle speed for the individual courses. Like in real tests the demanded speed is not identical to the real possible speed. Therefore the average speed was calculated and taken as result.

The following figures show the vertical seat accelerations as time histories for every individual run.
Figure 165: Vertical seat acceleration vs time - speed=5km/h / course 1.0in.

Figure 166: Vertical seat acceleration vs time - speed=10km/h / course 1.0in.

Figure 167: Vertical seat acceleration vs time - speed=15km/h / course 1.0in.

Figure 168: Vertical seat acceleration vs time - speed=20km/h / course 1.0in.
Figure 169: Vertical seat acceleration vs time - speed=25km/h / course 1.0in.

Figure 170: Vertical seat acceleration vs time - speed=30km/h / course 1.0in.

Figure 171: Vertical seat acceleration vs time - speed=35km/h / course 1.0in.

Figure 172: Vertical seat acceleration vs time - speed=40km/h / course 1.0in.
Figure 173: Vertical seat acceleration vs time - speed=45km/h / course 1.0in.

Figure 174: Vertical seat acceleration vs time - speed=50km/h / course 1.0in.

Figure 175: Vertical seat acceleration vs time - speed=55km/h / course 1.0in.

Figure 176: Vertical seat acceleration vs time - speed=60km/h / course 1.0in.
Figure 177: Vertical seat acceleration vs time - speed=65km/h / course 1.0in.

Figure 178: Vertical seat acceleration vs time - speed=70km/h / course 1.0in.

Figure 179: Vertical seat acceleration vs time - speed=5km/h / course 1.2in.

Figure 180: Vertical seat acceleration vs time - speed=10km/h / course 1.2in.
Figure 181: Vertical seat acceleration vs time - speed=15km/h / course 1.2in.

Figure 182: Vertical seat acceleration vs time - speed=20km/h / course 1.2in.

Figure 183: Vertical seat acceleration vs time - speed=25km/h / course 1.2in.

Figure 184: Vertical seat acceleration vs time - speed=30km/h / course 1.2in.
Figure 185: Vertical seat acceleration vs time - speed=5km/h / course 2.4in.

Figure 186: Vertical seat acceleration vs time - speed=10km/h / course 2.4in.

Figure 187: Vertical seat acceleration vs time - speed=15km/h / course 2.4in.

Figure 188: Vertical seat acceleration vs time - speed=20km/h / course 2.4in.
Figure 189: Vertical seat acceleration vs time - speed=25km/h / course 2.4in.

Figure 190: Vertical seat acceleration vs time - speed=30km/h / course 2.4in.

Figure 191: Vertical seat acceleration vs time - speed=5km/h / course 3.6in.

Figure 192: Vertical seat acceleration vs time - speed=10km/h / course 3.6in.
3.9 Sand Traction

3.9.1 Sand Traction based on Bekker Soil Mechanics

The vehicle and soil setup in this test is very similar to the soil slope gradeability test. The slope angle here is zero, but a external drawbar force tries to tie the vehicle speed down to zero. Like in the soft soil gradeability test we used three testphases, the dynamic equilibrium phase, the force sweep phase and the hold phase. Figure 197 shows how the drawbar force
changes over time. As long as the soil can support the contact forces and the engine torque is high enough, the vehicle can maintain the demanded speed of 5 mph. A value of 22000 N could be clearly identified as result of the drawbar pull test (Figure 198). In the figures 201, 202, 203 and 204, we can see no free spinning wheel. For this reason the test was not repeated with locked differentials. The longitudinal slip values were very low, despite some disturbances. This makes the resulting tractive effort chart different as probably expected (Figure 205).

![Figure 197: Drawbar force vs time during drawbar pull test.](image)

![Figure 198: Vehicle speed vs time during drawbar pull test.](image)

![Figure 199: Motor speed vs time during drawbar pull test.](image)

![Figure 200: Motor torque vs time during drawbar pull test.](image)
Figure 201: Front left wheel speed vs time during drawbar pull test.

Figure 202: Front right wheel speed vs time during drawbar pull test.

Figure 203: Rear left wheel speed vs time during drawbar pull test.

Figure 204: Rear right wheel speed vs time during drawbar pull test.
Figure 205: Tractive effort vs average longitudinal slip during soil grade-ability test.

3.9.2 Traction Test based on Granular Dynamics Soil

A patch of granular terrain is represented using 87,488 particles, each of radius 15 mm. The particle density was set to 1650 kg/m$^3$ and the inter-particle coefficient of friction to 0.9. Cohesion forces between the rigid bodies representing soil particles were calculated from an assumed cohesion pressure of 11 kPa. A moving patch approach is employed, wherein particles are relocated from behind the vehicle such that the vehicle front axle is never closer than 1.5 m from the front patch boundary. When needed, all particles within a slice of 0.25 m (in the X direction) are relocated from the back to the front of the patch. Figure 206 shows two simulation frames during a patch relocation.

![Frame A](image_a.png) ![Frame B](image_b.png)

Figure 206: Snapshots from two consecutive rendering frames of the tractive test on granular terrain. These two frames capture the time of a relocation of the granular patch.

Results from this test are shown in Fig. 207 as an overlay of the vehicle forward speed
(left axes) and a resistance force (right axes) applied to the COM of the vehicle chassis. The resistance force is applied after the vehicle has reached the target speed (5 mph = 2.235 m/s) and is then ramped for the remainder of the simulation. The drawbar pull is extracted as the resistance force magnitude at the time of loss of soil bearing capacity. This point is identified as the time at which the vehicle forward velocity drops below 2 m/s. The resulting estimate for drawbar pull under these conditions is obtained as 12.37 kN.

Figure 207: Drawbar pull results for granular terrain.

This simulation was performed with the Chrono::Parallel multi-core parallel solver, with a time-step of 1 ms and using 20 OpenMP threads on an Intel Xeon E5-2650 v3 processor. The average wall-clock time per step was approximately 1.2 s.

Acknowledgments

The development of Chrono has been supported with funding from the following projects:

- U.S. Army Research Office RIF W56HZV-14-C-0254 ”A Physics-based High Performance Computing Capability for Ground Vehicle Mobility Analysis”

- U.S. Army TARDEC, CREATE-GV project, W56HZV-08-C-0236 ”Development of a High Performance Computing Software Infrastructure for the Modeling and Simulation of Multibody Dynamics Applications: Part 1” (wheeled vehicles)

- U.S. Army TARDEC, CREATE-GV project, W56HZV-08-C-0236 ”Development of a High Performance Computing Software Infrastructure for the Modeling and Simulation of Multibody Dynamics Applications: Part 2” (tracked vehicles)

- U.S. Army Research Office, W911NF-15-1-0386 ”An Instrumentation Request for Upgrading a Mid-size Heterogeneous Computing System Supporting Research and Educational Activities in Computational Dynamics”
References


