A Physics-Based Terrain Model for Off-Road Vehicle Simulations

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-Motivation & goals of project -High level model Framework -Detailed Calculation Flowchart --Concentrates on advancing simulation by one time-step -Examples of terrain response to various applied loading conditions -Addressing performance issues through parallel computing -Conclusion

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Overview

- Motivation & goals of project
- High level model Framework
- Detailed Calculation Flowchart
  - Concentrates on advancing simulation by one time-step
- Examples of terrain response to various applied loading conditions
- Addressing performance issues through parallel computing
- Conclusion

Motivation

- Existing vehicle dynamics models incorporate deformable terrain in two general ways:
  1. Empirical methods
     - WES numerics, Bekker vertical pressure/sinkage
  2. Boundary Value Problem
     - Finite Element Analysis (FEA)
     - Particle/Discrete Element methods (DEM)

- Empirical methods are not suitable for general purpose vehicle mobility, energy/power, durability/reliability analyses

- FEA or DEM are accurate, but are computationally expensive and cannot achieve real-time performance

- Requires a lower-order, physics-based tire/terrain model that can interface to existing multibody-dynamic vehicle models

Overall Goals of Project

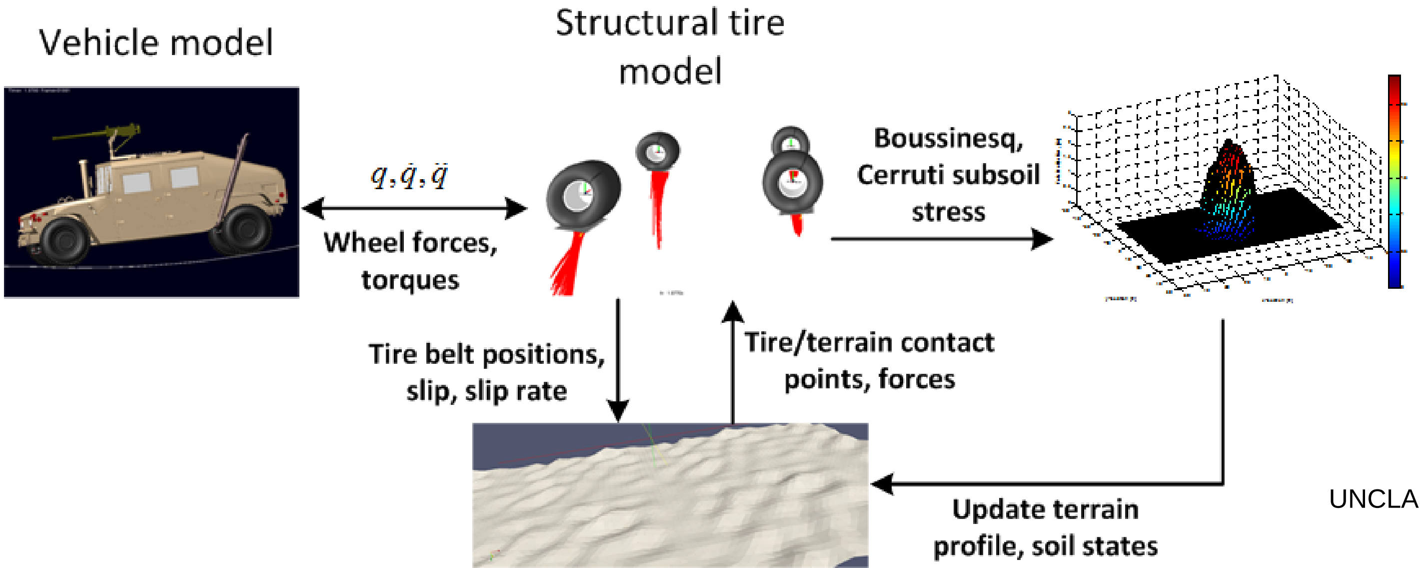
- Link existing vehicle models to physics-based deformable terrain interaction model
  - Soil Mechanics models developed by UT (Ayers, Bozdech)
  - Soil models and terrain database implemented by UW (Madsen, Seidl)

- Tire/terrain interaction model should run at real-time speed
  - Enables operator-in-the-loop simulations
  - Requires multi-core CPU and GPU parallel computing acceleration

- Develop universal vehicle/terrain model for deformable terrain that is capable of mobility, power/energy and reliability analysis

High level Framework

- Interface begins at the wheel spindle
- Can use any tire model that satisfies:
  1. Standard Tire Interface
  2. Accepts a discrete contact patch geometry to find force vectors at the interface
- Tire/Terrain interface forces assumed as a combination of radial, slip and bulldozing effects
- Interface forces applied to terrain to find subsoil stress beneath tire
- Soil deforms vertically according to visco-elastic-plastic compressibility relationship, in conjunction with loading history
  - Includes compression/rebound, repeated loading effects



Vehicle model

Structural tire model

$q, \dot{q}, \ddot{q}$

Wheel forces, torques

Boussinesq, Cerruti subsoil stress

Tire belt positions, slip, slip rate

Tire/terrain contact points, forces

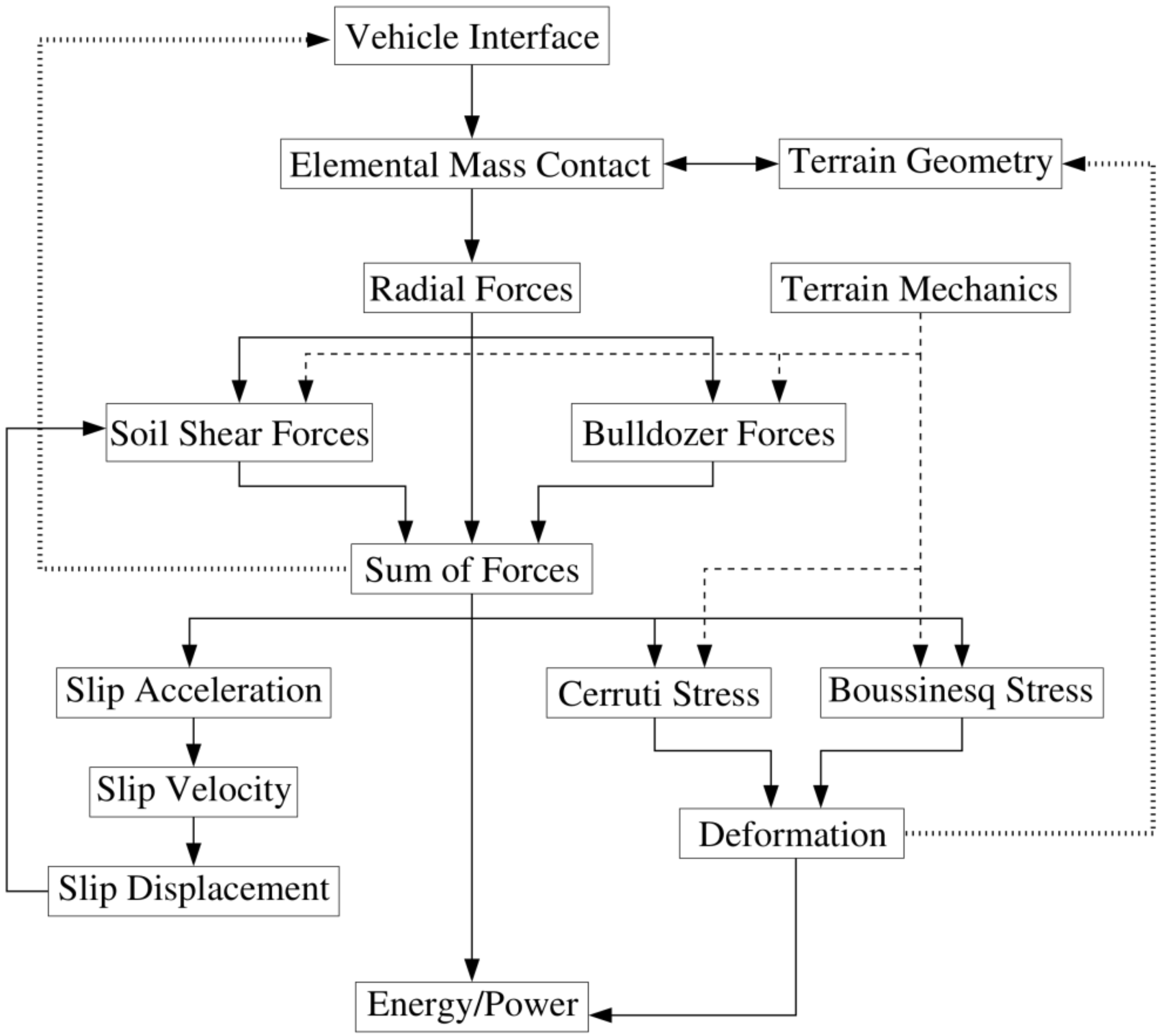
Update terrain profile, soil states

Simulation, taking one time-step…

- Modeling assumptions
    - Tire and terrain dynamics solved in a staggered fashion
    - No tire dynamics considered here (i.e., rigid wheel)
        - Slip computation is more involved with a deformable wheel

- Summary of major required computations
    - Identify contact between tire and terrain
    - Calculate contact patch force/pressure
        - Normal forces as a function of tire-terrain interpenetration
        - Tangent forces developed from slip & bulldozing effects
    - Contact patch forces used to approximate stress field in subsoil
        - Modified Boussinesq, Cerruti theory
        - Assumes linear superposition of subsoil stresses
    - Terrain model calculates:
        - Soil element stress-displacement effects
        - Power and energy to perform soil deformation
        - Updates soil states and terrain surface profile change

Detailed Calculation Flow



Quasi-static Contact Patch Model

- Need to have a force model at the tire tread/soil interface
- Tread deformations are fast & small when compared to carcass deformations (Svendenius, 2006)
  - Tire carcass model → Dynamic
  - Contact patch model → Static

- Contact patch pressure calculated at each discretized tire node once per time step
- Combines of normal, tractive and bulldozing effects

Contact Patch Model: Normal Forces

- Assume tire normal forces are approx. radial and a function of interpenetration between tire belt mass nodes and terrain geometry, δ_n^i
  - Using a penalty-based repulsion force
  - Able to use static vertical load tests to approximate radial stiffness per unit area, k_n

$$\sigma_n^i = \delta_n^i k_n \vec{n}^i$$

  - where

$$\vec{n}^i = (P_a^i - P_0^i)$$

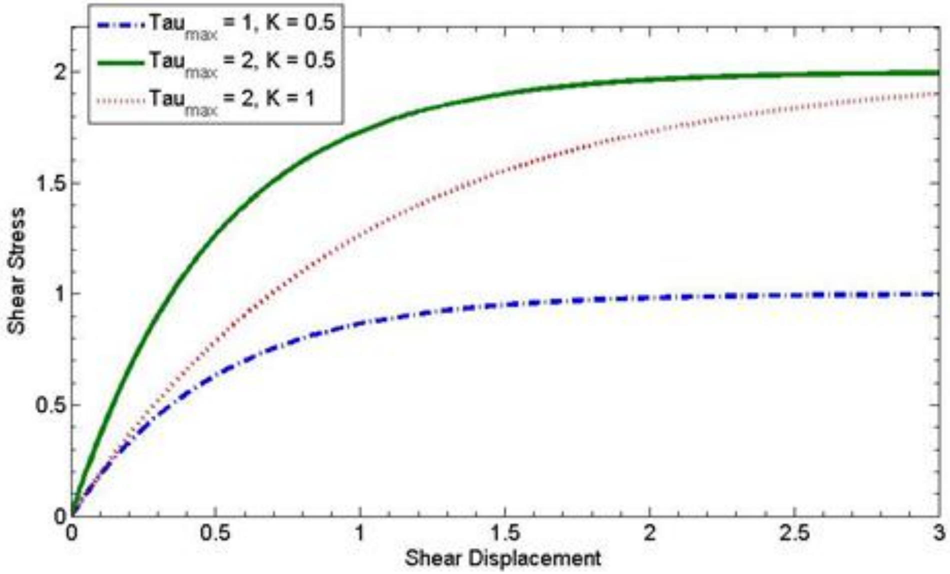
Contact Patch Model : Tire Slip and Bulldozing Forces

- Tire slip at the tire-terrain interface generates tangential forces
  - Responsible for tractive and turning forces
  - Janosi and Hanamoto model (1961)

$$\tau = \tau_{\max}(1 - e^{-j/K})$$

$$\tau = (c + p\tan\varphi)(1 - e^{-j/K})$$

  - Based on total slip displacement, soil shear attributes

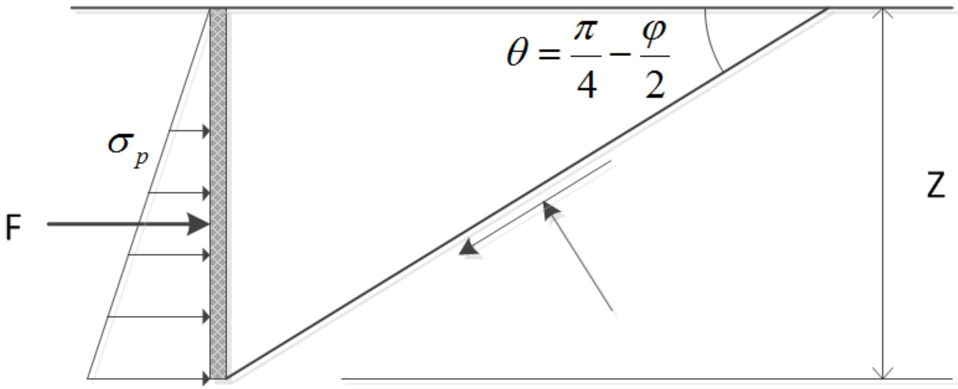


- Bulldozing effects add additional forces
  - Increases turning (lateral) forces
  - Reduces tractive (longitudinal) forces
  - Passive Lateral Earth Pressure Theory (Wong, 2001)

$$F = b(\tfrac{1}{2}\gamma Z^2 N_\phi + 2cZ\sqrt{N_\phi})$$

$$N_\phi = \tan^2(45 + \phi/2)$$

  - Force a function of: tire sinkage, soil friction angle and soil bulk density



Terrain (Compaction) Model: High Level Perspective

- Sum of normal, slip and bulldozing forces acting on tire are applied to the terrain surface
- Soil volume discretized into rectangular grid
- Only consider vertical stress-strain in soil (“Compaction”)

- Subsoil stress distribution calculated via. modified Boussinesq & Cerruti Equations

- Vertical subsoil pressure at the top of each element can cause bulk density change according to Visco-Elastic-Plastic soil model

- Soil element deformation and current soil state allow calculation of energy, power. **Discretized soil grid allows for power & energy distribution calculation**

Subsoil stress distribution

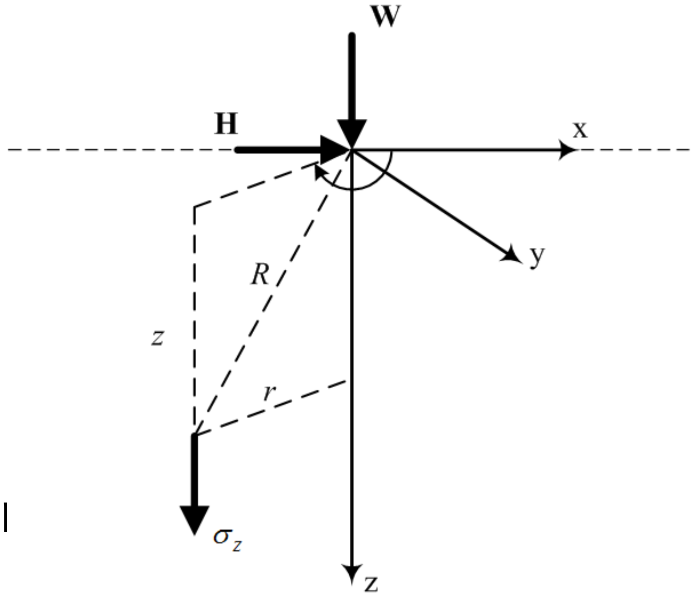
- Empirical in nature
- Vertical force results in stress via. Boussinesq according to Frolich (Ayers, 1991)

$$\sigma_z = \frac{\nu W z^{\nu}}{2\pi(r^2+z^2)^{(\nu/2+1)}}$$

- Horizontal force also results in stress via. Cerruti (Feda, 1978)

$$\sigma_z = \frac{3}{2\pi}\,\frac{r(\cos\Theta)}{[1+(r/z)^2]^{5/2}}\,\frac{H}{z^3}$$

- Only calculate subsoil stress distrubtion di underneath contact patch
- Limit the maximum subsoil stress to the contact patch pressure at the surface



Visco-Elastic-Plastic soil model

- Vertical subsoil stress known at discrete points
- Theoretical bulk density for given M.C., stress (Larson et al., 1980):

$$\rho = \left[\rho_k + S_T\left(S_1 - S_k\right)\right] + C\log\left(\sigma_a / \sigma_k\right)$$

- Include time-constant effects to bulk density

$$\left(1 - e^{t/\tau}\right)$$

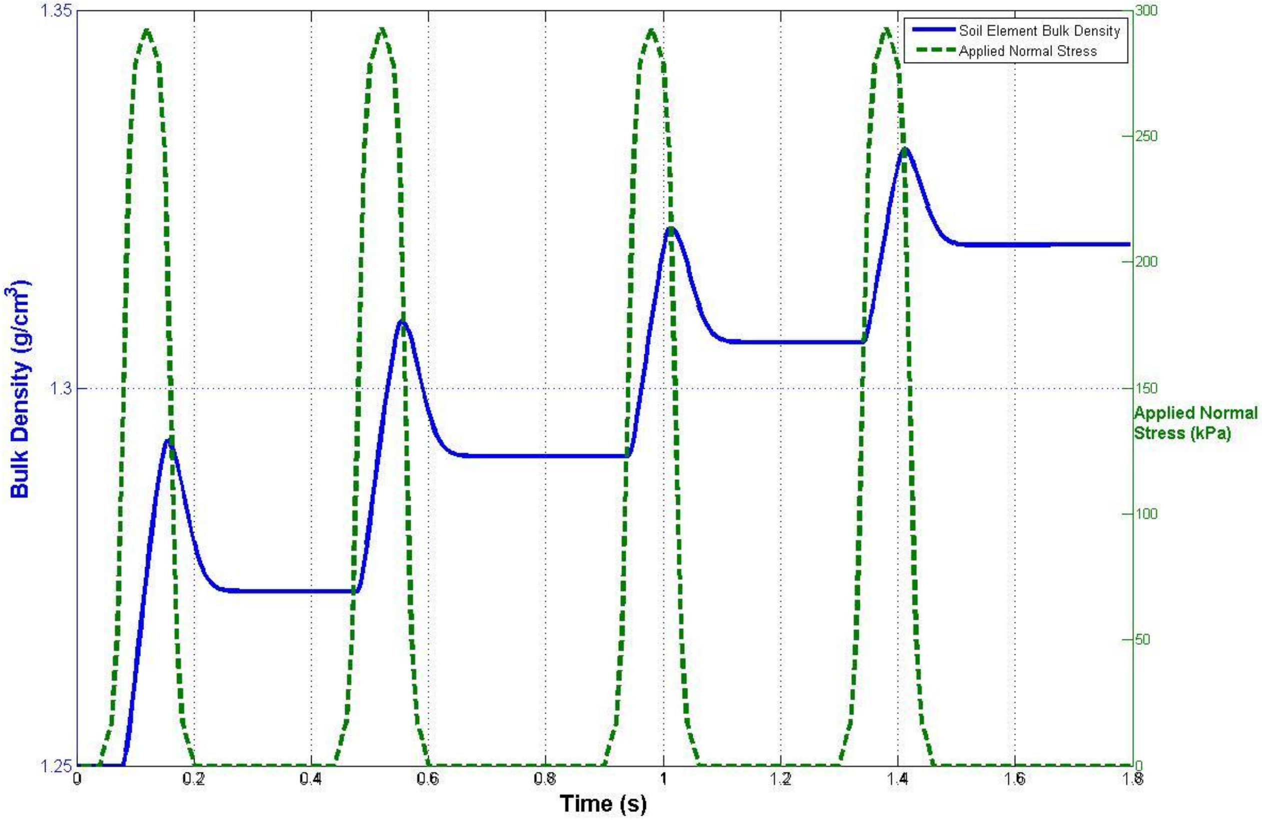
- Sinkage simply a function of initial, current bulk densities

$$z = \left(1 - \left(\rho_0 / \rho_1\right)\right)$$

- Power, Energy simply calculated as

$$E = F \cdot \Delta z = (\sigma \cdot A) \cdot \Delta z \qquad P = E / \Delta t$$

Soil Response to Surface Loads



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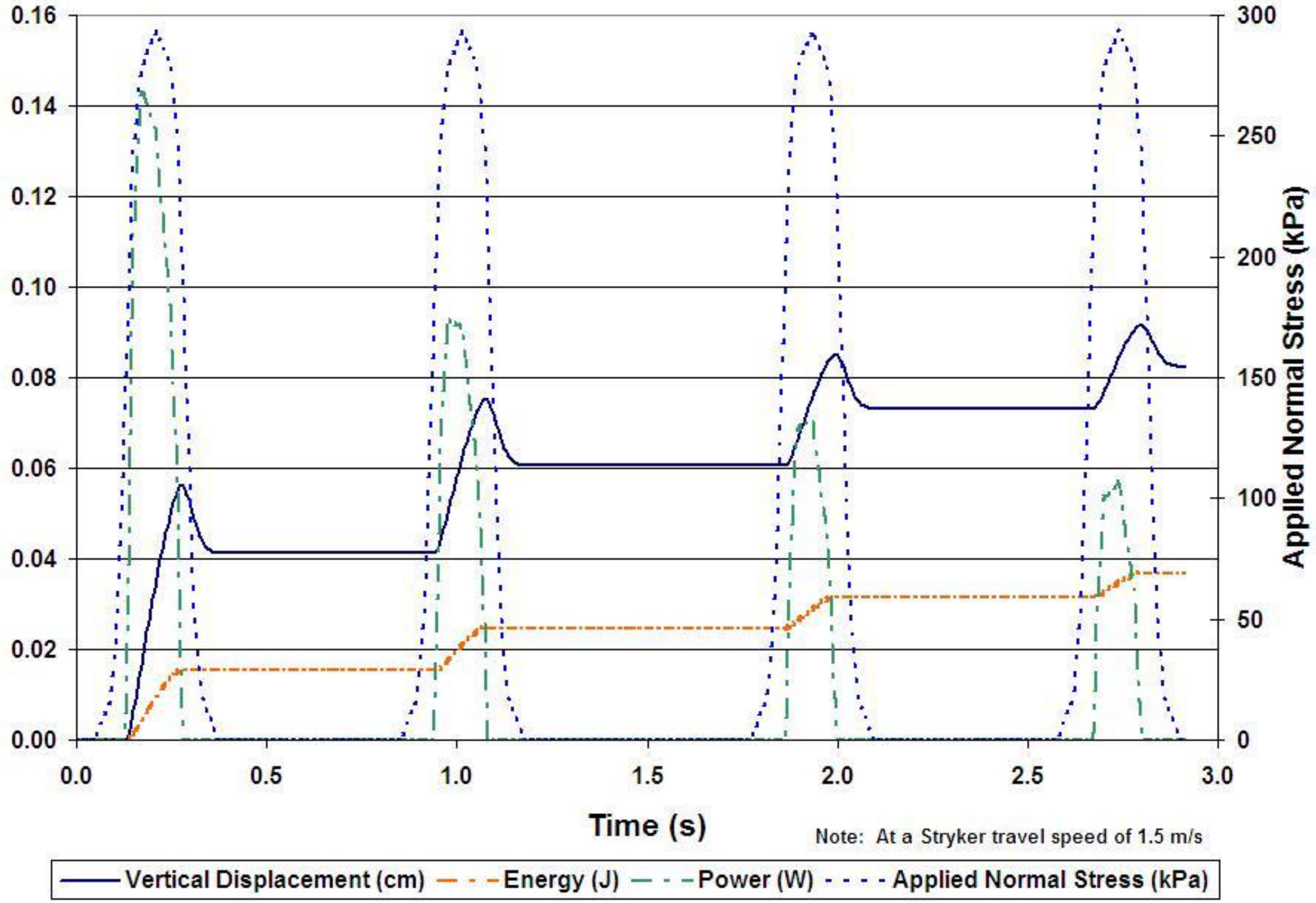
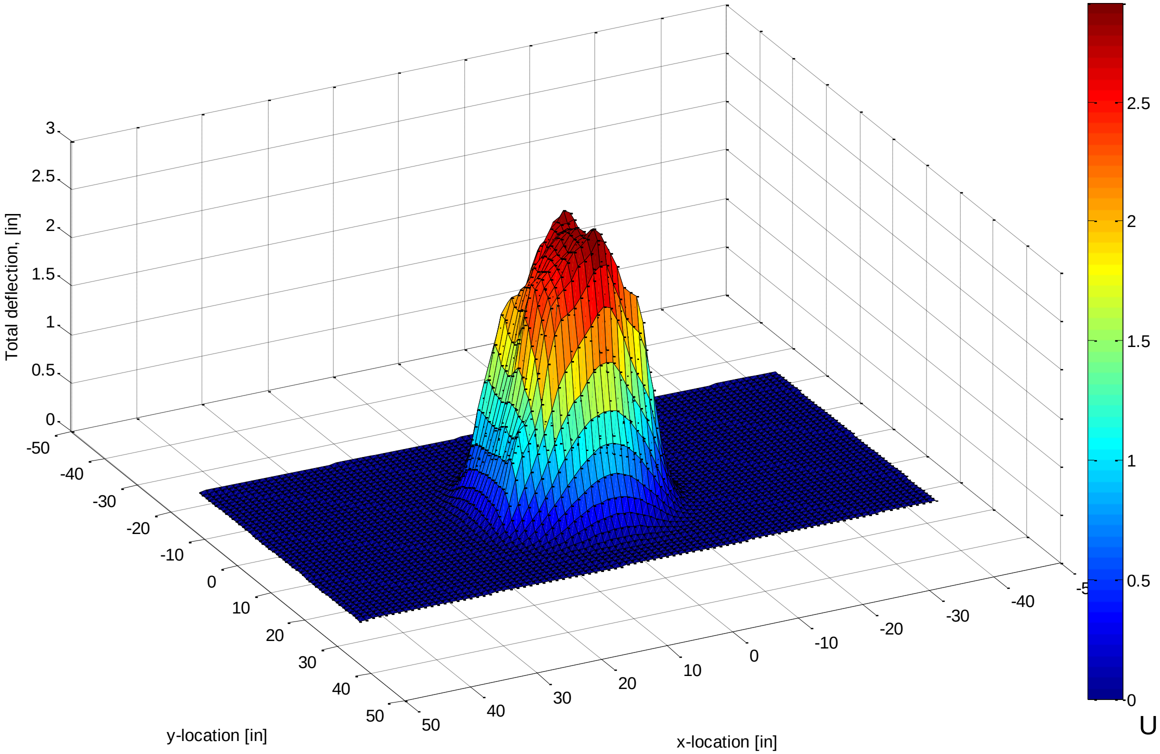
Soil Response to Surface Loads



Example Simulation Results, Vertical Deflection

- Database tracks soil state at many points, which allows for the calculation of: overall soil deflection, energy and power required
  - Ex) Using a rigid tire
    - Vertical deflection of tire: 5” compression, followed by 5” rebound



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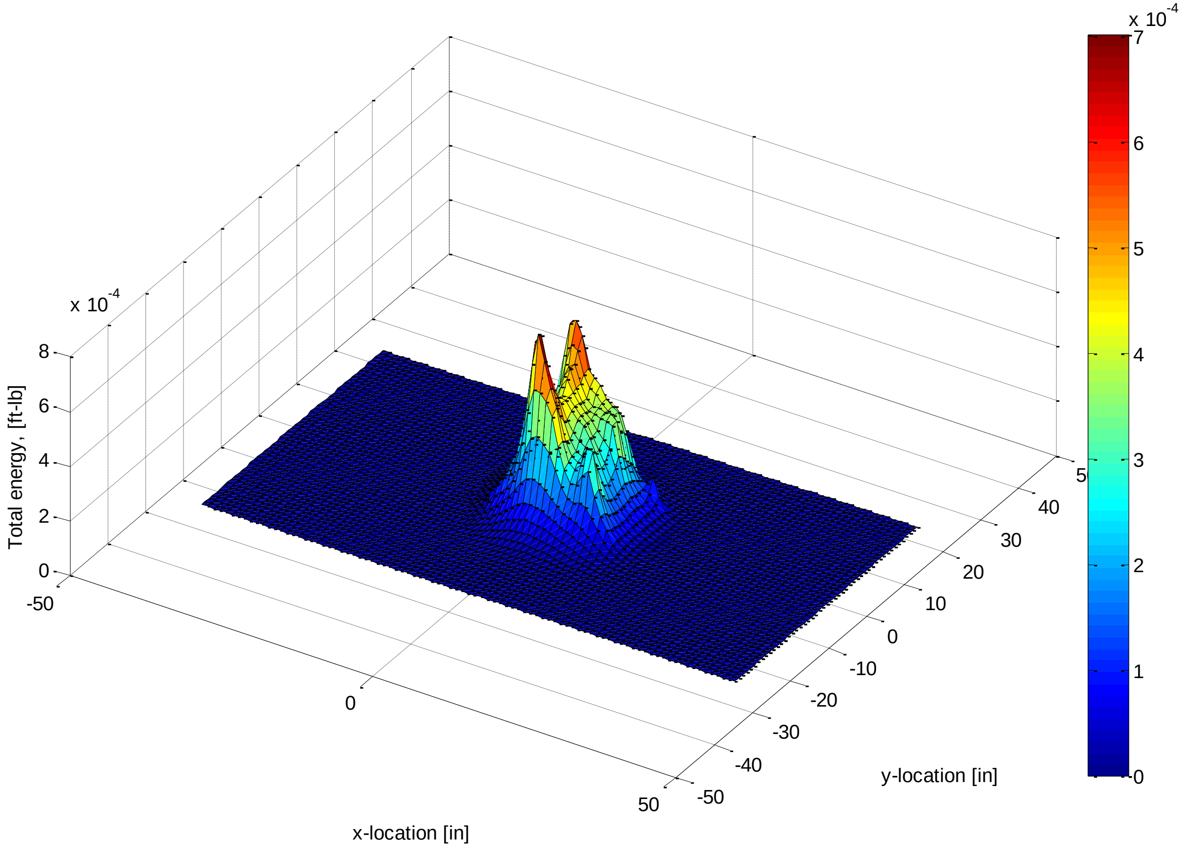
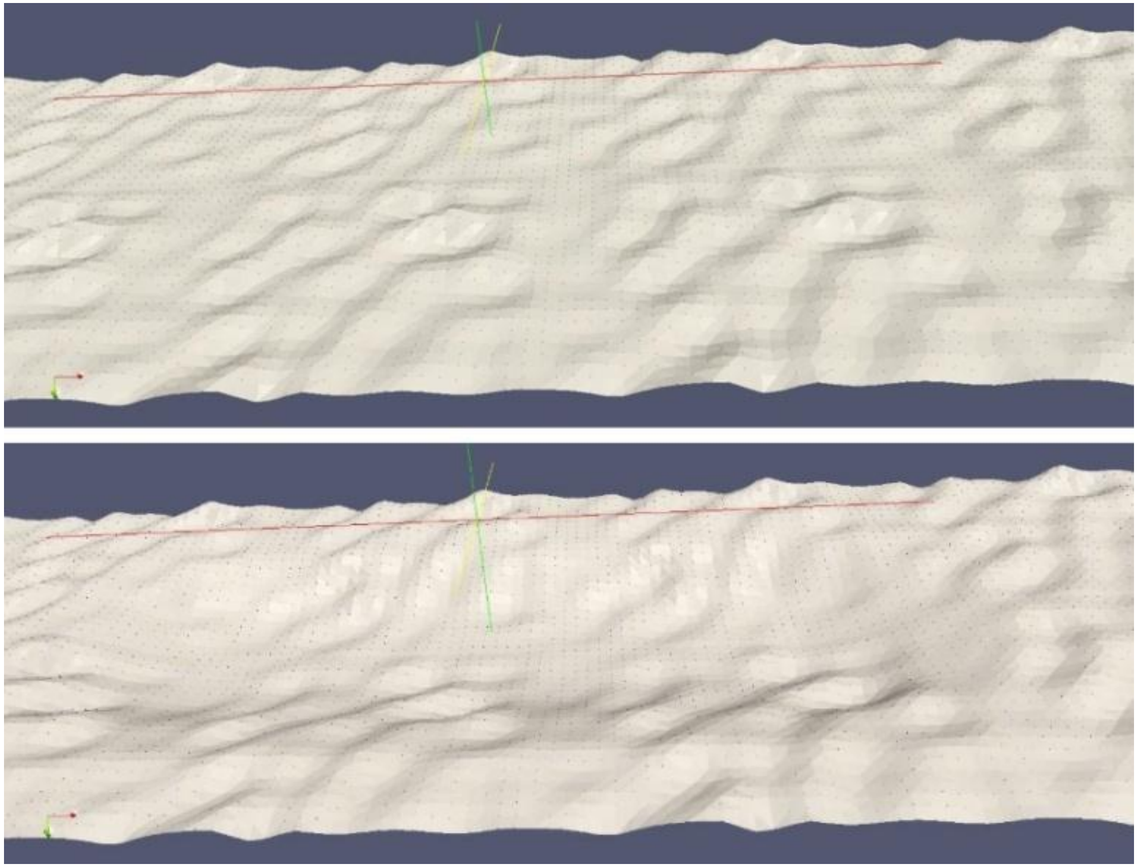
Example Simulation Results, Energy

- Can calculate the energy required to deform the terrain at each timestep
- Can calculate the overall energy dissipation from plastic soil deformation



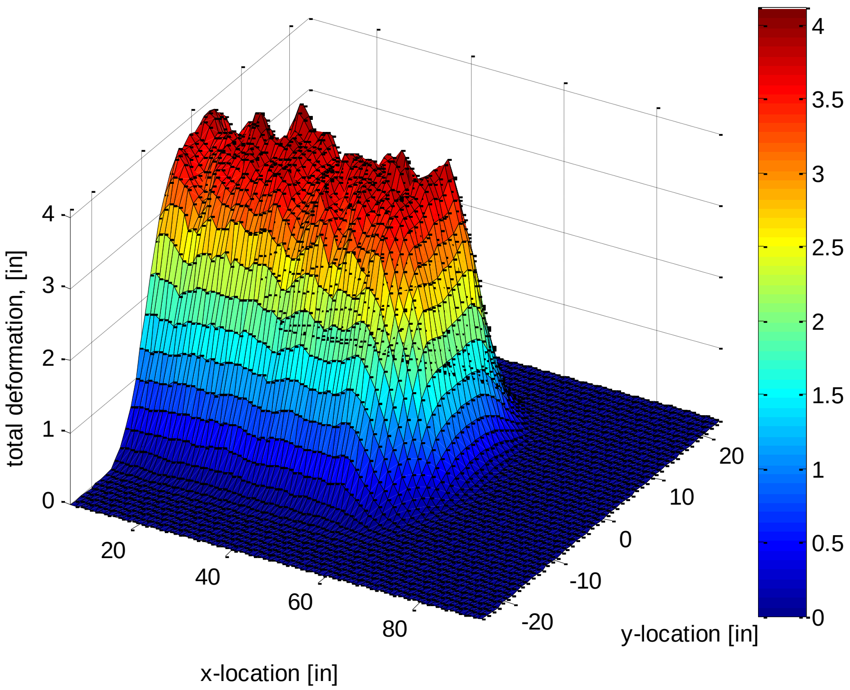
Example Simulation Results, Forward rolling

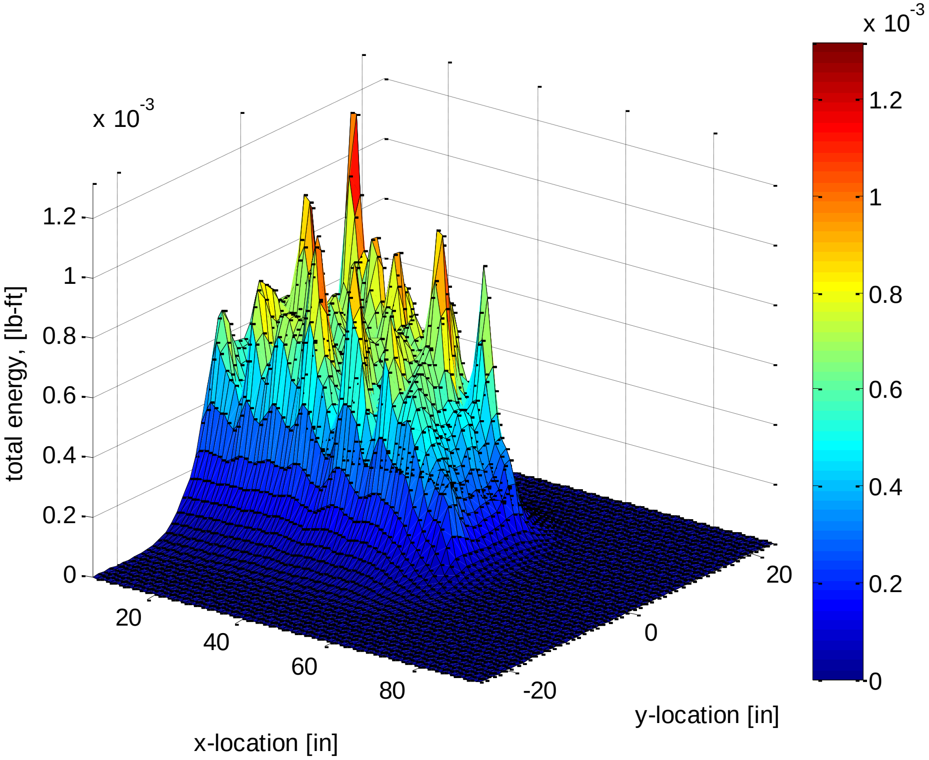
- Vertical deflection of tire: 5” compression
- Followed by traveling at a steady state velocity of 1.5 MPH.
  - An applied rotational displacement of the tire ensures that the tire is operating at minimal slip



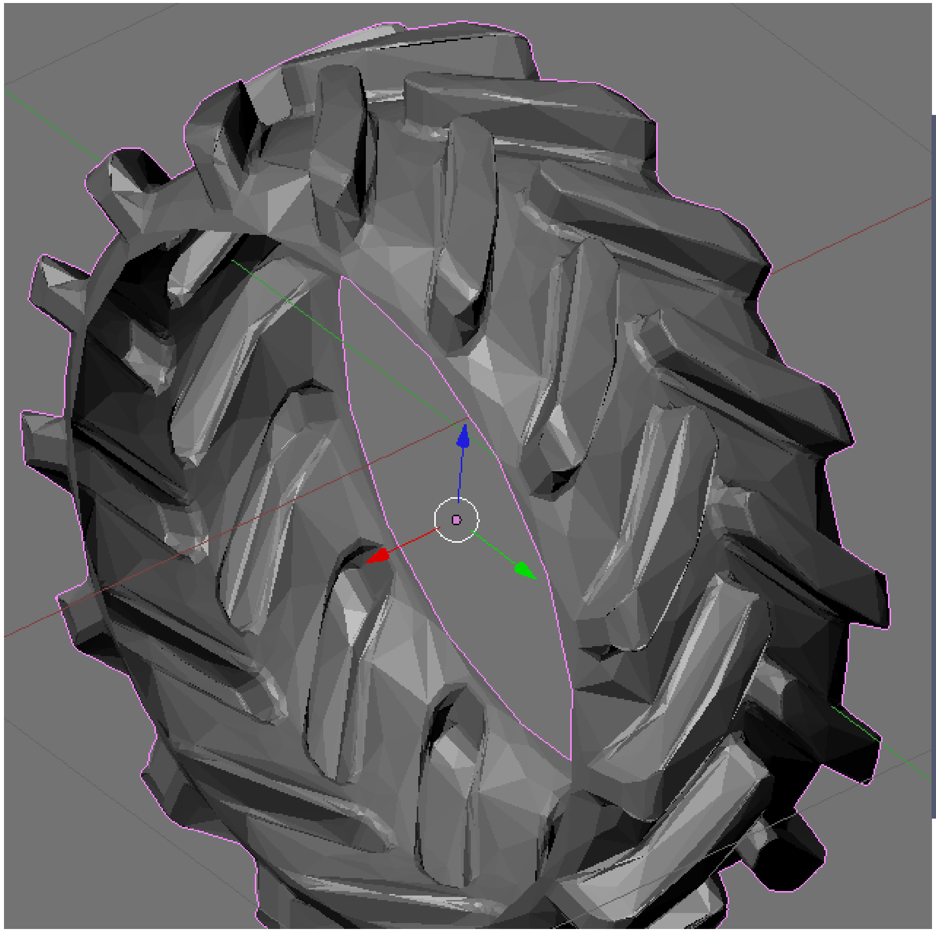
Example Simulation Results, Forward rolling

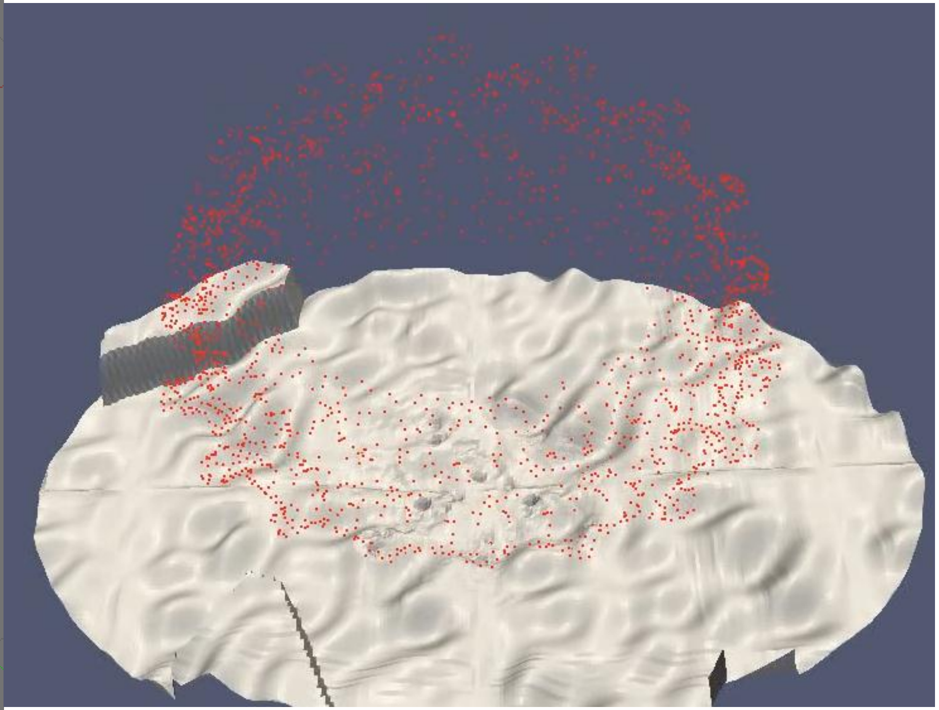
- Total soil displacement and deformation energy (right)





Terrain Deformation Rigid Tire with Lugs





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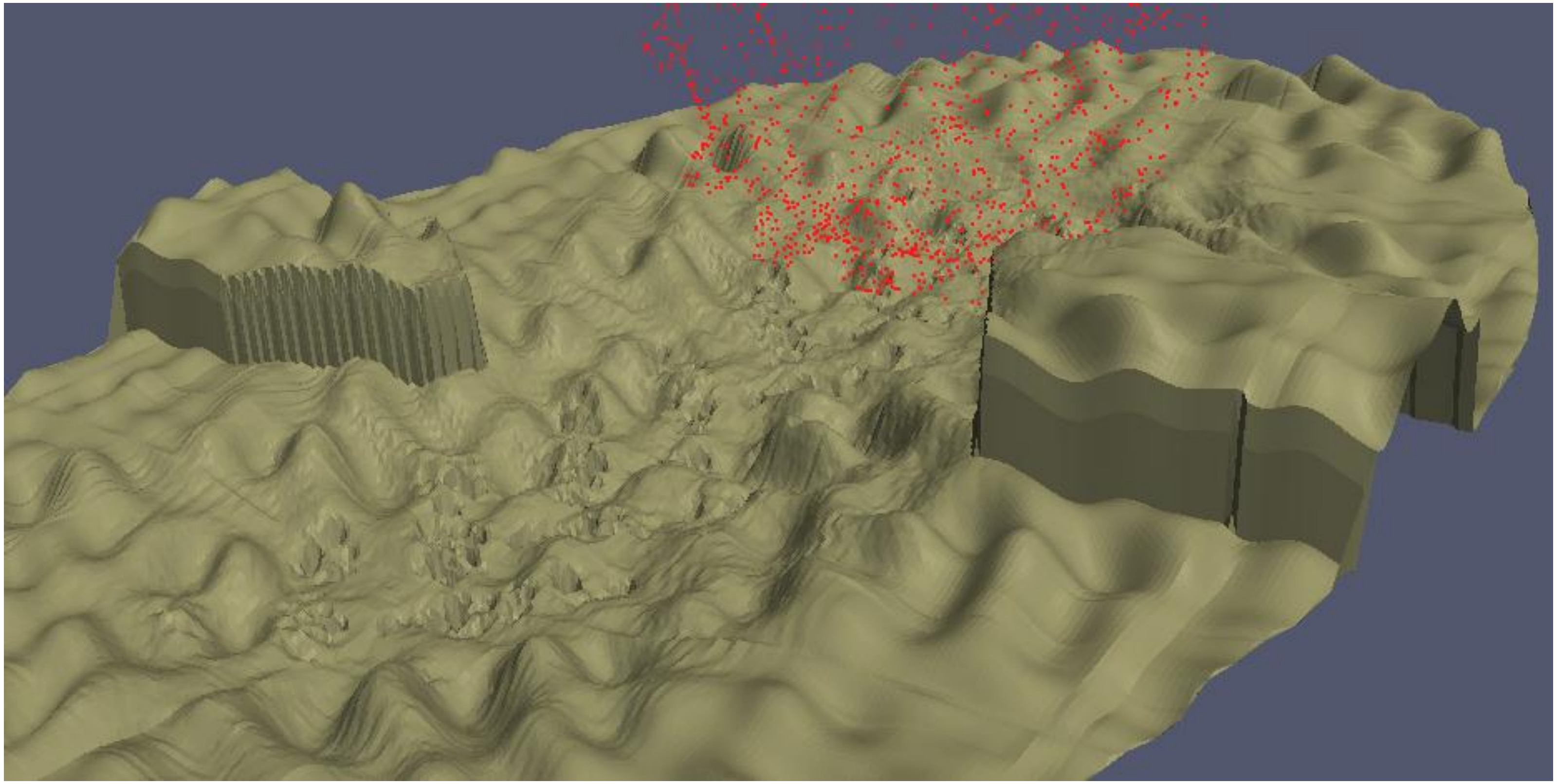
Terrain Deformation Rigid Tire with Lugs



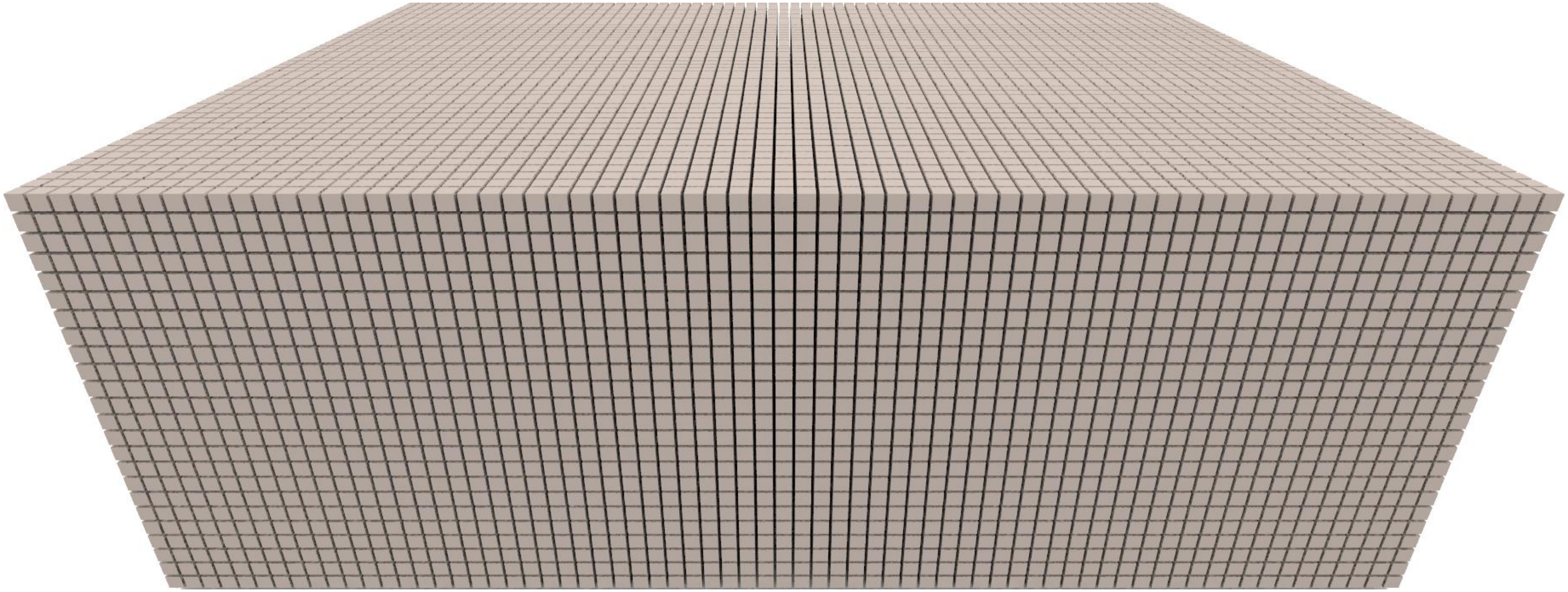
Terrain Deformation Rigid Tire with Lugs

Terrain Deformation – Computations

- Each point on the surface now has a volume of soil associated with it
  - Each volume is a vertical soil column, discretized into equally spaced cubes –***subsoil volumes***
- Sum of forces acting on tire are applied to the terrain surface
- Subsoil vertical stress calculated via modified Cerruti & Boussinesq Equations
  - Calculated at ***each*** subsoil volume for ***every*** surface force
  - Sum the vertical stress contributions of all the surface forces at ***each*** subsoil volume
  - Profiling of code showed 99.5% of time is spent computing the subsoil stress
- Vertical stress applied at the top of elements, causes bulk density change resulting in soil deformation for each of the soil volumes according to Ayers & Bozdech
- Overall deformation at the surface is a summation of the contributions of each subsoil volume in the soil column
- Calculation of energy, power to perform deformation is tracked for every subsoil volume
  - Result is a 3-D distribution of bulk density, energy, power

Terrain Deformation

- Discretized volumetric soil layer (flat surface, pre-deformation)



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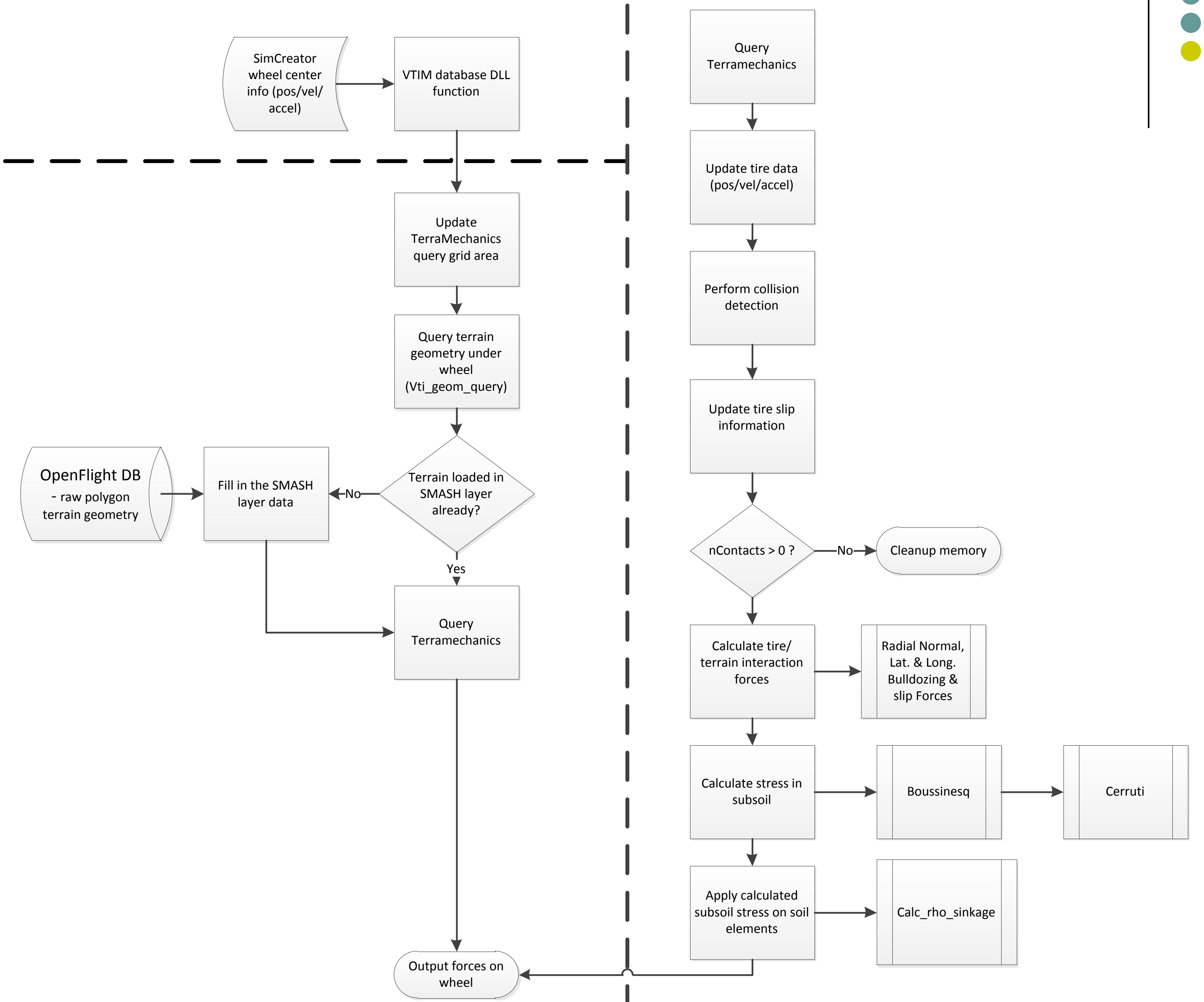
Sequential Implementation



SimCreator wheel center info (pos/vel/accel)

VTIM database DLL function

Update TerraMechanics query grid area

Query terrain geometry under wheel (Vti_geom_query)

Terrain loaded in SMASH layer already?

No

Fill in the SMASH layer data

OpenFlight DB - raw polygon terrain geometry

Yes

Query Terramechanics

Output forces on wheel

Query Terramechanics

Update tire data (pos/vel/accel)

Perform collision detection

Update tire slip information

nContacts > 0 ?

No

Cleanup memory

Calculate tire/terrain interaction forces

Radial Normal, Lat. & Long. Bulldozing & slip Forces

Calculate stress in subsoil

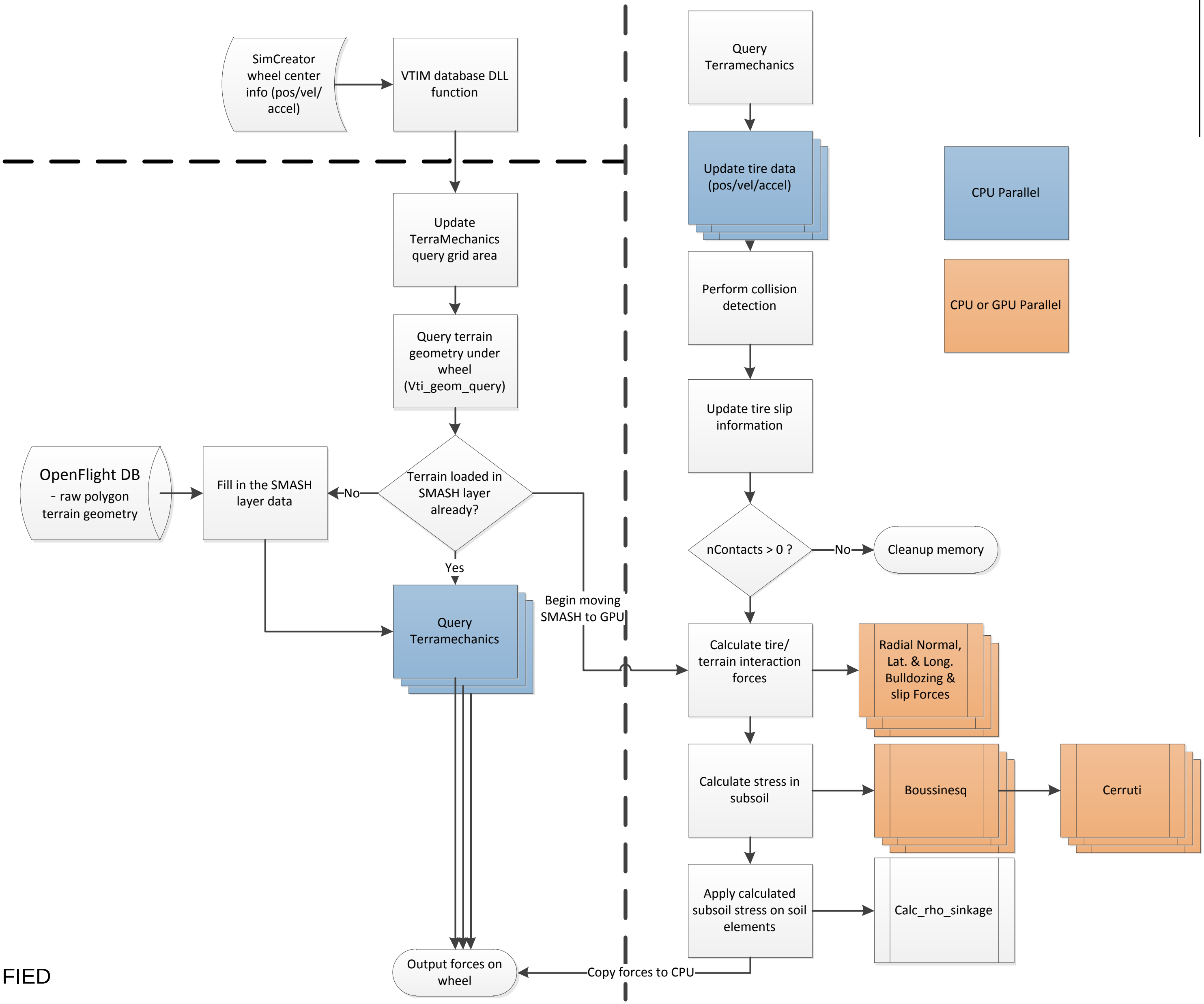
Boussinesq

Cerruti

Apply calculated subsoil stress on soil elements

Calc_rho_sinkage

Parallel Implementation



SimCreator wheel center info (pos/vel/accel)

VTIM database DLL function

Update TerraMechanics query grid area

Query terrain geometry under wheel (Vti_geom_query)

Terrain loaded in SMASH layer already?

No

Yes

OpenFlight DB - raw polygon terrain geometry

Fill in the SMASH layer data

Query Terramechanics

Begin moving SMASH to GPU

Output forces on wheel

Copy forces to CPU

Query Terramechanics

Update tire data (pos/vel/accel)

Perform collision detection

Update tire slip information

nContacts > 0 ?

No

Cleanup memory

Calculate tire/terrain interaction forces

Radial Normal, Lat. & Long. Bulldozing & slip Forces

Calculate stress in subsoil

Boussinesq

Cerruti

Apply calculated subsoil stress on soil elements

Calc_rho_sinkage

CPU Parallel

CPU or GPU Parallel

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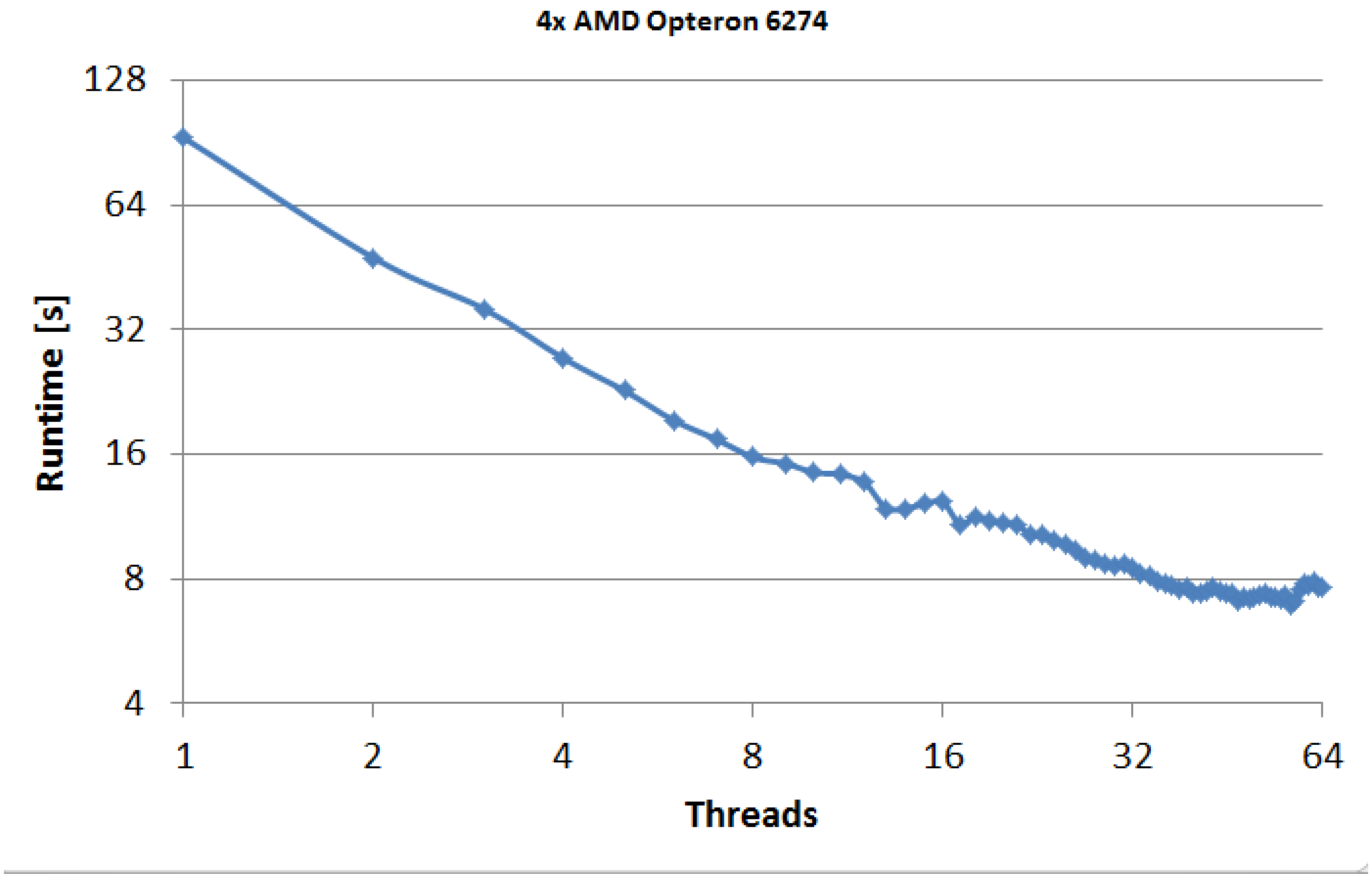
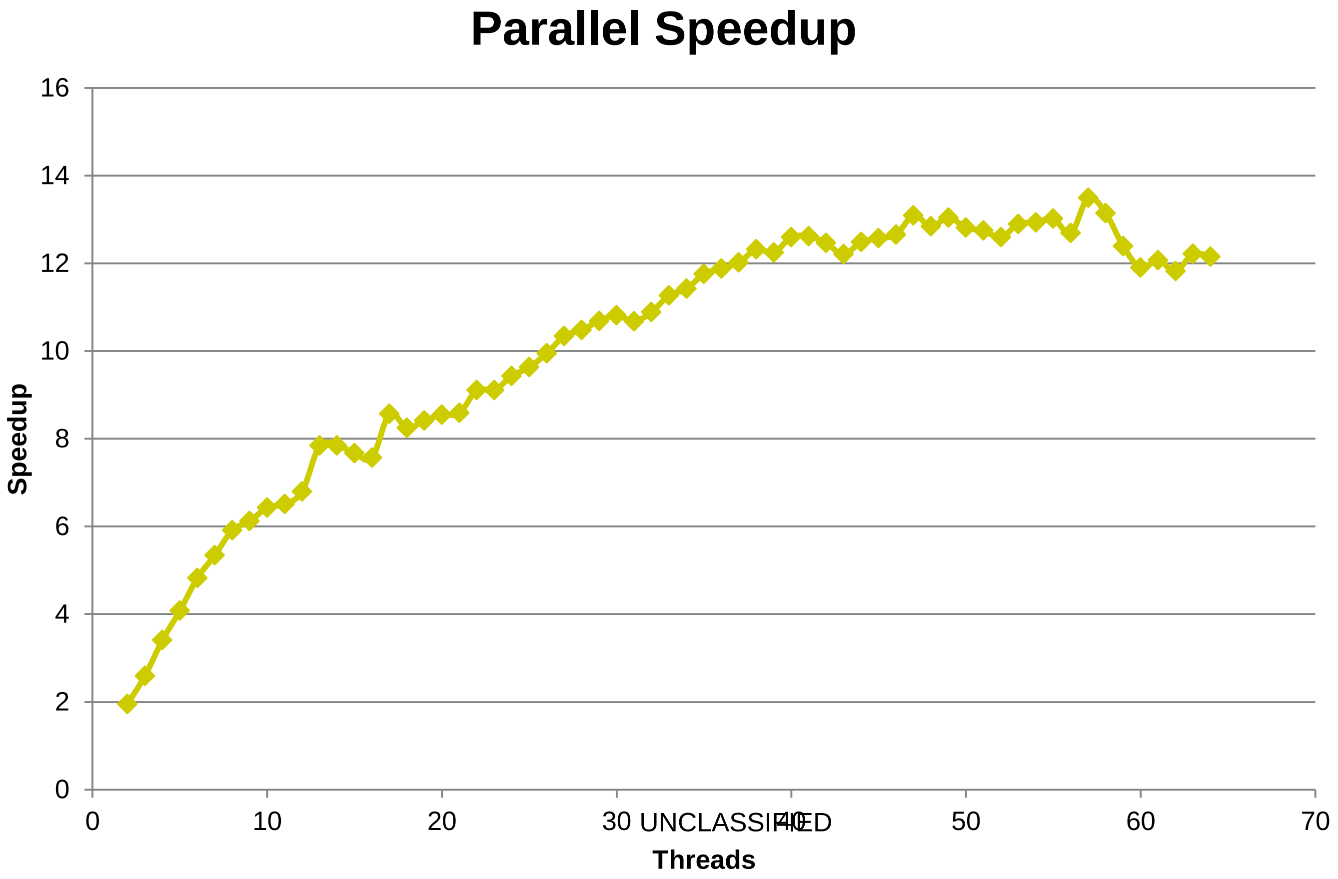
Parallel Scaling

- OpenMP-based
- Computational bottlenecks were targeted
- Parallel code shown to have strong scaling



Parallel Speedup

- Number of threads vs. sequential implementation
- GPU comparison in progress



Conclusions

- VTI terrain database reflects physics-based soil models developed by UT
  - Supports soil non-homogeneities in the vertical direction
  - Visco-elastic-plastic soil mechanics model captures most important soil response effects other than soil flow

- Terrain accepts a set of tire-terrain interaction forces at the interface
  - Allows for tire and terrain models to be developed independently
  - Modularized to use with existing vehicle dynamics software

- Implementation results in parallel computation of soil state change
  - Relies on a stress-bulk density relationship
  - Ability to calculate power, energy required for soil deformation
  - Pursuing both multi-core and GPU avenues

References

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Thank You.