



MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



Tracked Vehicle – Soft Soil Interactions and Design Sensitivities for Path Clearing Systems Utilizing Multi-Body Dynamics Simulation Methods



Joseph Raymond
Paramsothy Jayakumar, Ph.D.
US Army TARDEC

GVSETS

Report Documentation Page				Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE 07 AUG 2013		2. REPORT TYPE Briefing Charts		3. DATES COVERED 07-02-2013 to 13-07-2013		
4. TITLE AND SUBTITLE Tracked Vehicle - Soft Soil Interactions and Design Sensitivities for Path Clearing Systems Utilizing Multi-Body Dynamics Simulation Methods				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Joseph Raymond; Paramsothy Jayakumar				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				8. PERFORMING ORGANIZATION REPORT NUMBER #24079		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) #24079		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited						
13. SUPPLEMENTARY NOTES GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM (GVSETS), SET FOR AUG. 21-22, 2013						
14. ABSTRACT briefing charts						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 24	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified				



Objective: compare multiple path clearing vehicle designs in the medium unmanned vehicle category (~800 kg)

- Introduction and mobility events
- Design alternatives
- Soft soil theory
- Modeling methodology
- Design Comparison
- Sensitivity Study
- Conclusion



Comparative Study Introduction

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION



- Path clearing design comparative objective
- Performance study of possible vehicle configurations
 - 2 or 4 road wheels per side
 - Segmented track or band track
 - Flail or roller-rake path clearing implement.
- Soft soil mobility events conducted over clay and sand:
 - Half-round bump: 17.5 cm radius
 - Pot hole: 17 cm deep x 60 cm long
 - V-ditch: 1.4 m deep x 7.8 m long
 - Grades: 40%-60%
 - Cross-country (clay only)

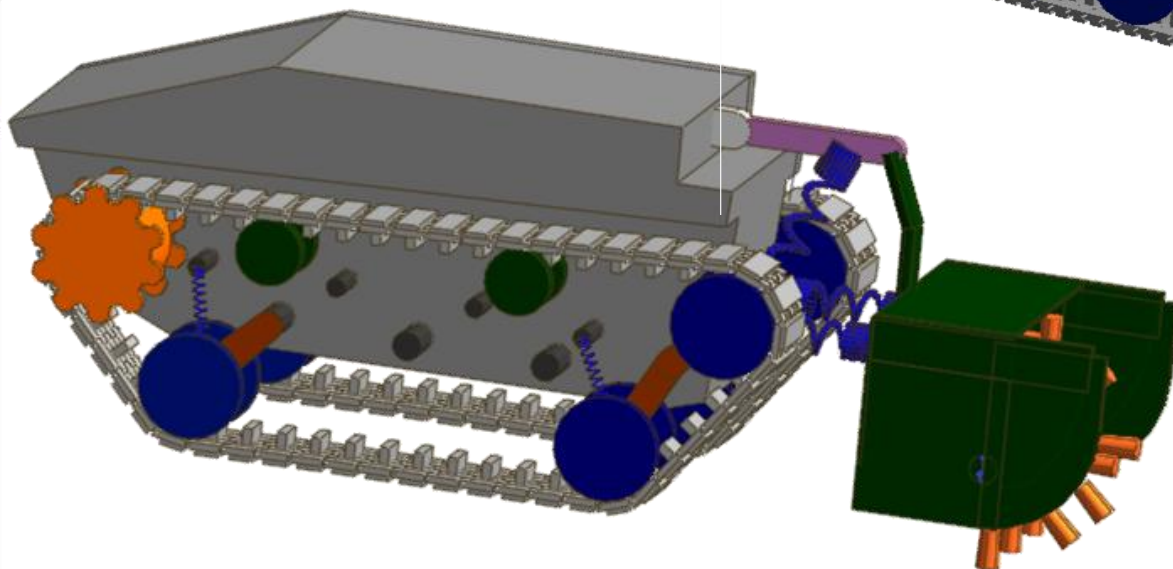
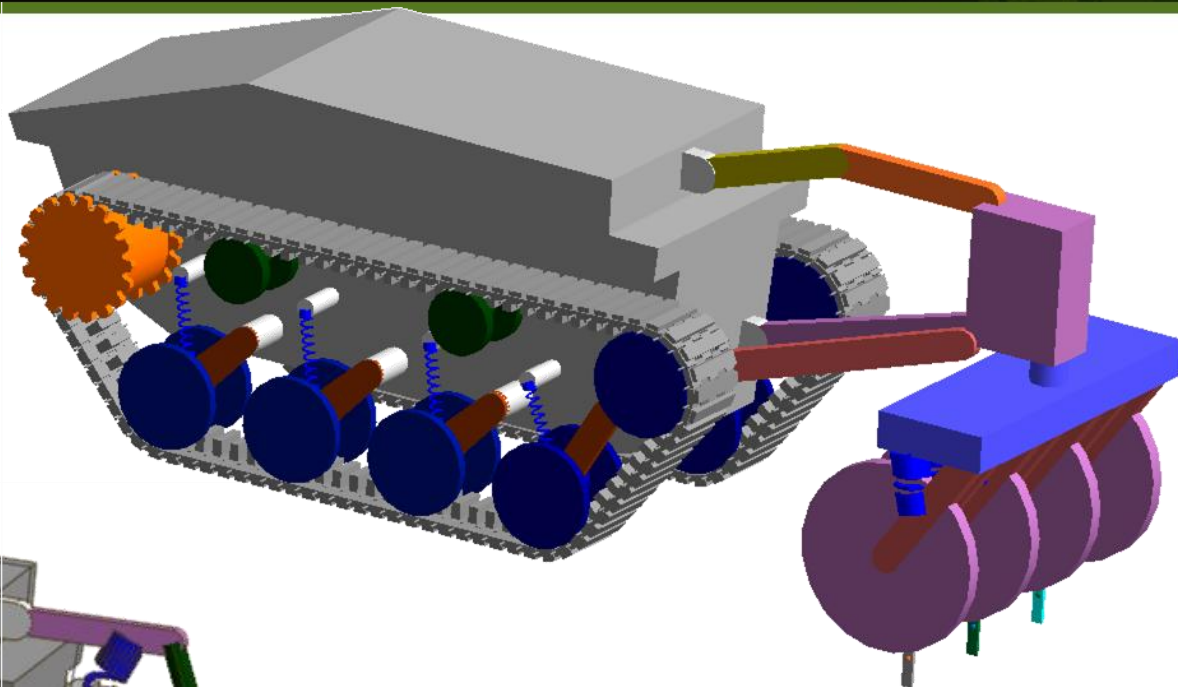
- Combination of soft soil terramechanics, vehicle dynamics, and Multi-Body Simulation (MBD) code
 - Soft soil models supported within MBD code for tire-soil and track-soil interactions
 - Soft soil models not supported within MBD for rake-soil or flail-soil interactions
 - Custom algorithms / user-defined functions (UDF) needed
- Used code does not support band tracks
 - Modeled as a multitude of small segments

Design Configurations

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

- Eight configurations designed and tuned for comparison
- All eight configurations were tested over ten events each



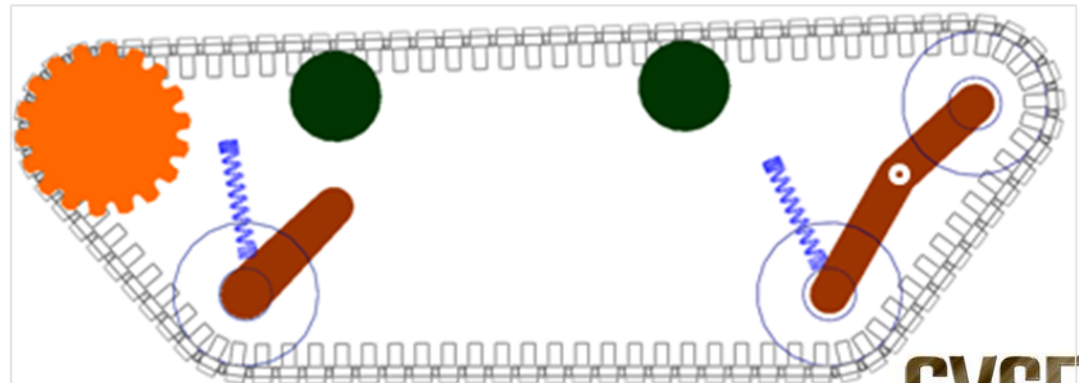
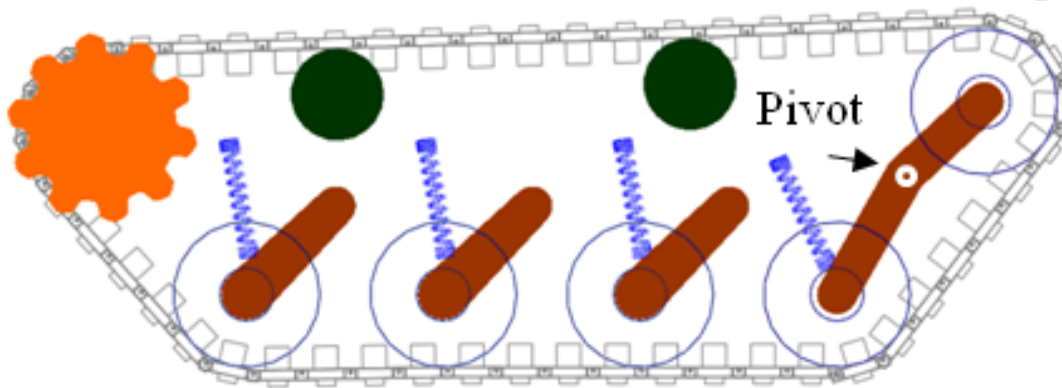
- Top figure – 4 road wheels per side, roller-rake, band track
- Bottom figure – 2 road wheels per side, flail, segmented track

Track Suspension Design

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

- Two road wheels allow for simpler design; mass and cost savings
- Four road wheels allow for lower ground pressure



Track Design: Band Track vs. Segmented Track



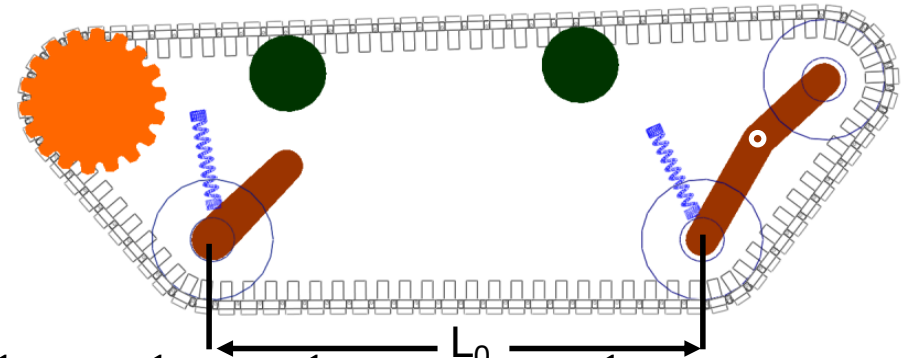
- Material stiffness measured as multiple equivalent springs:

- 90 segments
- Hookes Law
- Young's Modulus
- $E = 47 \text{ MPa}$: $K = 5618 \text{ kN/m}$

$$F_m = \frac{E * A_0 * \Delta L}{L_0}$$

K_{eq} points to the fraction $\frac{E * A_0 * \Delta L}{L_0}$

$$\frac{1}{K_{eq}} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{1}{K_3} + \dots + \frac{1}{K_n} = \frac{n}{K}$$



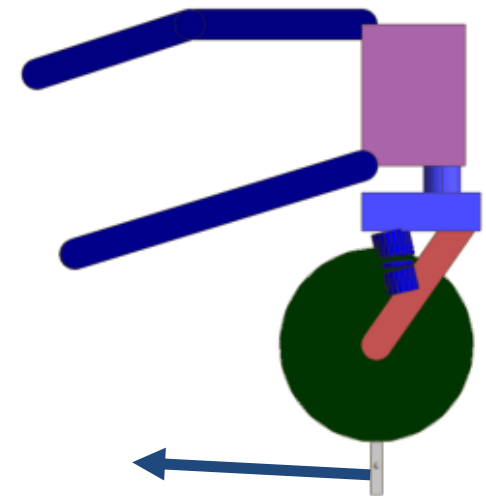
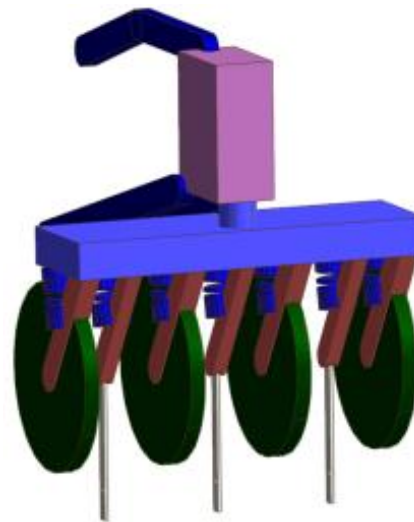
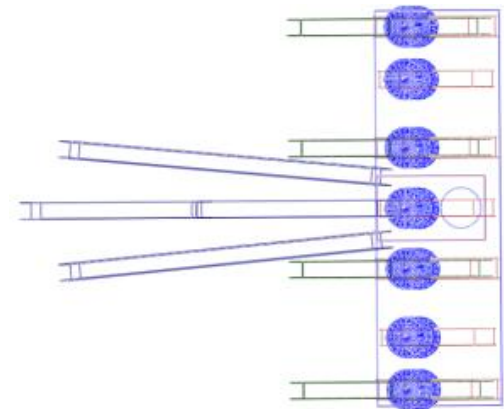
- Segmented track:

- 50 segments, Default bushing stiffness

Path Clearing Implement: Rake



- 4 rollers; 3 rake blades
- Trailing-arm suspension
- 13 cm max penetration depth
 - Penetration depth is dependent on terrain's resistance



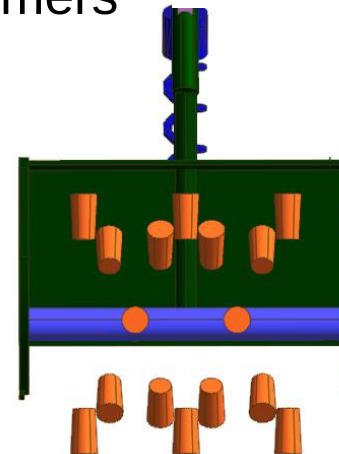
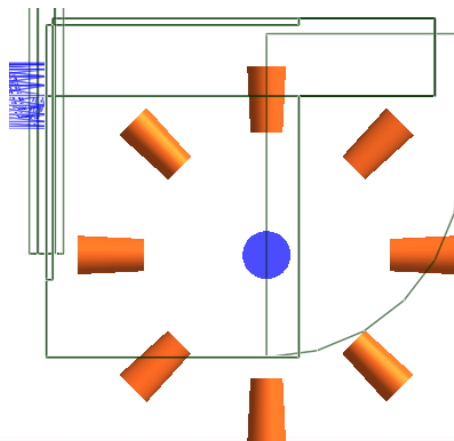
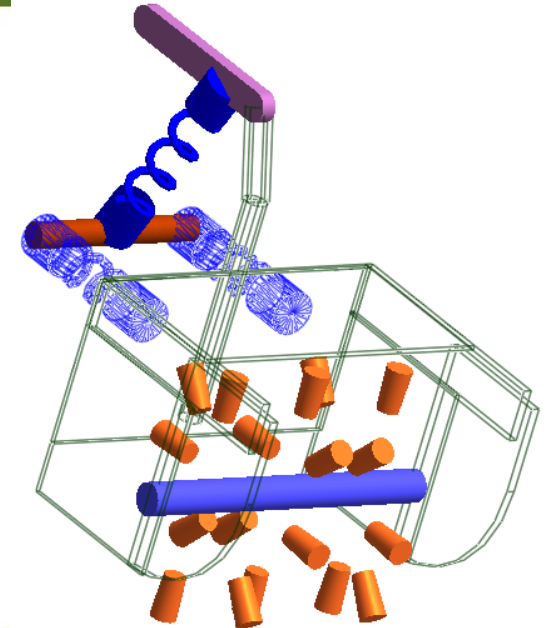
Path Clearing Implement: Flail

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



- Flail consists of 9 pairs of rapidly rotating hammers
- Hammer pairs counterbalance
 - 180° offset
- Impact regions of hammer pairs overlap
 - 45° offset between neighboring hammers



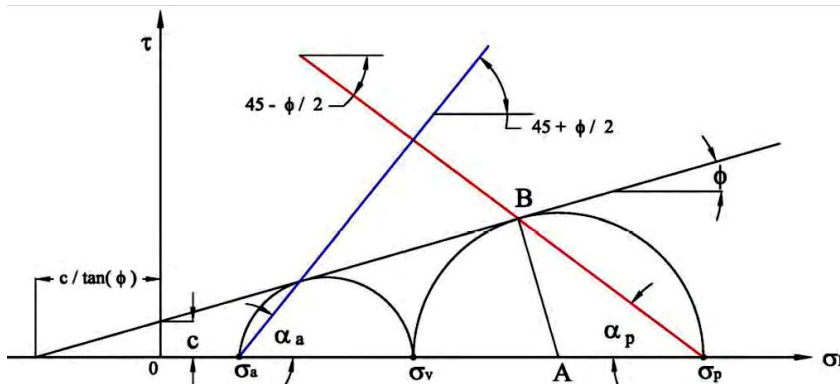
Soft Soil Theory – Mohr-Coulomb

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

(1)

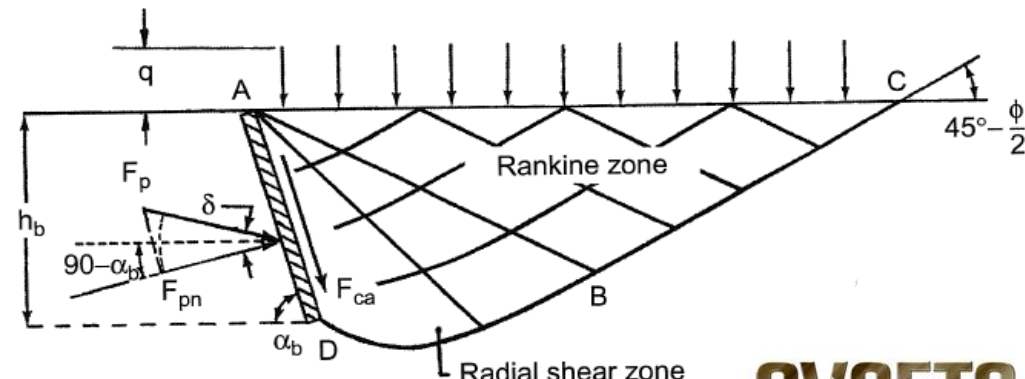
$$\tau_{max} = c + \sigma \tan \phi$$



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

$$\sigma_p = \gamma_s z N_\phi + q N_\phi + 2c \sqrt{N_\phi}$$

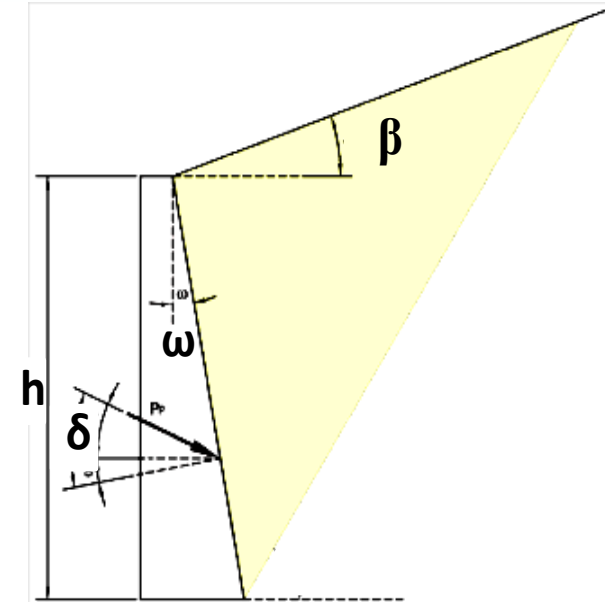
Soil Property	Sand	Clay
Exponent Number (n) []	1.1	0.13
Terrain Stiffness (k_c) [kN/m ¹⁺ⁿ]	0.99	12.7
Terrain Stiffness (k_ϕ) [kN/m ²⁺ⁿ]	1528	1556
Cohesion (c) [kN/m ²]	1.04	68.95
Shear Resistance Angle (ϕ) [rad]	0.70	0.35
Soil Flow Value (N_ϕ) []	4.60	2.04
Soil Specific Gravity (γ) [N/m ³]	14.91	11.77
Blade-Terrain Interface Friction (δ) [rad]	14.91	11.77



Soft Soil Theory – Coulomb Theory



$$K_p = \frac{\cos^2(\varphi + \omega)}{\cos^2(\omega) * \cos(\delta - \omega) \left[1 - \sqrt{\frac{\sin(\delta + \varphi) * \sin(\varphi + \beta)}{\cos(\delta - \omega) * \cos(\beta - \omega)}} \right]^2}$$



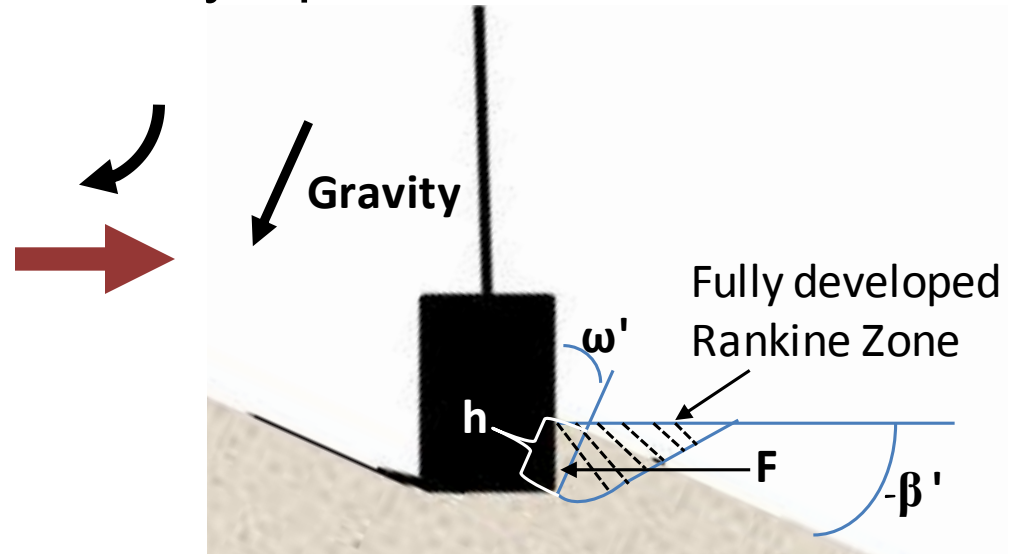
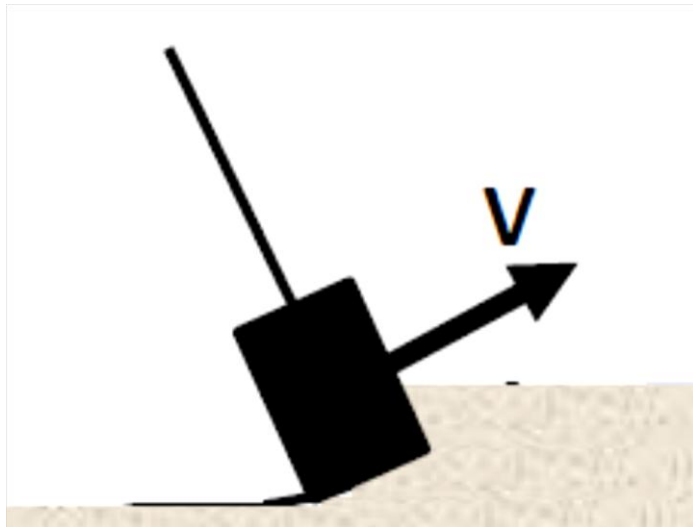
- K_p replaces N_φ ; accounts for more conditions
- Assumptions of Coulomb Theory:
 - Pure horizontal motion
 - Soil resistance zone is fully developed (Rankine Zone)
- Suitable model for rake blade – terrain interaction
- Must be modified for flail hammer – terrain interaction
- Terzaghi's Bearing Pressure equation used for resultant force

$$F_p = b * (0.5\gamma_s h_b^2 K_p + q h_b K_p + 2c h_b \sqrt{K_p})$$

Soft Soil Theory – Flail and Coulomb Theory



- Flail hammers rotate in an arc
- Internal resistance of soil must develop to resist the direction of motion
- Reimagined Coulomb Theory's passive failure model

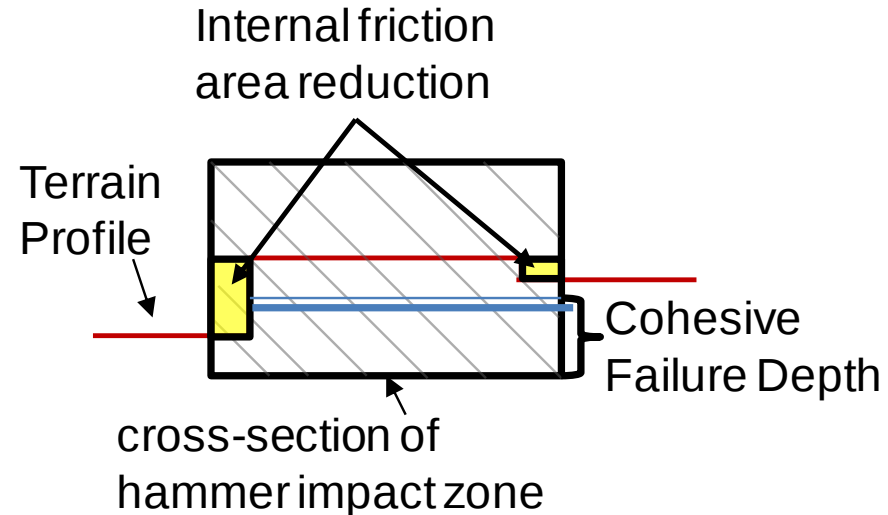
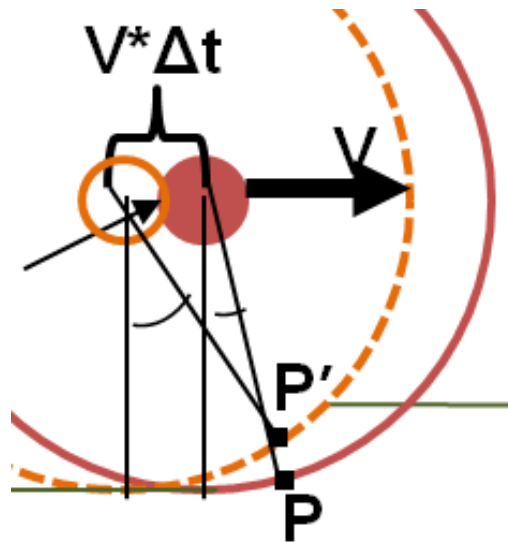


- ω' , β' substituted into Coulomb Theory's equation for K_p
- Impact forces not modeled

Modified Depth Calculation of Counterbalancing Hammer Pairs

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



- Counterbalancing hammer, P' , may have previously cleared the terrain at current impact location, P
- Neighboring hammers have overlapping clearance areas

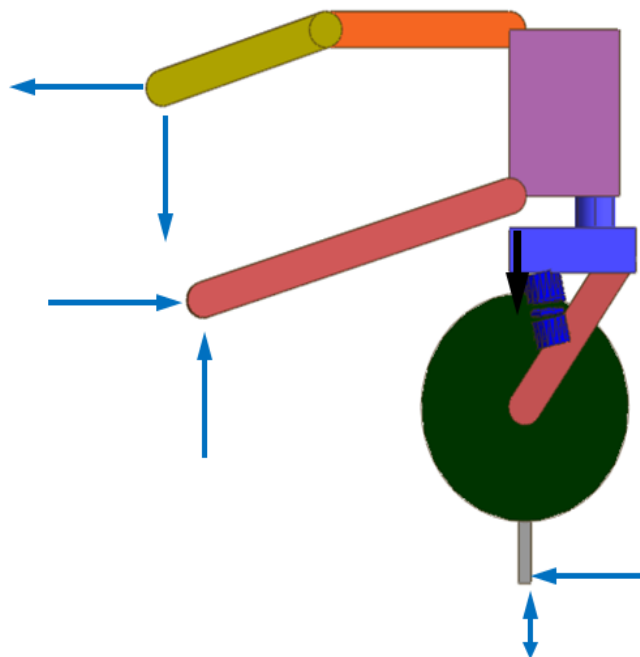
Roller Rake Loads over Sand vs. Clay

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



- Two-dimensional force breakdown – 2 m/s, flat soft-soil terrain

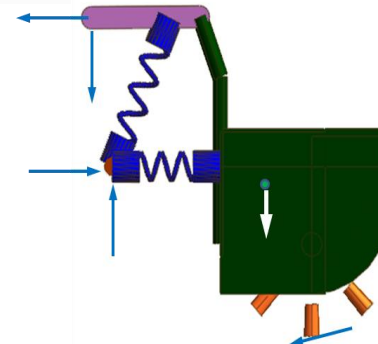
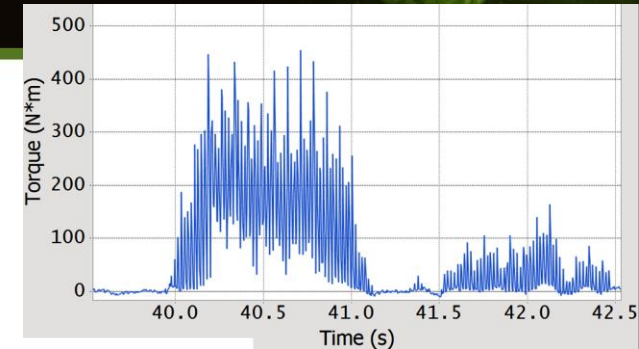
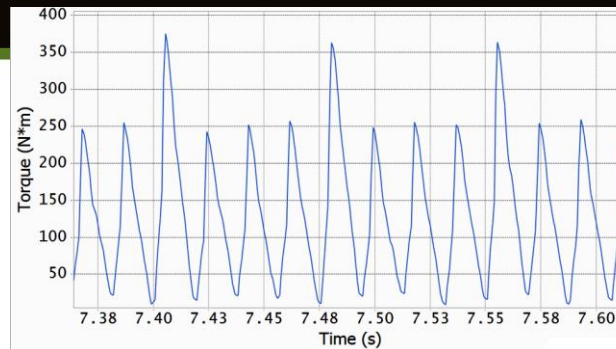
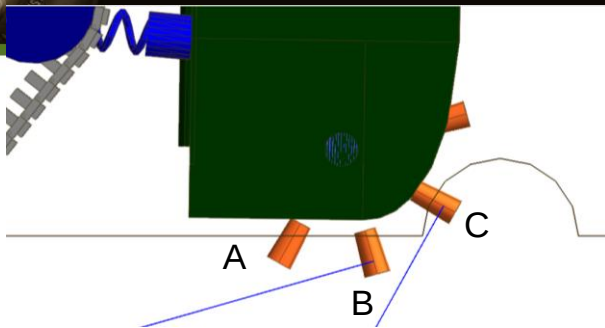


Load Location	Sum of Forces: +X Direction (lbs)	
	Sand	Clay
Combined Lower Interface Brackets	984	3329
Upper Interface Bracket	-863	-2392
Rolling Resistance	-51	-55
Blade Horizontal Force	-71	-899
Summation	-1	-17
Load Location	Sum of Forces: +Y Direction (lbs)	
	Sand	Clay
Combined Lower Interface Brackets	385	1078
Upper Interface Bracket	-33	-336
Wheel Normal Force	3348	2868
Blade Vertical Force	6	80
Weight	-3686	-3686
Summation	20	4

Flail Loads over Sand vs. Clay

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

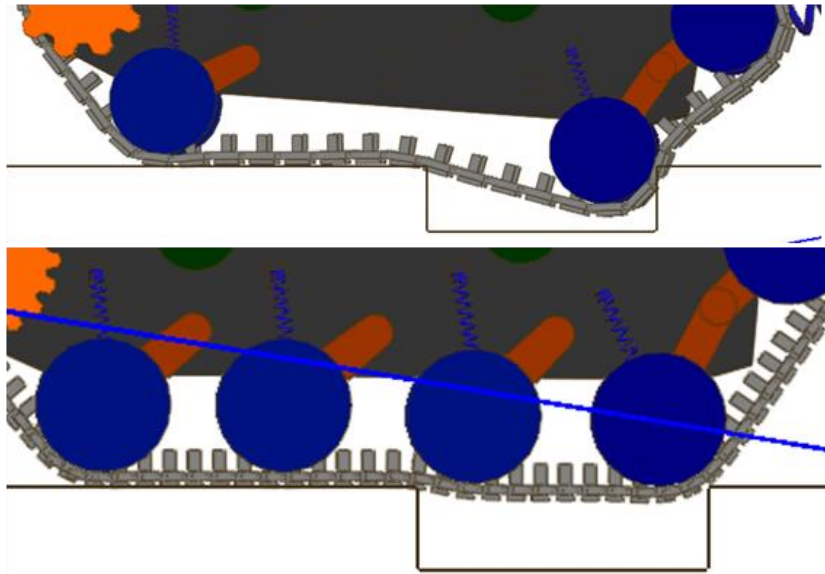


- Two-dimensional force breakdown
 - 2 m/s, flat soft-soil terrain

Load Location	Sum of Forces: +X Direction (lbs)	
	Sand	Clay
Combined Lower Interface Brackets	1768	3017
Upper Interface Bracket	-1757	-2550
Hammer Impact Horizontal Force	-16	-469
Summation	-5	-2

Load Location	Sum of Forces: +Y Direction (lbs)	
	Sand	Clay
Combined Lower Interface Brackets	2153	2046
Upper Interface Bracket	-671	-414
Hammer Impact Vertical Force	-2	-164
Weight	-1472	-1472
Summation	8	-4

Performance of 2 vs. 4 Road Wheels Per Side

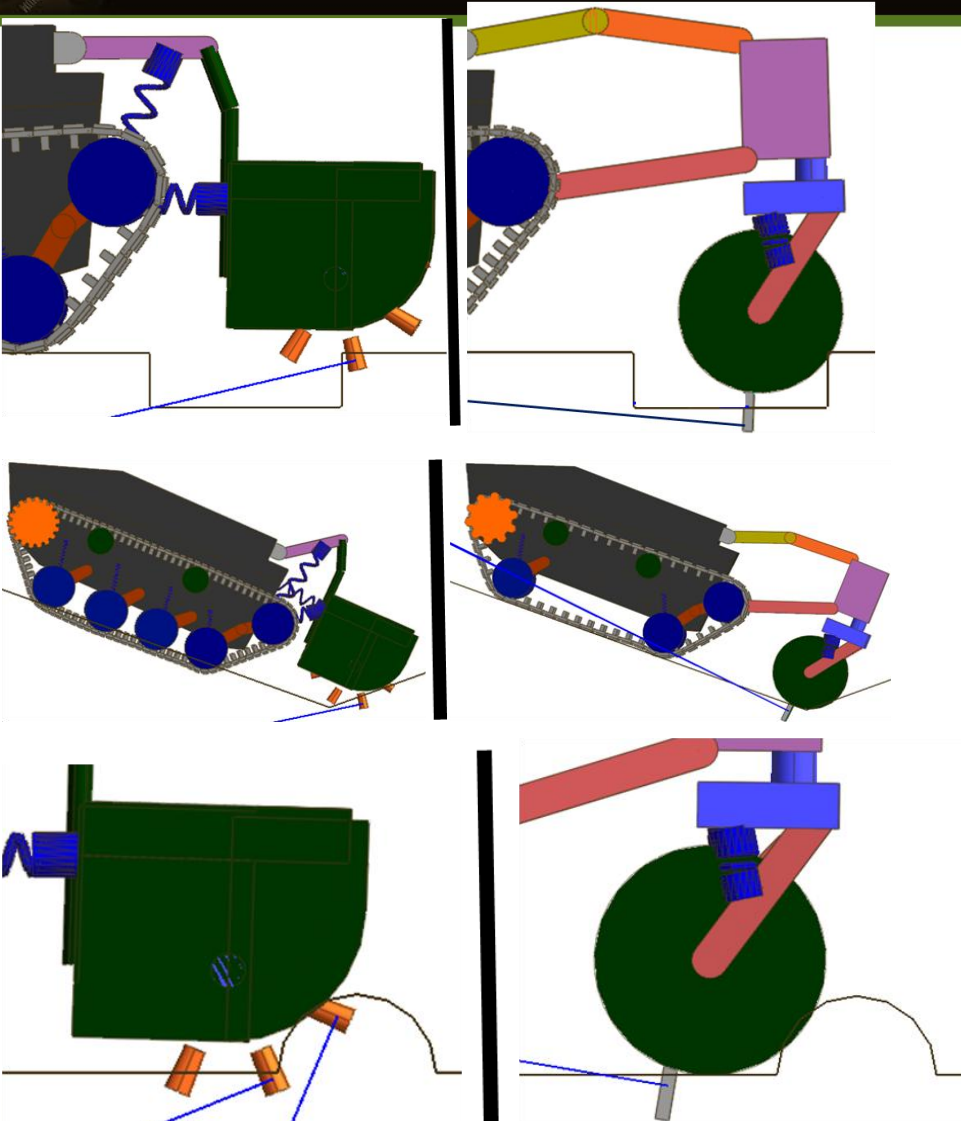


- Average peak interface loads with Flail over pot hole event:
 - 3395 N with 4 road wheels
 - 3750 N with 2 road wheels
 - Peak acceleration magnitude at chassis over pothole:
 - 1.76 g's with 4 road wheels
 - 2.09 g's with 2 road wheels
-
- Performance on grades:
 - 2 road wheels: 60% with flail over sand, 45% over clay
 - 4 road wheels: 55% with flail over sand, 55% over clay

Roller vs. Flail Loads Comparison

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



- Average peak interface loads higher with roller in all cases.

Event	Average of Peak Interface Loads [N]	
	Flail	Roller
Half Round	4405	8224
Pothole	3572	11545
Vditch	3229	5041

- Average magnitude of forces over cross country:
 - Flail: 1761N; Roller: 1980 N

Band vs. Segmented Track



- Surrogate band track modeled had slight improvement in average chassis vibration magnitudes
 - Band Track: 0.36 g's; Segmented Track: 0.42 g's
- Care must be taken – 90 segments may lead to higher frequency vibrations
 - Not realistic of actual band track

Sensitivity Study



- Sensitivity study performed varied single parameter
 - Half round event, without any implement, over clay, with 4 road wheels per side

Design Sensitivity	% Change of values	Configuration Tested
Initial Track Bushing Tension / Preload	25 – 100 – 400	Segmented Track
Band Track Material Properties (Youngs Modulus)	50 – 100 – 200	Band Track
Backing Pad - Road Wheel Contact Stiffness	50 – 100 – 200	Segmented Track



Sensitivity Results

- Segmented Track Bushing Preload: 125 N – 500 N – 2000 N
 - Increasing the bushing preload increased the peak chassis acceleration magnitude
- Band Track Material Properties – Young's Modulus: 23.5 MPa – 47 MPa – 94 MPa
 - Increasing the Young's Modulus increases the peak chassis acceleration magnitude
- Segmented Track Backing Pad and Road Wheel Contact Stiffness: 1751 kN/m – 3502 kN/m – 7005 kN/m
 - Increasing the contact stiffness increases the peak chassis acceleration magnitude

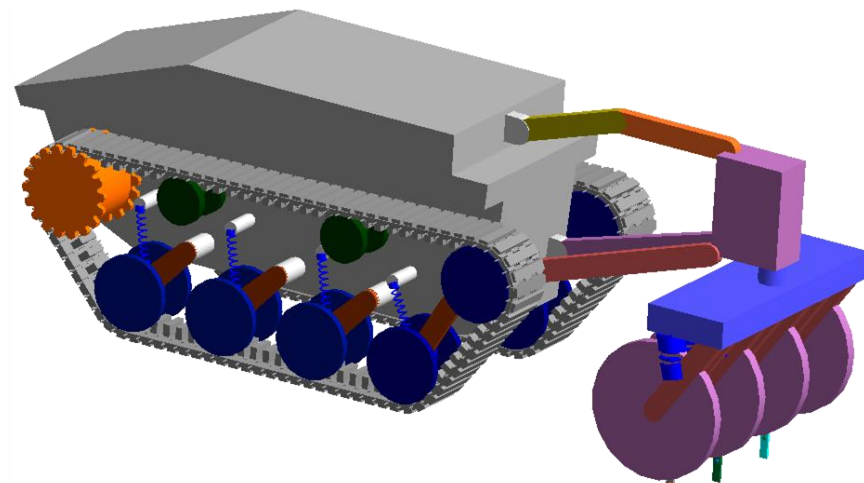
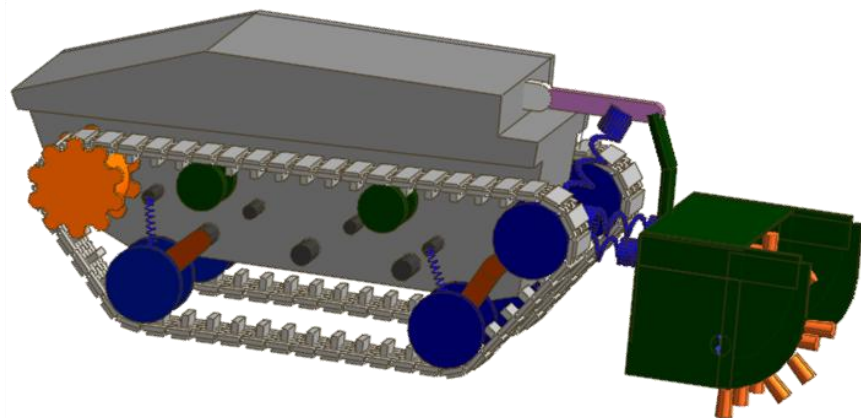
Conclusion

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



- Configuration with 4 road wheels per side, band track, with the flail had lower interface loads and chassis accelerations overall
- Innovative terramechanics application of rake shearing and hammer impact





MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

BACKUP

Notional Vehicle Parameters

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



Constant Design Parameter	Value
Chassis Mass	450 kg
Overall Length (less implement)	2.1 m
Overall Width (less implement)	1 m
Wheelbase	1.13 m
Vehicle Track Width	0.746 m
Width of Individual Tracks	0.203 m
Chassis Roll Inertia	35.80 kg-m ²
Chassis Pitch Inertia	134.01 kg-m ²
Chassis Yaw Inertia	127.14 kg-m ²
Sprocket Carrier Radius	0.14 m
Road Wheel & Idler Radii	0.14 m

Sensitivity Results



Bushing Preload (N)	Peak Chassis Acceleration Magnitude [g]
500	1.34
125	1.31
2000	1.37

Young's Modulus [Mpa]	Radial "Bushing" Stiffness [kN/m]	Peak Chassis Acceleration Magnitude [g]
47	5618	1.56
23.5	1433	1.36
94	11235	1.67

Track-Road Wheel Contact Stiffness (kN/m)	Peak Chassis Accelerations [g]
3502	1.34
1751	1.28
7005	1.57