

Modeling Simulation and Software (MS2)

GVSETS

GROUND VEHICLE SYSTEMS ENGINEERING & TECHNOLOGY SYMPOSIUM
& ADVANCED PLANNING BRIEFING FOR INDUSTRY



NDIA
Michigan

INVERSE DYNAMICS APPROACH TO ESTABLISH MOBILITY MARGINS

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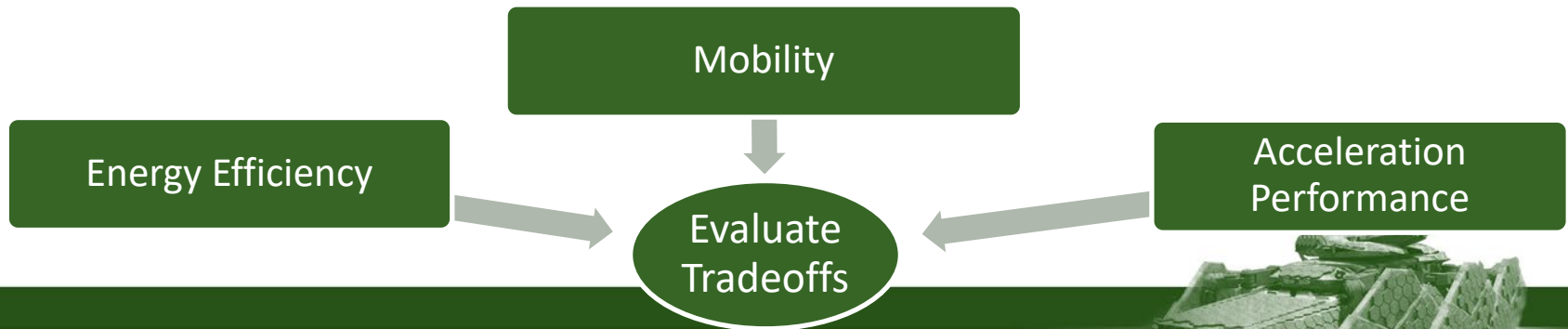
OUTLINE:

1. Motivation and problem statement
2. Approach
3. Model of single wheel module
4. Mobility margins
5. Simulation in stochastic terrain conditions
6. Relation between torque and mobility margin
7. Tradeoff between acceleration and energy losses for assigned mobility margin
8. Conclusions/summary





- Consider mobility and energy efficiency as separate aspects and develop an approach to evaluate and make tradeoffs between them.
- Approach to mobility assessment based on vehicle dynamics.
- Impact of tire slippage on mobility and energy efficiency under assigned acceleration.





- Overall Goal: maintain acceptable wheel mobility by exerting boundaries on the wheel torques to keep tire slippages far enough from complete mobility loss of the vehicle.
 - Integrative method aims for fast-enough-acceleration to a target linear velocity while maintaining tire mobility margins and energy efficiency at a high level.
 - Inverse Dynamics Approach: recover time histories of the torque that should be generated for movements with target velocity profiles.





Inverse dynamics method:

- Calculate forces/torques from kinematic parameters (e.g. $F = ma$: determine force for assigned acceleration)

Approach to Inverse Dynamics:

- Assign velocity profiles with different longitudinal acceleration.
- Determine reference torque that should be applied for assigned profile.
- Link tire slippages to mobility of the vehicle.
- Calculate resulting mobility margins, power losses that occur under the applied reference torque profiles.

Velocity Profile

Reference Torque

Tire Slippage

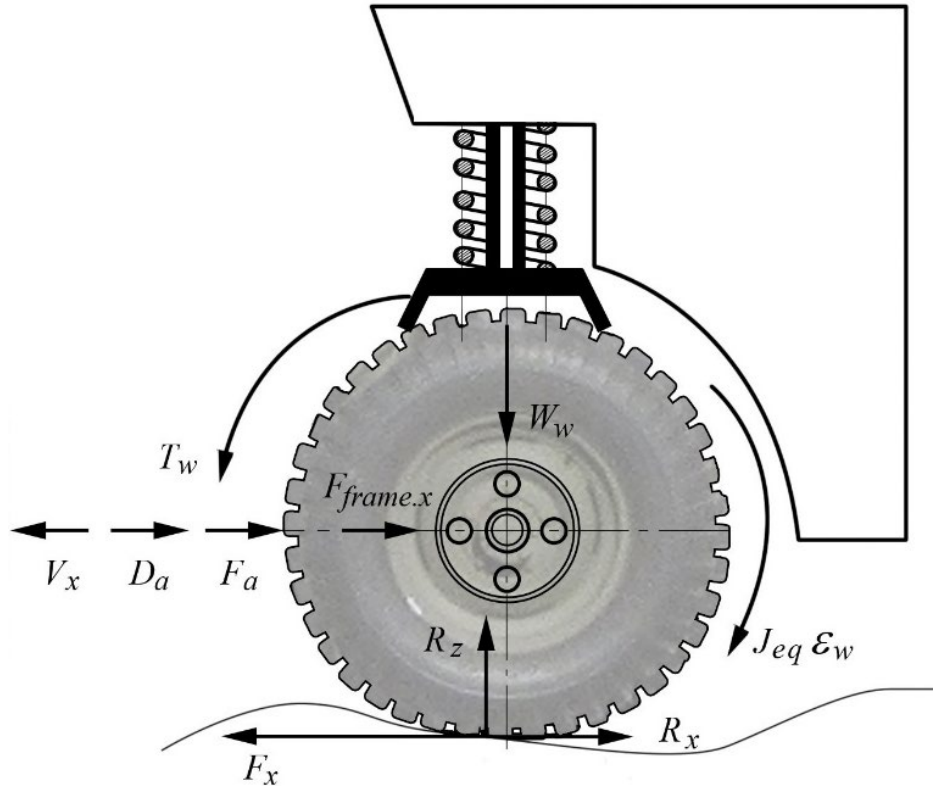
• Mobility

• Efficiency





- Single-wheel Module:



- Reference Torque T_w :

$$T_w = F_x r_w^0 + J_{eq} \epsilon_w + B_{eq} \omega_w$$

- Circumferential Force F_x :

$$F_x = R_x + F_{frame.x} + D_a + F_a$$

- Inverse dynamics approach:

- Required acceleration a_x for an assigned velocity profile
- Determine acceleration force $F_a = m a_x$
- Calculate torque T_w for acceleration





- Circumferential Force and tire slip:

$$F_x = \mu_{px} R_z (1 - e^{-ks\delta})$$

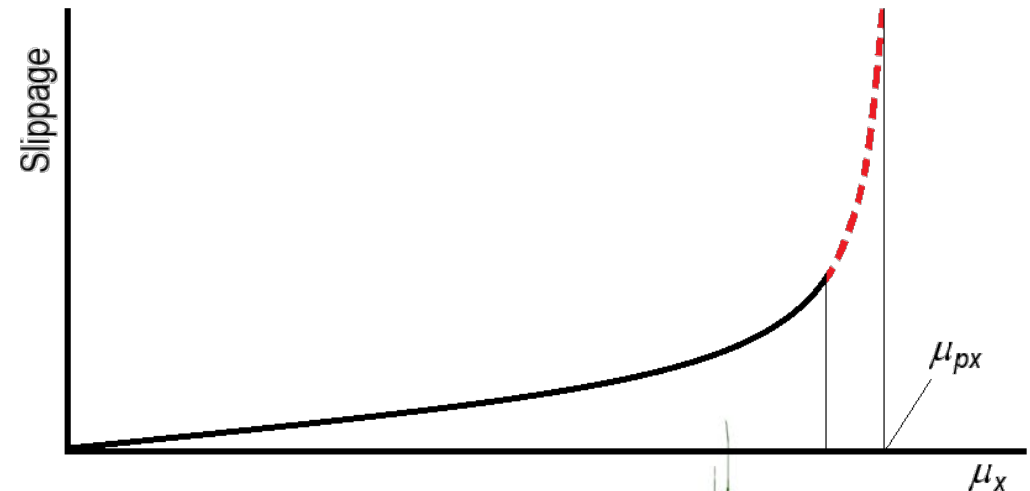
- Normalized by R_z :

$$\mu_x = \mu_{px} (1 - e^{-ks\delta})$$

- μ_x is the percentage of R_z used in generating the circumferential force F_x

$$\mu_x = \frac{F_x}{R_z}$$

- μ_x asymptotically approaches μ_{px} .
- μ_{px} determines maximum possible circumferential force under current condition





- Mobility Margin: Wheel Mobility Index
 - Wheel's remaining capacity for mobility
- In steady motion:

$$WMI = 1 - \frac{F_x}{F_x^{max}} = 1 - \frac{F_x}{\mu_{px} R_z}$$

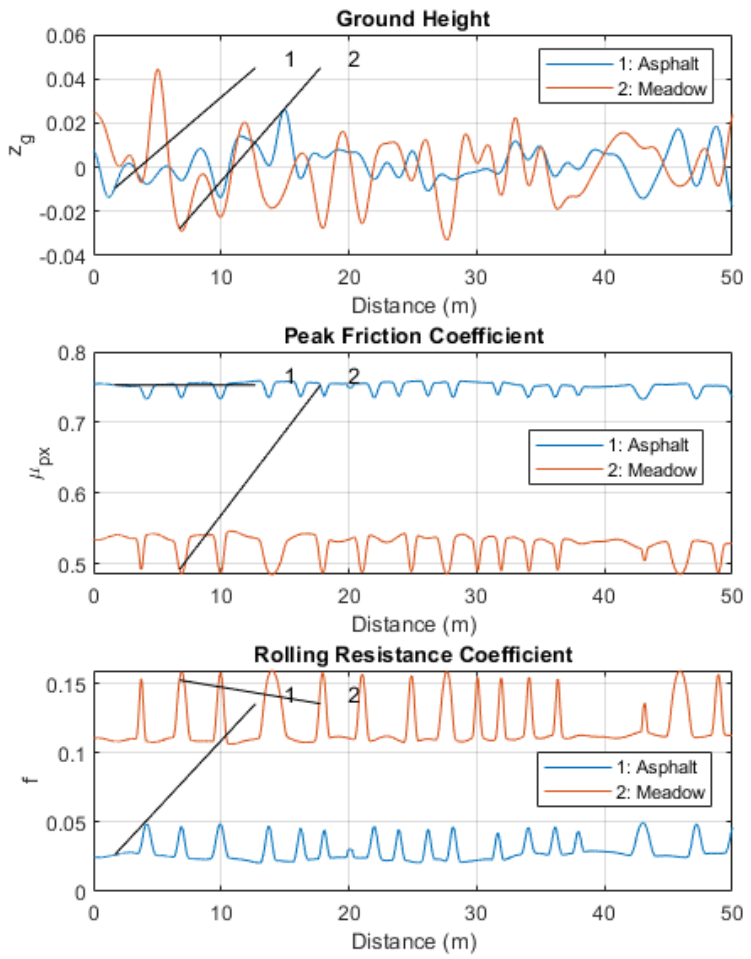
$$F_x^{max} = \mu_{px} R_z$$

- In non-steady motion:
(calculation based on the torque)

$$WMI = 1 - \frac{T_w - J_{eq} \varepsilon_w - B_{eq} \omega_w}{r_w^0 \mu_{px} R_z}$$

$$F_x = \frac{T_w - J_{eq} \varepsilon_w - B_{eq} \omega_w}{r_w^0}$$



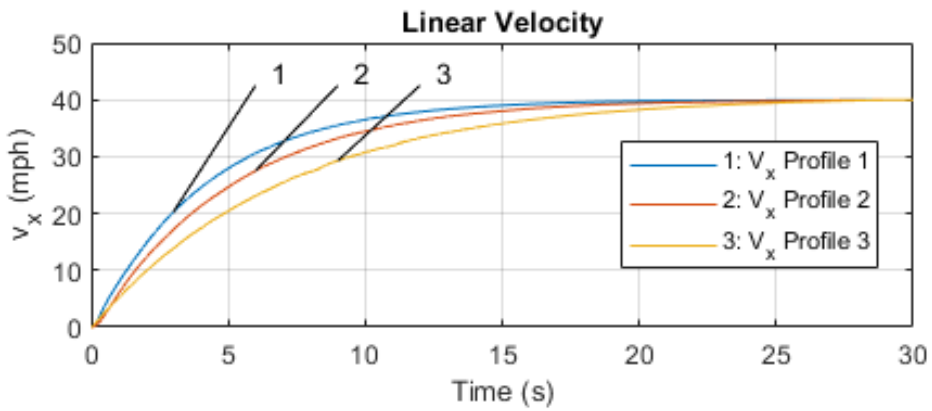


- Stochastic terrain input for simulation (asphalt and off-road):
 - Ground height, z_g
 - Peak friction coefficient, μ_{px}
 - Rolling resistance coefficient, f





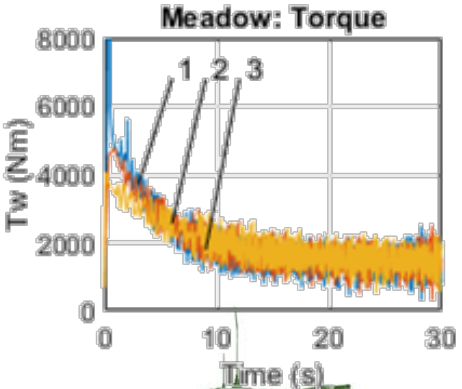
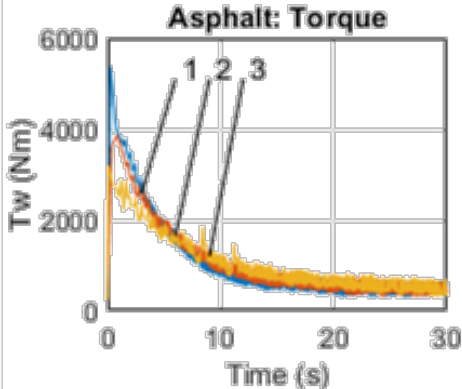
- Simulation of 3 velocity profiles:

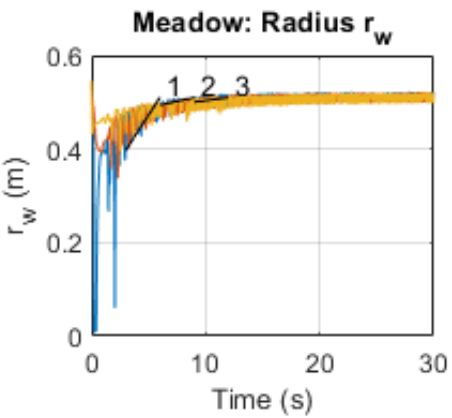
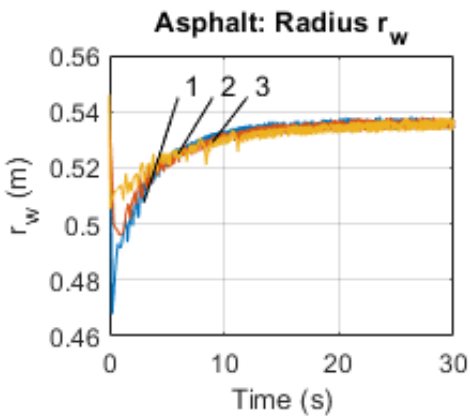
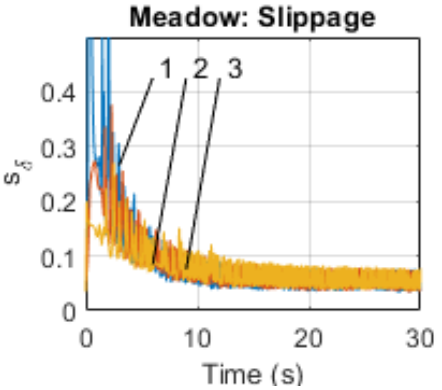
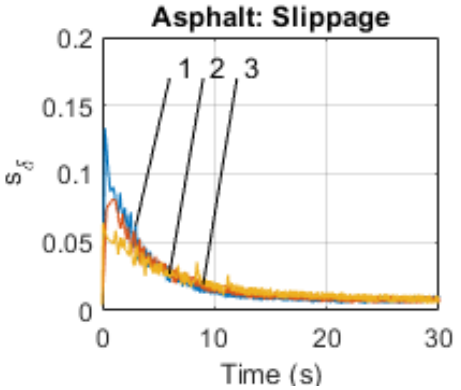


Max acceleration:

- 1: 4.7236 m/s^2
- 2: 3.3499 m/s^2
- 3: 2.7260 m/s^2

- Required wheel torque to make assigned velocity profile:





- Tire slippage:

$$s_{\delta} = \frac{V_t - V_x}{V_t}$$
- Actual velocity:

$$V_x = r_w \omega_w$$
- Theoretical velocity (without slip):

$$V_t = r_w^0 \omega_w$$
- Rolling radius:

$$r_w = r_w^0 (1 - s_{\delta})$$



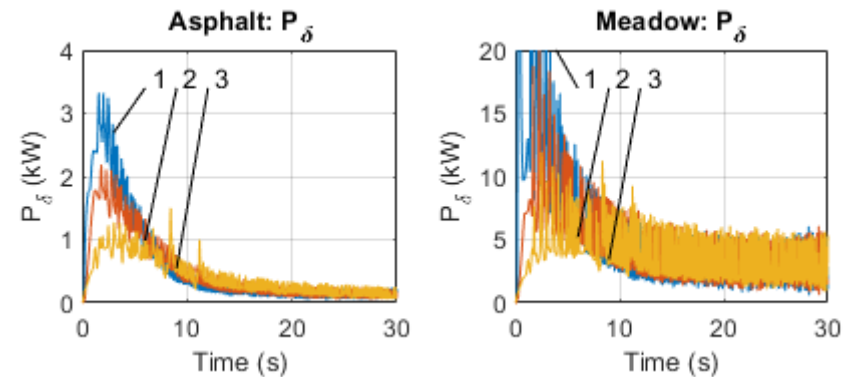


- Loss of linear velocity of the wheel due to slippage:

$$V_{\delta} = V_t - V_x$$

- Slip power (power losses due to slippage):

$$P_{\delta} = F_x \omega_w (r_w^0 - r_w)$$





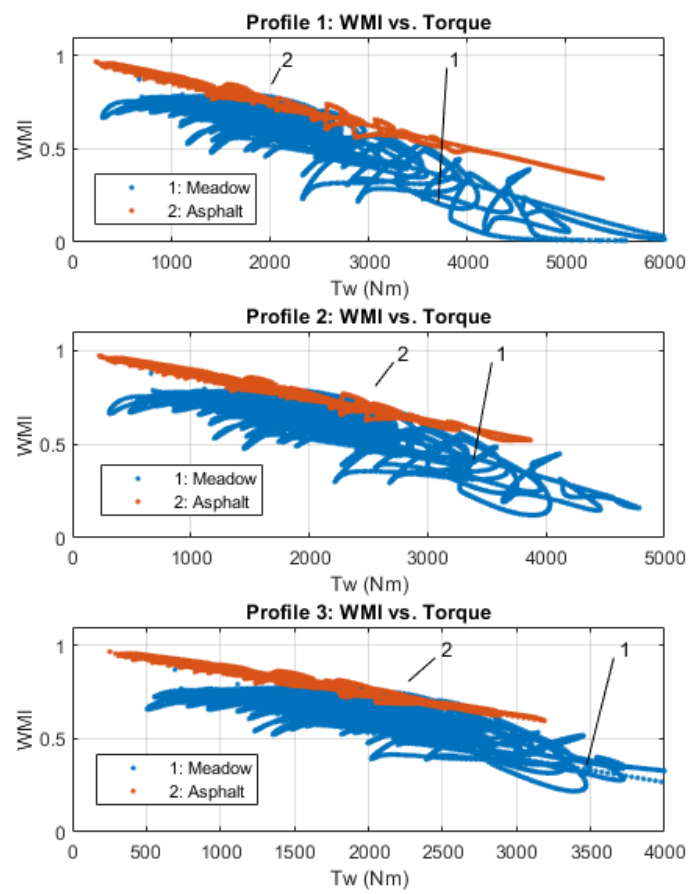
Determine reference boundaries:

- Analyze results to determine interrelations between the mobility indices, energy efficiency and the reference torques recovered by the inverse dynamics approach
- Establish upper boundaries of the reference wheel torque to prevent a drop of the mobility index below a certain desired value.

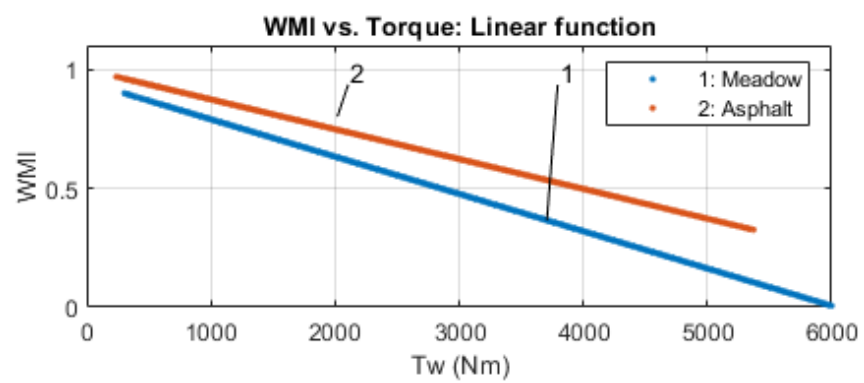




- Mobility Margin vs. Torque

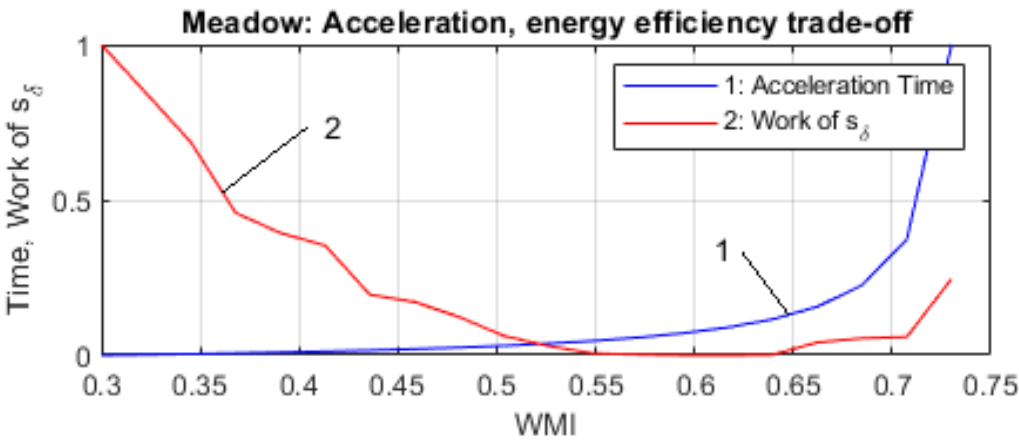
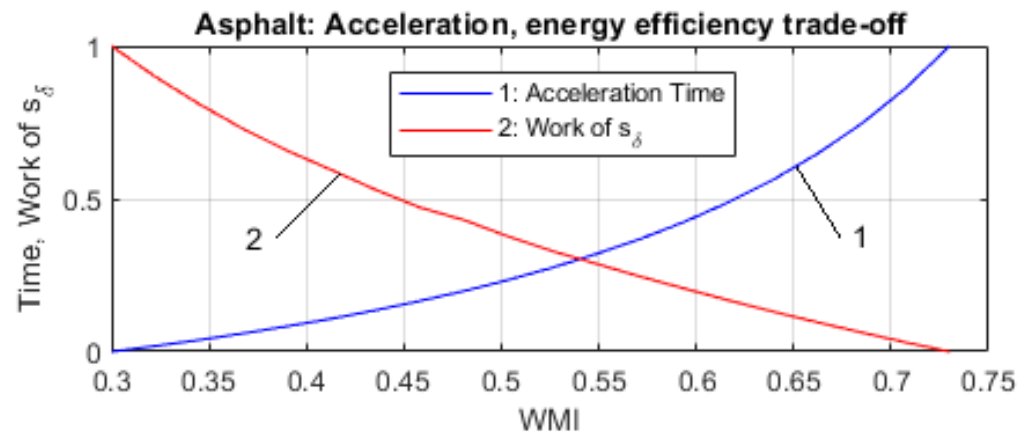


- Linear function approximating the relationship between torque and mobility index:



- Can assign torque boundary based on WMI





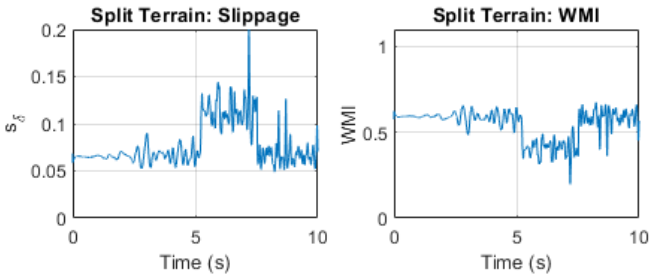
- Tradeoff between acceleration time and energy losses:
 - Assign WMI margin
 - Different margins lead to change in acceleration performance vs. energy efficiency
 - Select margin based on current performance needs



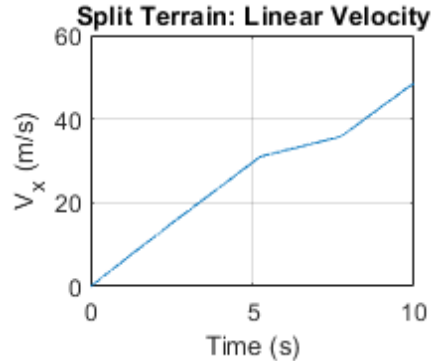
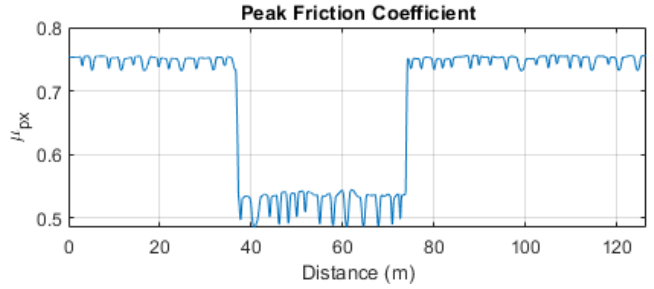
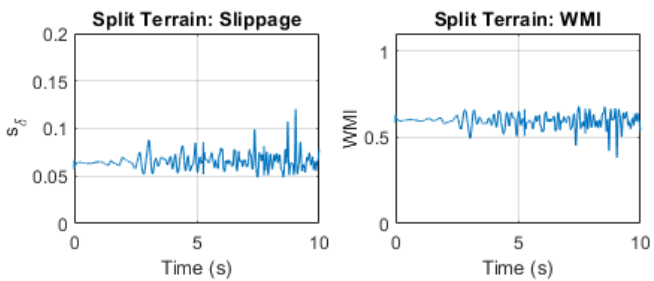


- Response to change in terrain:

- Without changing torque boundary:



- Torque boundary for average WMI = 60%:





Conclusions/summary:

- Inverse dynamics problem formulated to establish balance between acceleration performance and energy efficiency while maintaining the mobility.
- Wheel mobility index is, as the remaining capacity for mobility, is used to determine boundaries on the torque which keep mobility at a desired margin.
- Boundaries provide a guideline for balancing tradeoffs between mobility, performance, and efficiency.





- Q&A

