ROBUST SEMI-ACTIVE RIDE CONTROL UNDER STOCHASTIC EXCITATION

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Outline

- **Introduction/Overview**
- Vehicle Modeling
- Road Profile and Stochastic Excitation
- Performance Metrics
- Control Methodology
- Simulation Results
  - Robust for parameter range
  - Robust for unknown input
  - Comparison
- Conclusions

Ride comfort for military vehicles are important for several reasons:

1) **Fatigue caused by vehicle vibrations**
2) **Motion sickness reduction by smoothed vehicle motions**
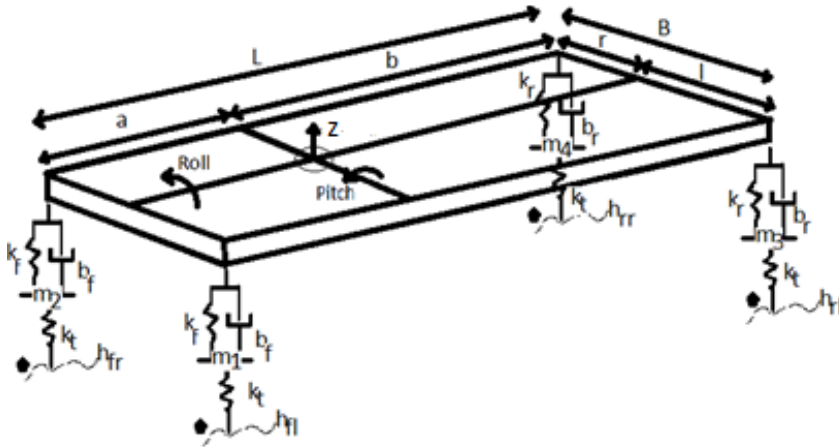3) **Ability to modify handing conditions based upon terrain**

Suspension Type:

1) **Fully Active Suspension**
2) **Passive Suspension**
3) **Semi-Active Suspension**

Control Method:

1) **LQR/H-Infinity/Linear Methods**
2) **Nonlinear/Adaptive**
3) **Discontinuous (Parameterized or otherwise)**

Seven Degree of Freedom Vehicle Model

Suspension Forces

$$F_{fl} = k_{fl}(z - a\,\theta + l\phi - z_{fl}) + c_{fl}(\dot{z} - a\dot{\theta} + l\dot{\phi} - \dot{z}_{fl}) \tag{1}$$

$$F_{fr} = k_{fr}(z - a\,\theta - r\phi - z_{fr}) + c_{fr}(\dot{z} - a\dot{\theta} - r\dot{\phi} - \dot{z}_{fr}) \tag{2}$$

$$F_{rl} = k_{rl}(z + b\,\theta + l\phi - z_{rl}) + c_{rl}(\dot{z} + b\dot{\theta} + l\dot{\phi} - \dot{z}_{rl}) \tag{3}$$

$$F_{rr} = k_{rr}(z + b\,\theta - r\phi - z_{rr}) + c_{rr}(\dot{z} + b\dot{\theta} - r\dot{\phi} - \dot{z}_{rr}) \tag{4}$$

Wheel Dynamics

$$\ddot{z}_{fl} = \frac{-k_{u,fl} * (z_{fl} - z_{g,fl})H(z_{g,fl} - z_{fl}) + F_{fl}}{m_{fl}} - g \tag{5}$$

$$\ddot{z}_{fr} = \frac{-k_{u,fr} * (z_{fr} - z_{g,fr})H(z_{g,fr} - z_{fr}) + F_{fr}}{m_{fr}} - g \tag{6}$$

$$\ddot{z}_{rl} = \frac{-k_{u,rl} * (z_{rl} - z_{g,rl})H(z_{g,rl} - z_{rl}) + F_{rl}}{m_{rl}} - g \tag{7}$$

$$\ddot{z}_{rr} = \frac{-k_{u,rr} * (z_{rr} - z_{g,rr})H(z_{g,rr} - z_{rr}) + F_{rr}}{m_{rr}} - g \tag{8}$$

Vehicle Body Dynamics

$$\ddot{z} = \frac{-(F_{fl} + F_{fr} + F_{rl} + F_{rr})}{mass} - g \tag{9}$$

$$\ddot{\theta} = \frac{a(F_{fl} + F_{fr}) - b(F_{rl} + F_{rr})}{J_{Pitch}} \tag{10}$$

$$\ddot{\phi} = \frac{-l(F_{fl} + F_{rl}) + r(F_{fr} + F_{rr})}{J_{Roll}} \tag{11}$$

Road Profile and Stochastic Representation

Third Order Auto Regressive Time-Series Model

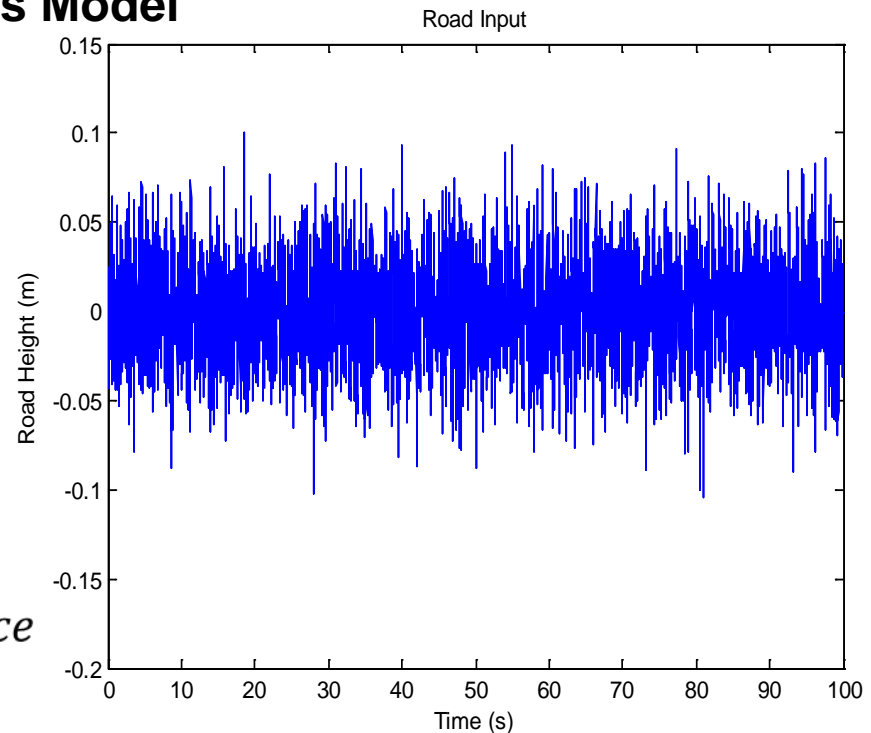$$u_i = \phi_1\, u_{i-1} + \phi_2\, u_{i-2} + \phi_3\, u_{i-3} + \varepsilon_i \qquad (12)$$

Feedback Coefficients

$$\phi_1 = 1.2456,$$
$$\phi_2 = -0.2976,$$
$$\phi_3 = -0.1954,$$
$$\varepsilon_i = Gaussian\, White\, Noise, Unity\, Variance$$

Road Input

A series of statistical tests were conducted to examine the validity of the time-series model representation of the road profile

Third Order Auto Regressive Model

$$u_i = \phi_1\, u_{i-1} + \phi_2\, u_{i-2} + \phi_3\, u_{i-3} + \varepsilon_i \qquad\qquad (12)$$

Front-Left-Wheel: $\qquad\qquad z_{\mathrm{wfl}}(t) = z_r(t) = u_i$

Front-Right-Wheel: $\qquad\quad z_{wfr}(t) = z_r(t + \delta) = u_{i+\delta}$

Rear-Left-Wheel: $\qquad\qquad z_{wrl}(t) = z_r\left(t + \dfrac{L}{v_s}\right) = u_{i+\frac{L}{v_s}}$

Rear-Right-Wheel: $\qquad\qquad z_{wrr}(t) = z_r\left(t + \dfrac{L}{v_s} + \delta\right) = u_{i+\frac{L}{v_s}+\delta}$

Wheelbase: L $\qquad\qquad$ Vehicle Speed: v_s $\qquad\qquad$ Delay: δ

- **Absorbed Power (At the seat locations)**
  - Next Slide

- **RMS Acceleration (At the seat locations)**
  - $\sqrt{\ddot{z}/N}$

- **Road Holding (At each wheel)**
  - $z_{wheel} - z_{road}$

- **Rattle Space (For each suspension strut)**
  - $z_{body} - z_{wheel}$

- **Absorbed Power**
  - Measure of ride comfort
  - Amount of energy absorbed from ride vibration

$$\overline{AP} = \lim_{T \to \infty} \frac{1}{T} \int_0^T F(t)V(t)dt$$

  - Actual absorbed power with physical characteristics
  - Typical coefficients of a 50th percentile man are used
  - For the 7-DOF model, the absorbed power is computed at all the four seats (two in front and two in rear), and averaged to represent a single ride comfort metric used for the study.
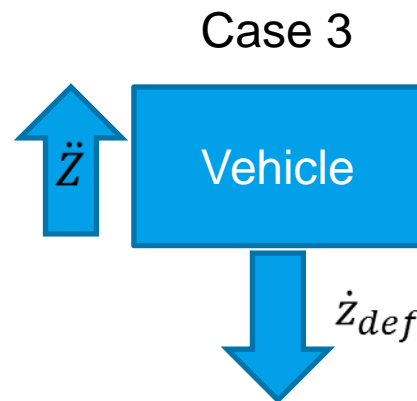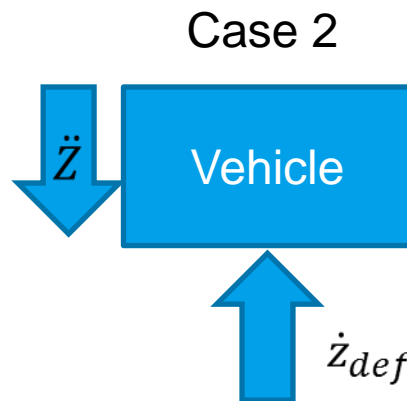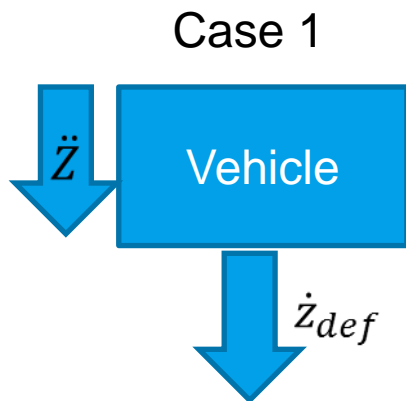
Control Methodology – Accelerometer Driven Damper (ADD)
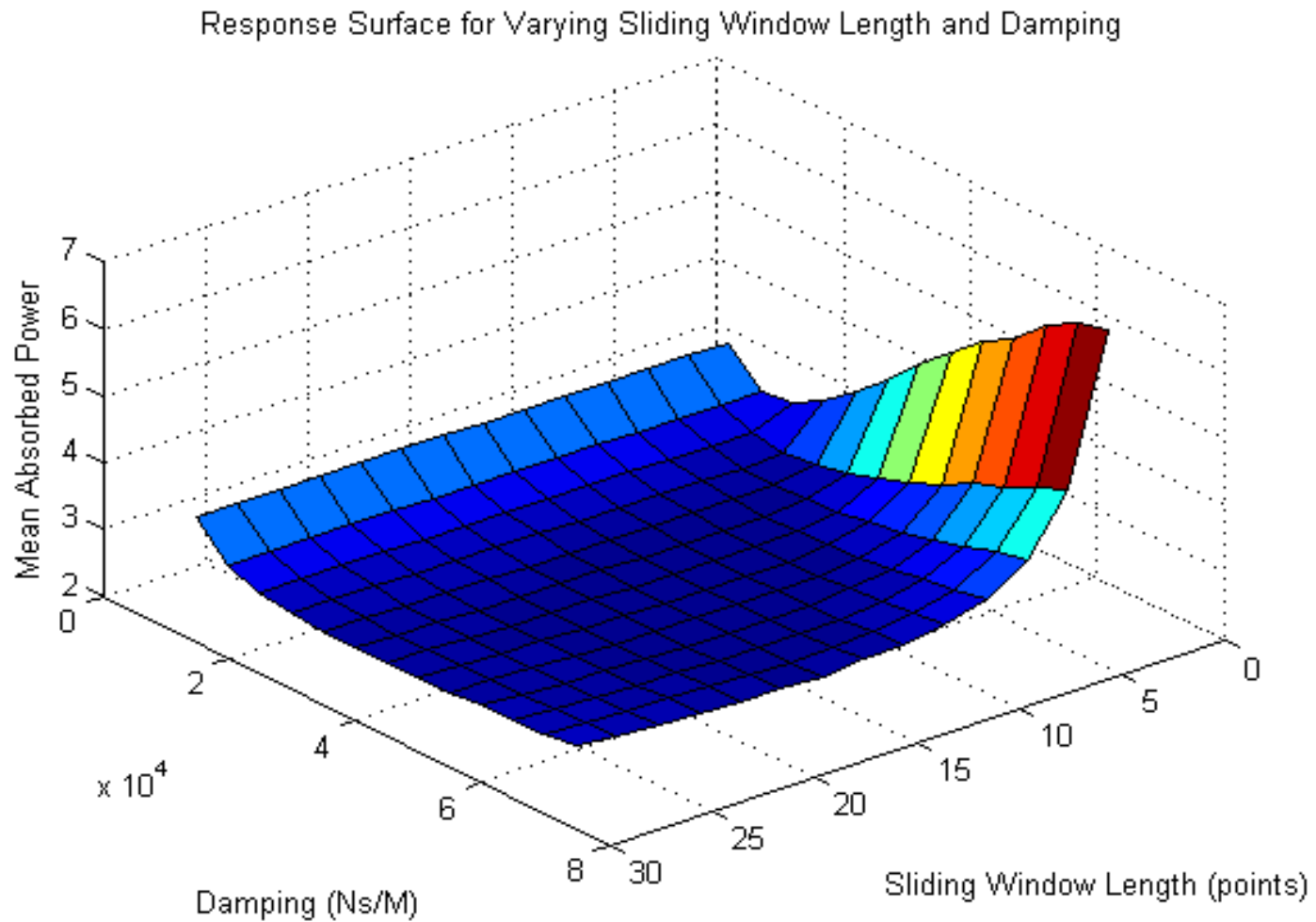
Infinite Control Authority ADD

$$C_{desired} = C_{min} + H(\ddot{z}\dot{z}_{def})(C_{max} - C_{min}) \quad (13)$$
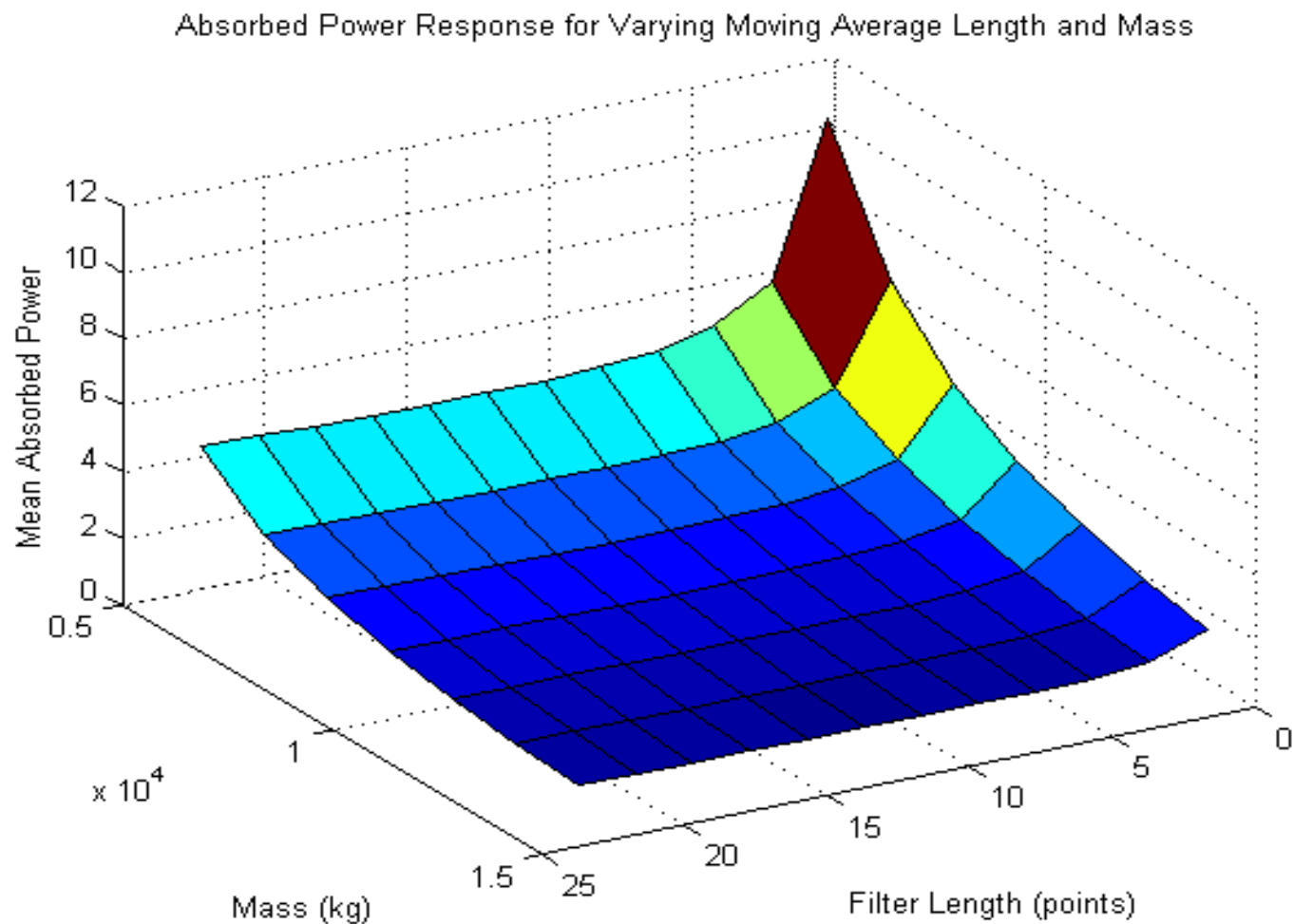
Moving Average Filter

$$Z_k = \sum_{i=0}^{N} \frac{1}{N+1} z_{K-i} \quad (14)$$
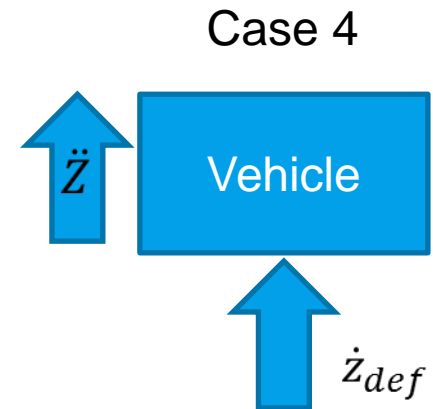
Case 4

Case 1

Case 2

Case 3

Response Surface for Varying Sliding Window Length and Damping

Absorbed Power Response for Varying Moving Average Length and Mass

Response Surface for Varying Sliding Window Length and Road Roughness, 15 MPH
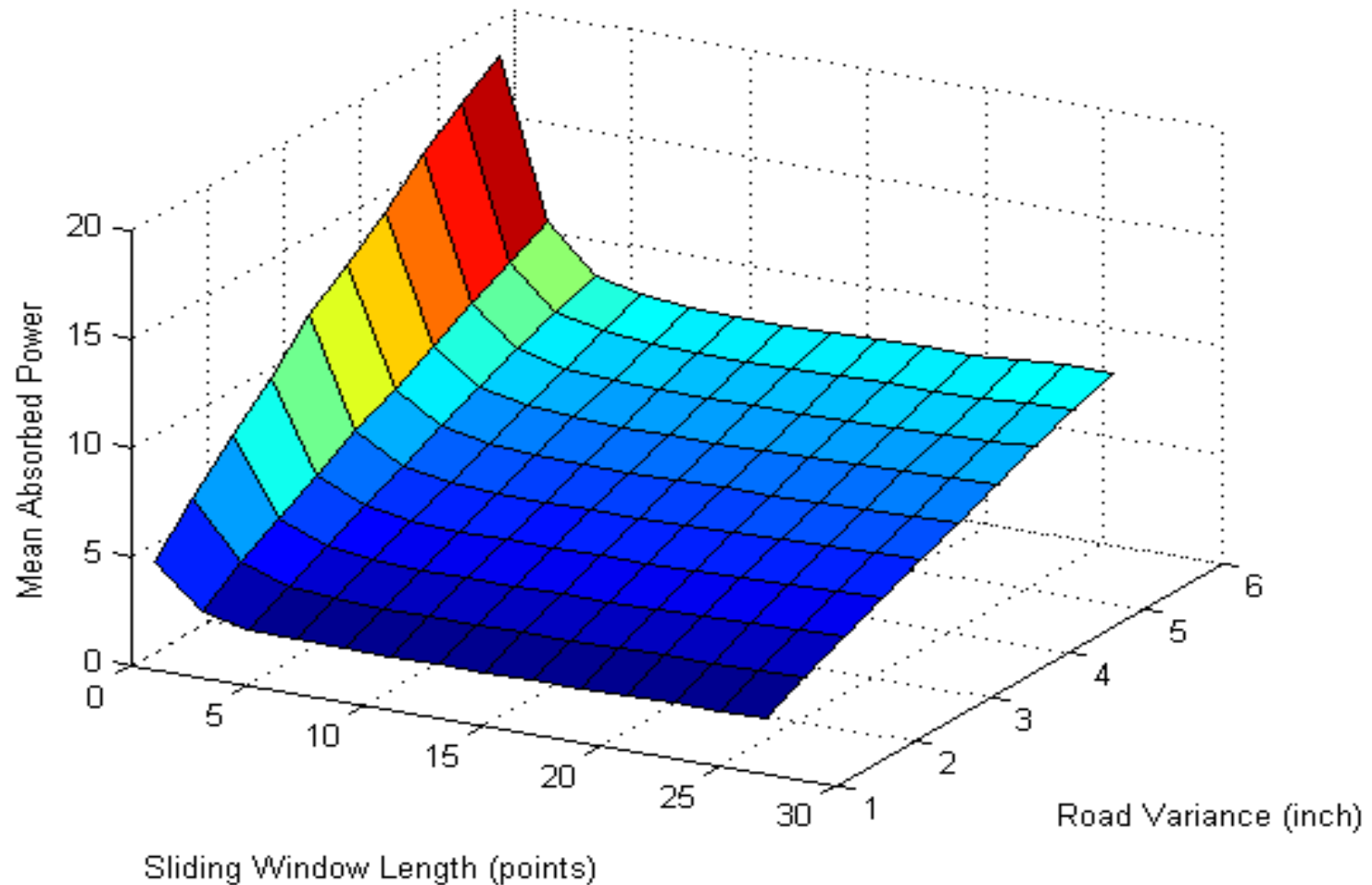
Response Surface for Varying Sliding Window Length and Road Roughness, 30 MPH
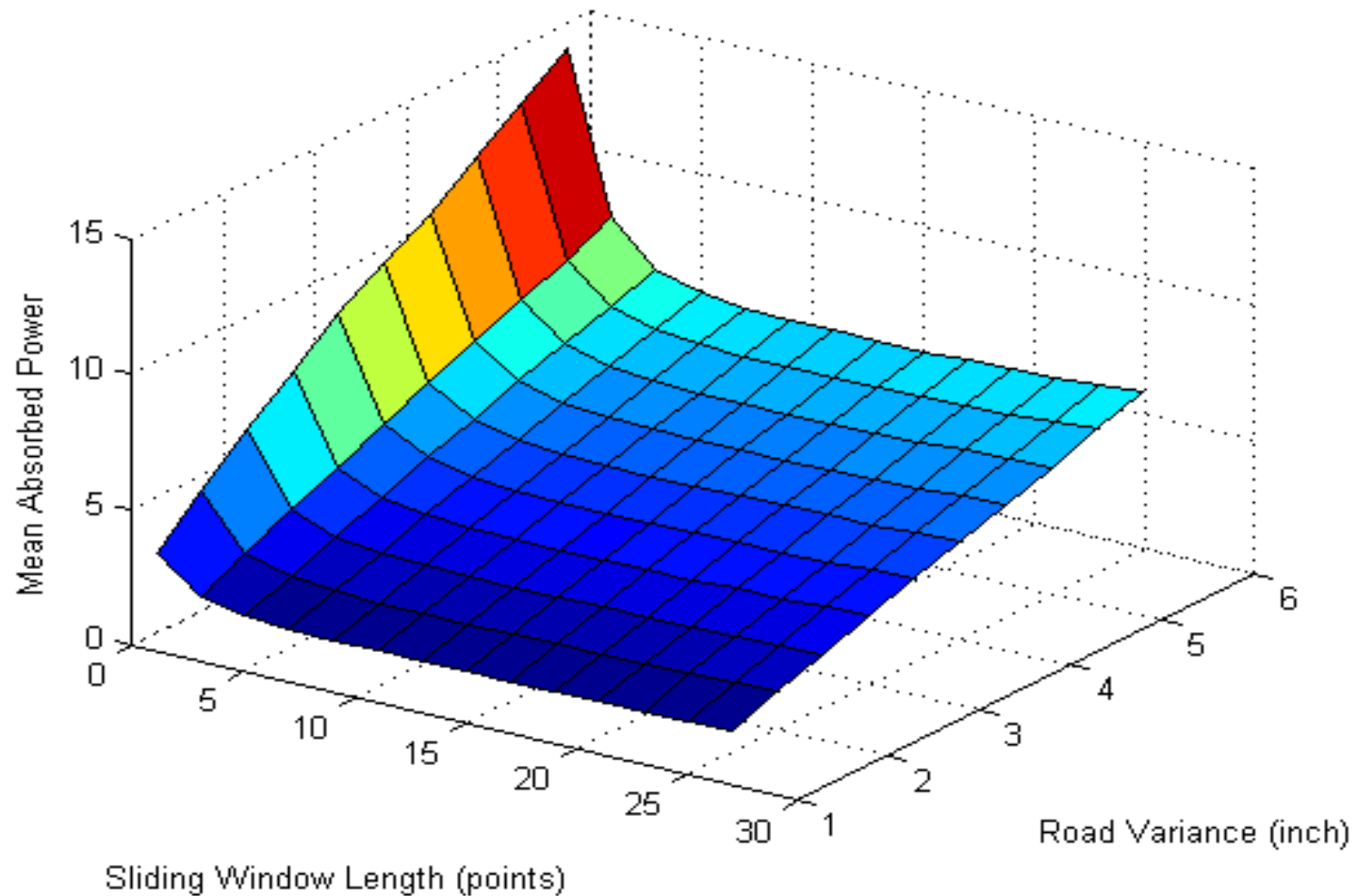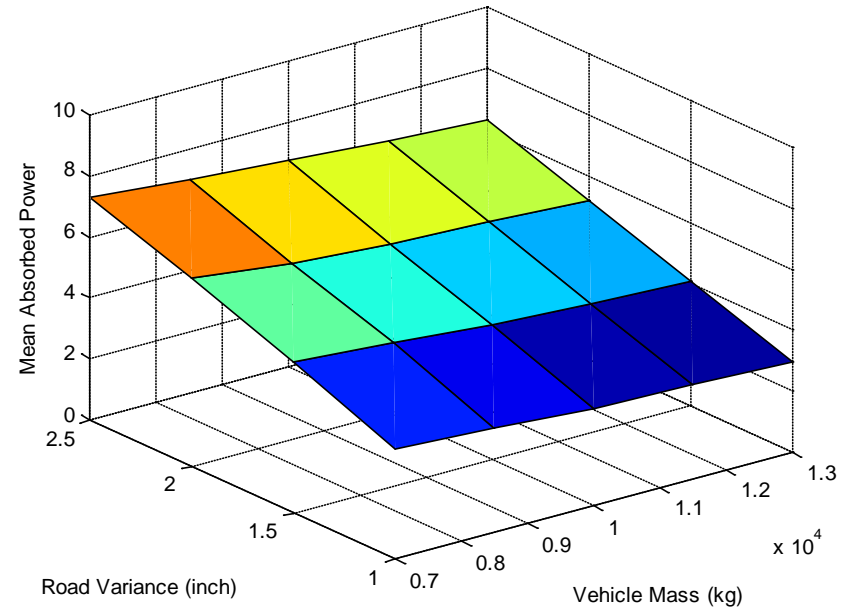
Simulation Results – Ride Comfort Comparison

Comfort Performance for Smoothed ADD Control
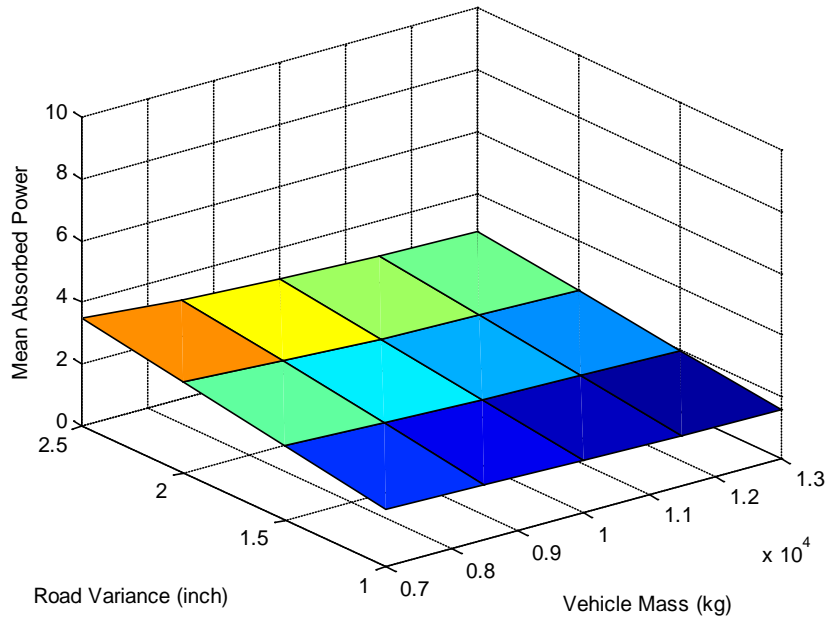
Comfort Performance for Original ADD Control

Quarter Car Results	Average Absorbed Power (W)	Sprung Mass Acceleration RMS (g's)	Road Holding Max (in)
Passive	26.65	0.61	4.45
SH 2-state	6.19	0.39	4.87
SH-ADD	3.43	0.25	4.87
SH Linear	3.05	0.23	5.54
ADD	1.28	0.19	5.11
Smoothed ADD (Proposed)	1.09	0.17	5.18

Conclusions

- Smoothing function significantly improves over the original ADD control for the higher fidelity models than just quarter car models.

- Invariant with respect to vehicle mass/inertia (Does not require any vehicle parameters)

- Invariant with respect to road profile

- Computationally efficient algorithm. Challenge comes from sensor implementation