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Effect of Roughness-Induced Dynamic Load on Pavement Fatigue Life Using Mechanistic-Empirical Approach

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Presentation Outline

- Introduction
- Single-Point Contact (SPC) Models
- Effect of Roughness on Fatigue Life
- Conclusions

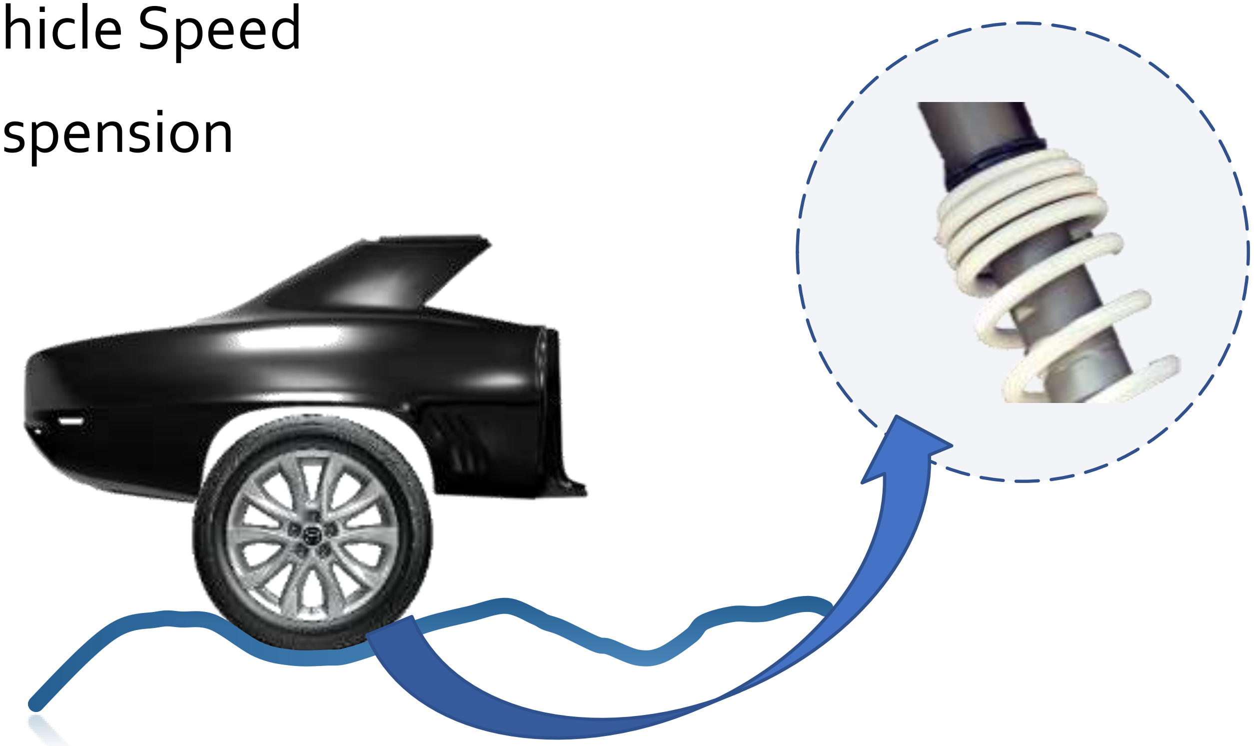
Introduction

- Dynamic load is a significant parameter in pavement responses analysis models.
- It is essential to reliably estimate pavement mechanical responses under dynamic loading.
- Road roughness is one of the main contributing factors to vehicle dynamic loads.
- International Roughness Index (IRI) is the most common measure for road roughness.

Introduction

Dynamic loading Factors

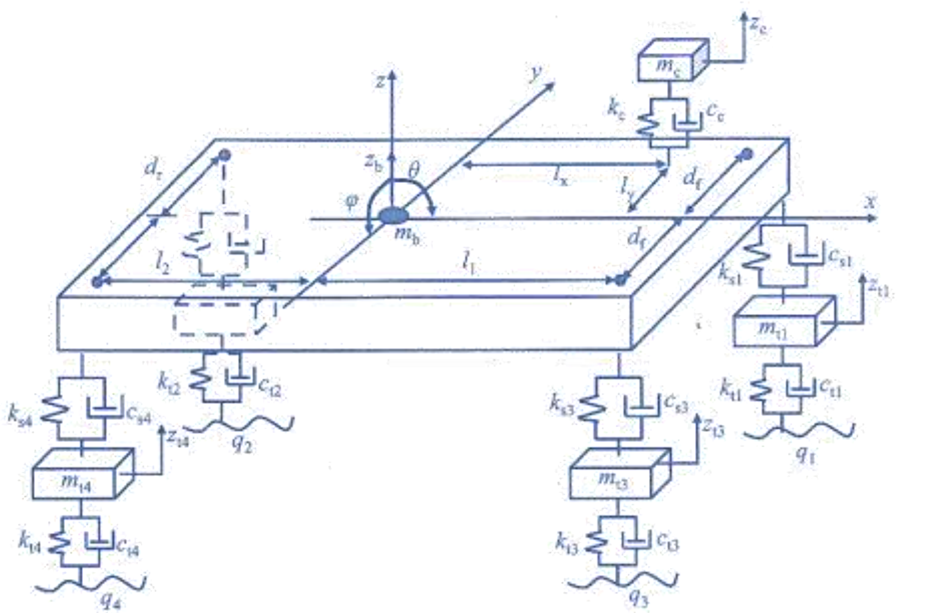
- Road Profile
- Vehicle Speed
- Suspension



Full-Car Simulation

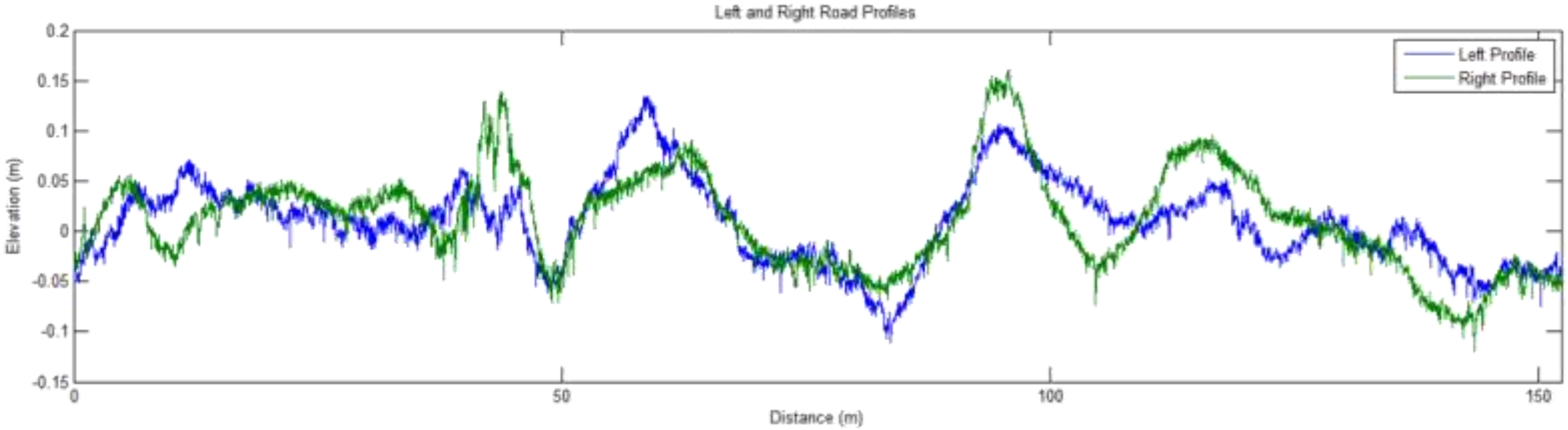
Formulation

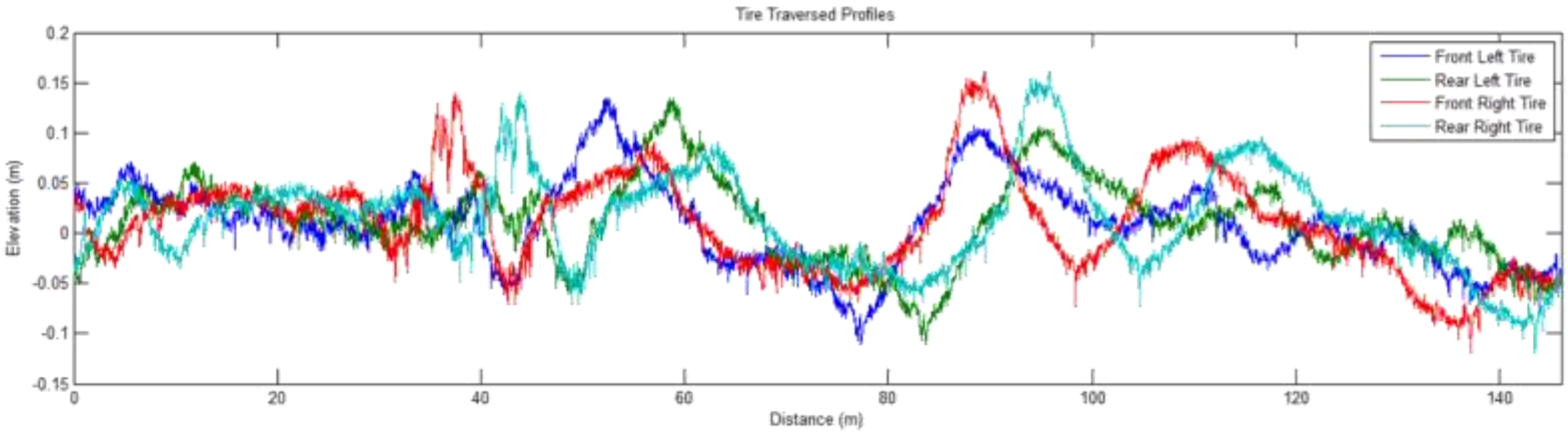
- There are 12 unknowns associated with the model shown below.
- Solution is based on state-space modeling.
- Yaw, pitch, and roll effects are considered in this type of simulation.



Full-Car Simulation

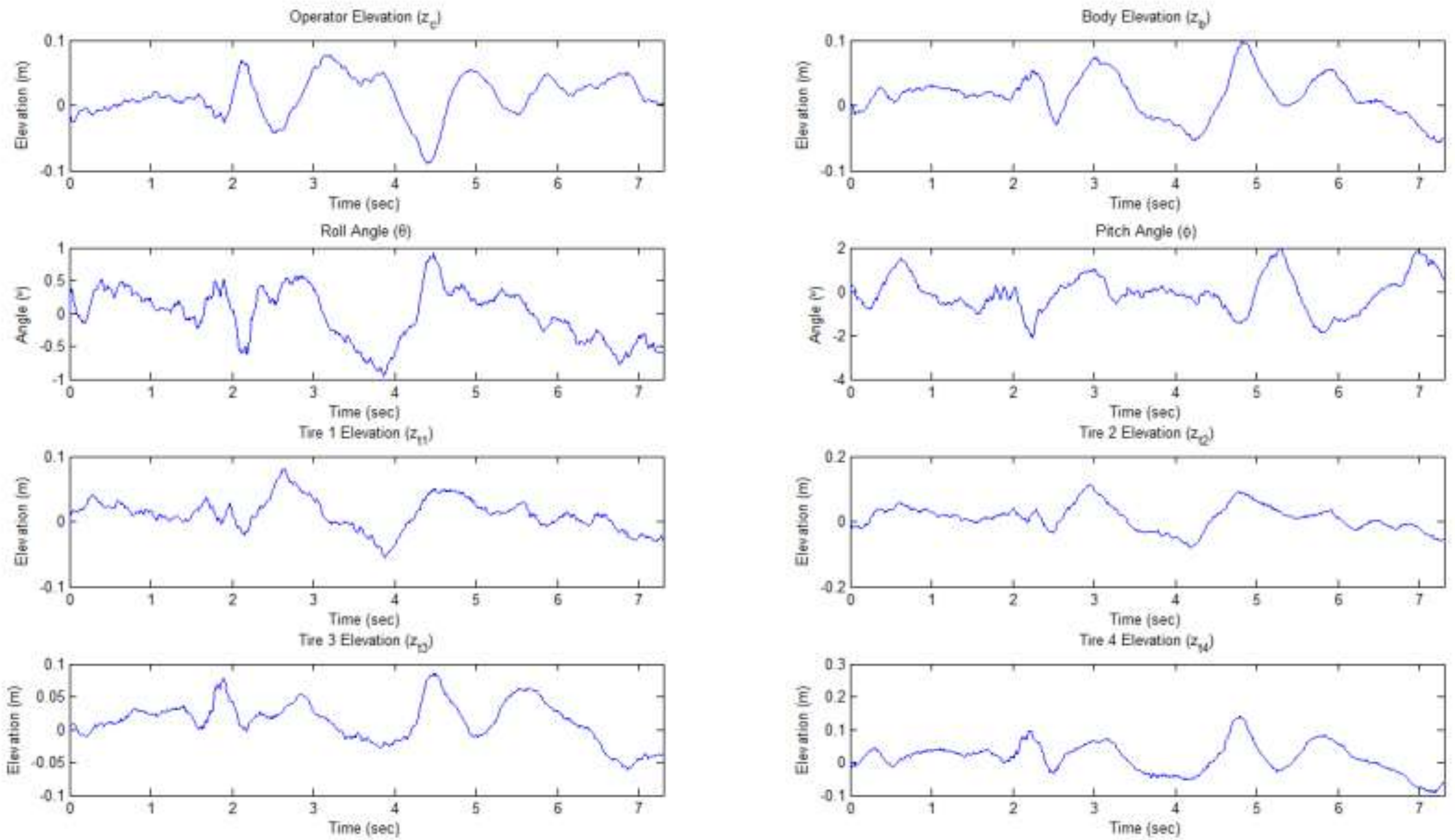
Road Profile





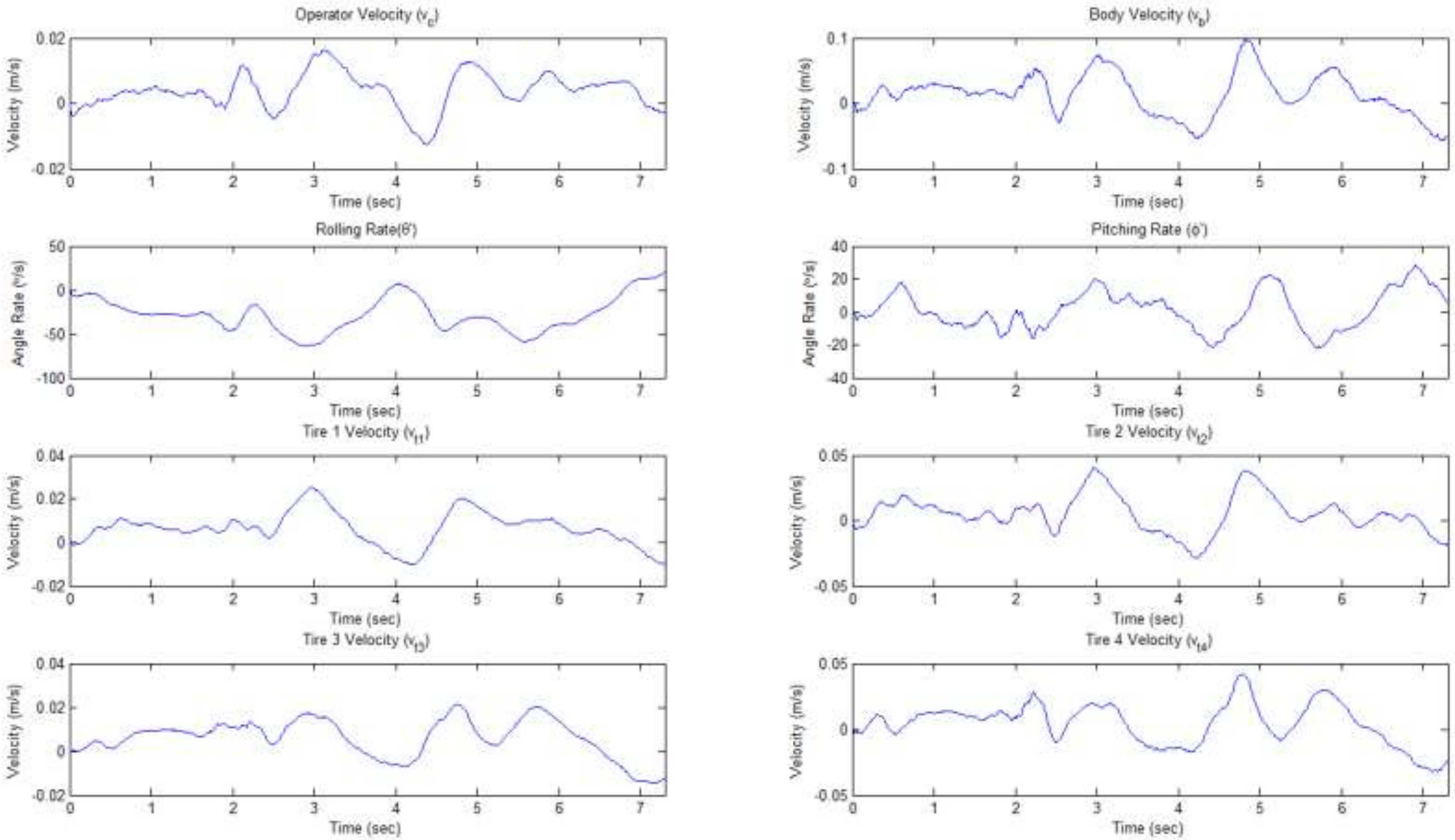
Full-Car Simulation

Elevations

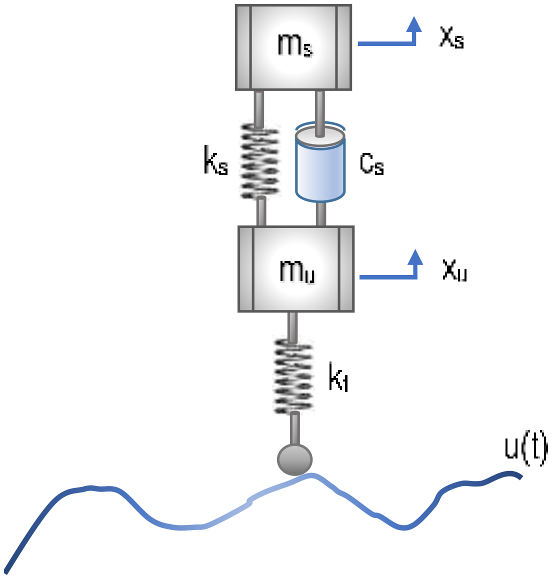


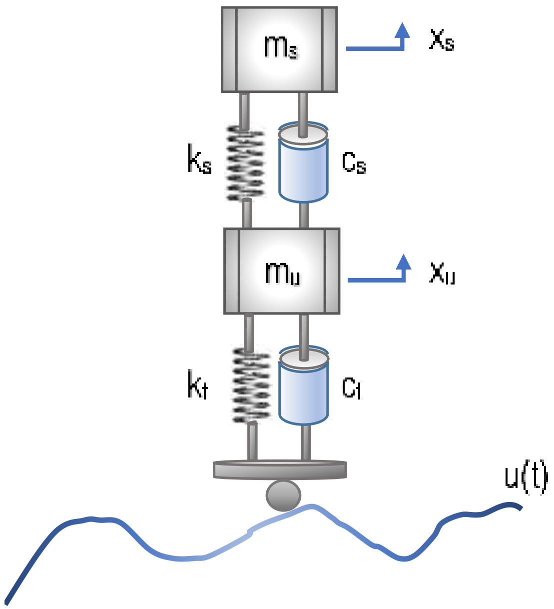
Full-Car Simulation

Velocities



Single-Point Contact (SPC) Models





Quarter-Car Simulation

Quarter-Truck Simulation

$$\begin{cases} m_u\ddot{x}_u + c_s(\dot{x}_s - \dot{x}_u) - k_s(x_s - x_u) + k_t(x_u - u(t)) = 0 \\ m_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_u) + k_s(x_s - x_u) = 0 \end{cases}$$

Single-Point Contact (SPC) Models

Quarter-Car

Parameter	Value
$c = c_s / m_s$	6.0
$k_1 = k_t / m_s$	653
$k_2 = k_s / m_s$	63.3
$\mu = m_u / m_s$	0.15

$$IRI = \frac{1}{L}\int_0^T |\dot{x}_s(t) - \dot{x}_u(t)| \ dt$$

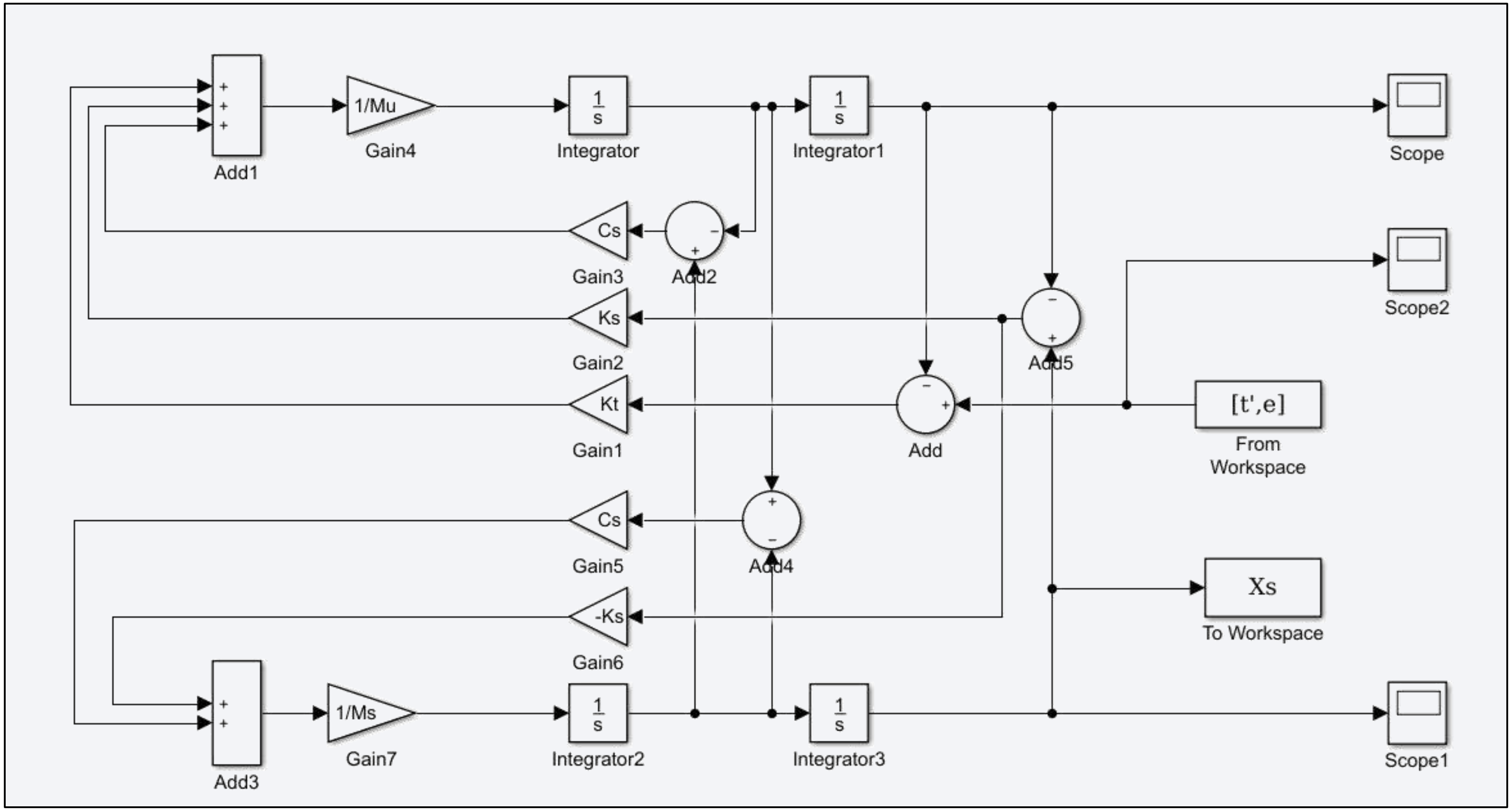
(V = 50 mph = 80 km/h)
1 m/km = 63.36 in./mile

Quarter-Truck

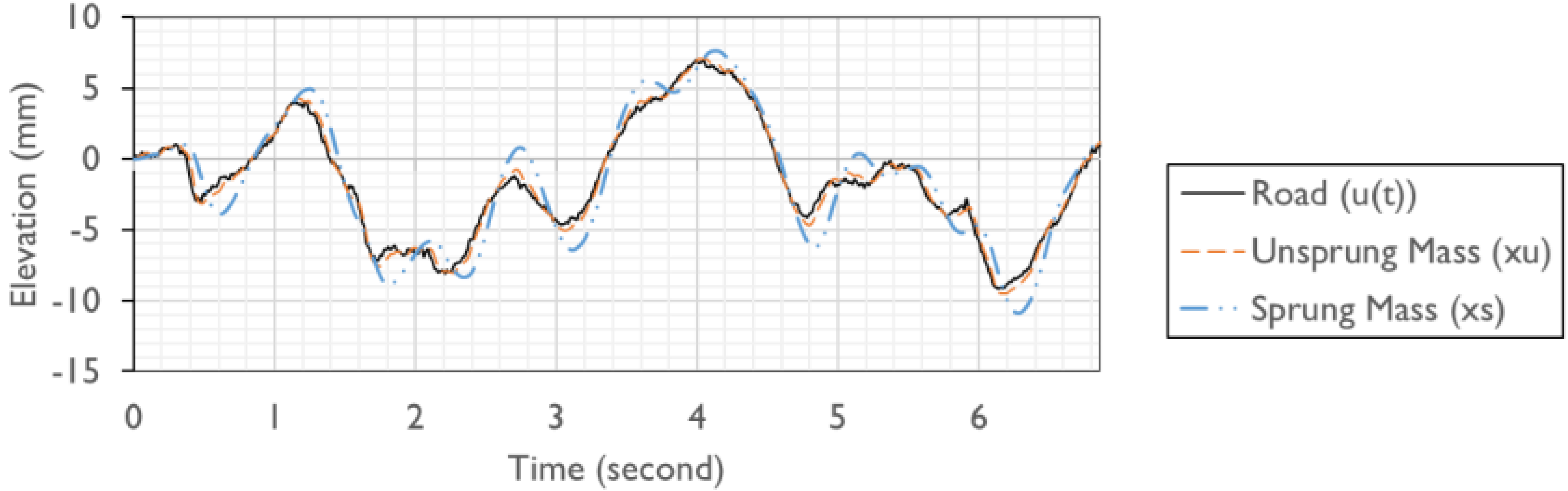
Parameter	Symbol	Unit	Howe et al.	Wambold	Collop
Sprung Mass	m_s	*kg*	3,400	m_s	-
Suspension Elastic Constant	k_s	*N/m*	270,000	118.1 m_s	230,000
Suspension Damping Constant	c_s	*N.s/m*	6,000	4.71 m_s	1,500
Unsprung Mass	m_u	*kg*	350	0.146 m_s	400
Tire Elastic Constant	k_t	*N/m*	950,000	755.1 m_s	1,000,000
Tire Damping Constant	c_t	*N.s/m*	300	-	1,000

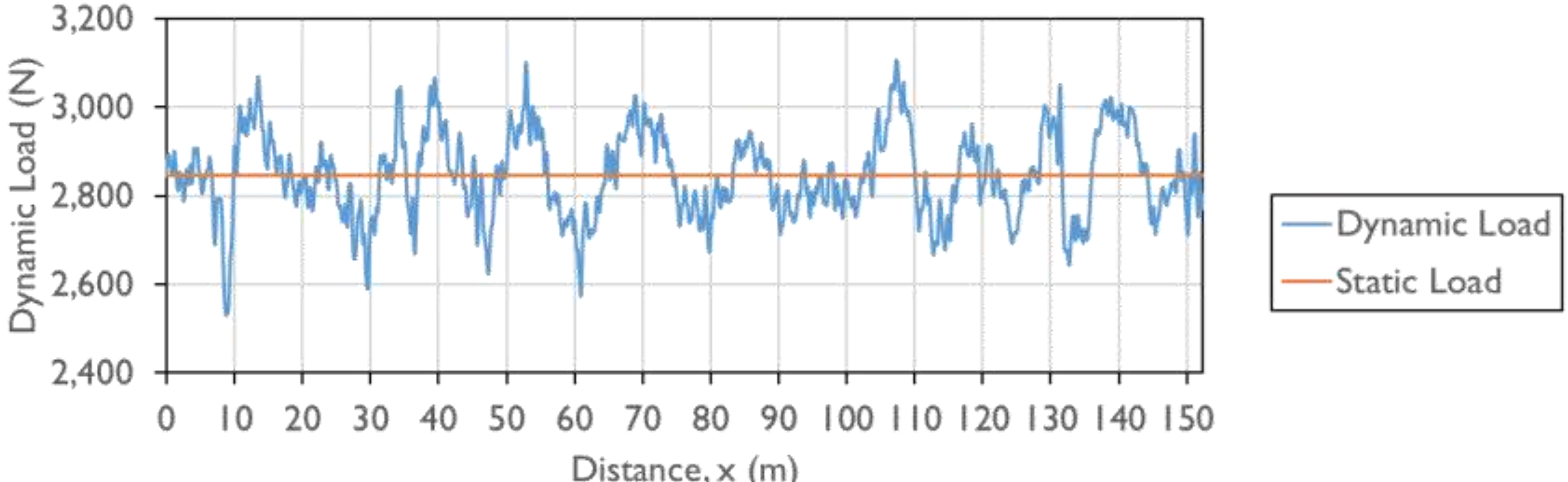
Dynamic Loading Simulation

Simulink Model



Dynamic Loading Simulation





Dynamic Loading Indices

Static and Perturbation Load

$$F_{perturbation} = k_t(x_s - u(t)) + c_s(\dot{x}_s - \dot{u}(t))$$

$$F = F_{static} + F_{perturbation} = (m_u + m_s) \cdot g + k_t(x_s - u(t)) + c_s(\dot{x}_s - \dot{u}(t))$$

Dynamic Load Coefficient (DLC)

$$DLC = \frac{1}{\bar{F}} \sqrt{\frac{\sum_{i=1}^{N} |F_i - \bar{F}|}{N - 1}} \times 100$$

Impact Factor

$$I = \frac{F - F_{static}}{F}$$

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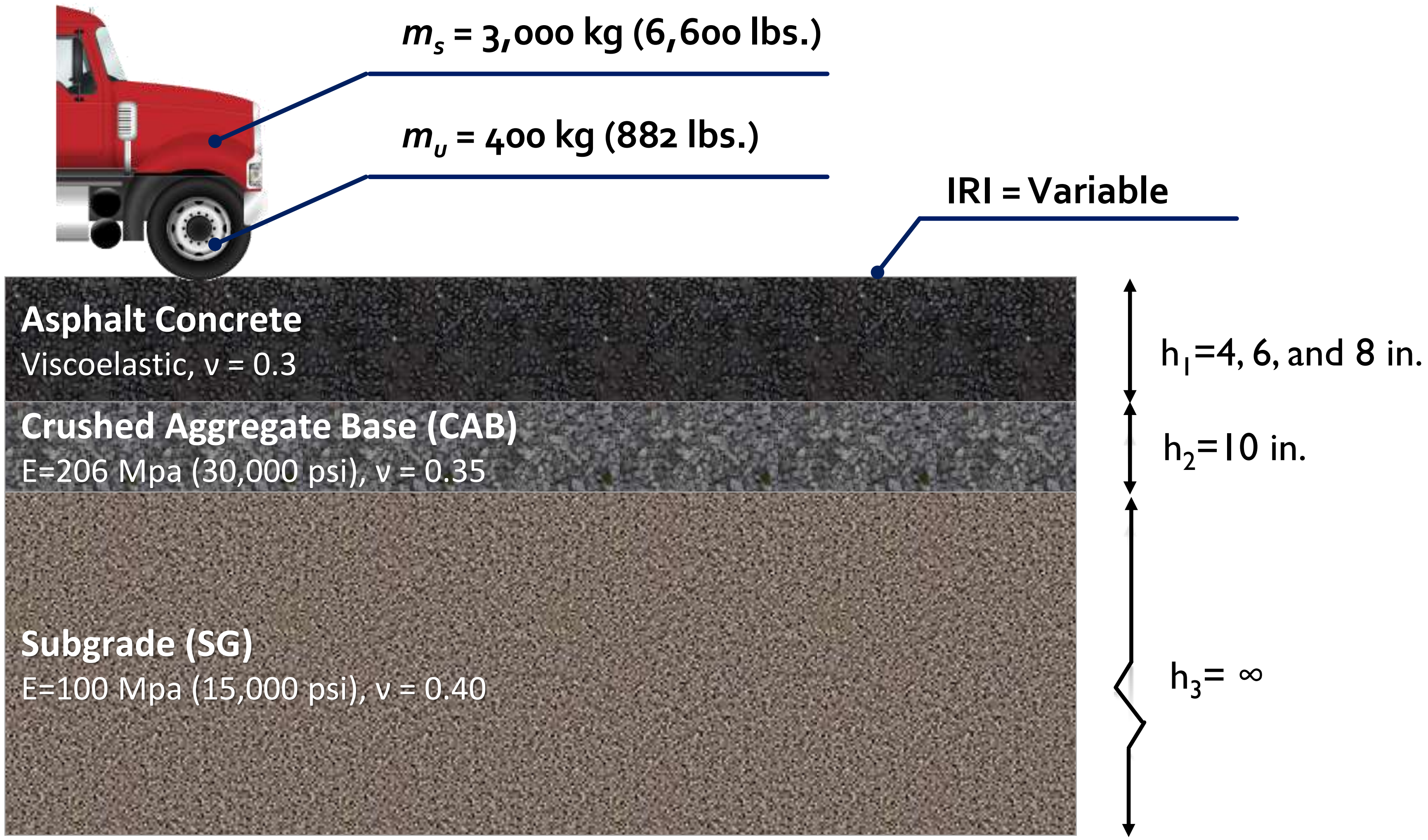
Fatigue Cracking

- MEPDG Fatigue Performance Models was used.
- Assuming linear viscoelasticity modeling to calculate ε_t

$$\log(N_f) = \beta_{f_1} k_{f_1} \cdot \left(\frac{1}{\varepsilon_t}\right)^{\beta_{f_2} k_{f_2}} \cdot \left(\frac{1}{E}\right)^{\beta_{f_3} k_{f_3}}$$

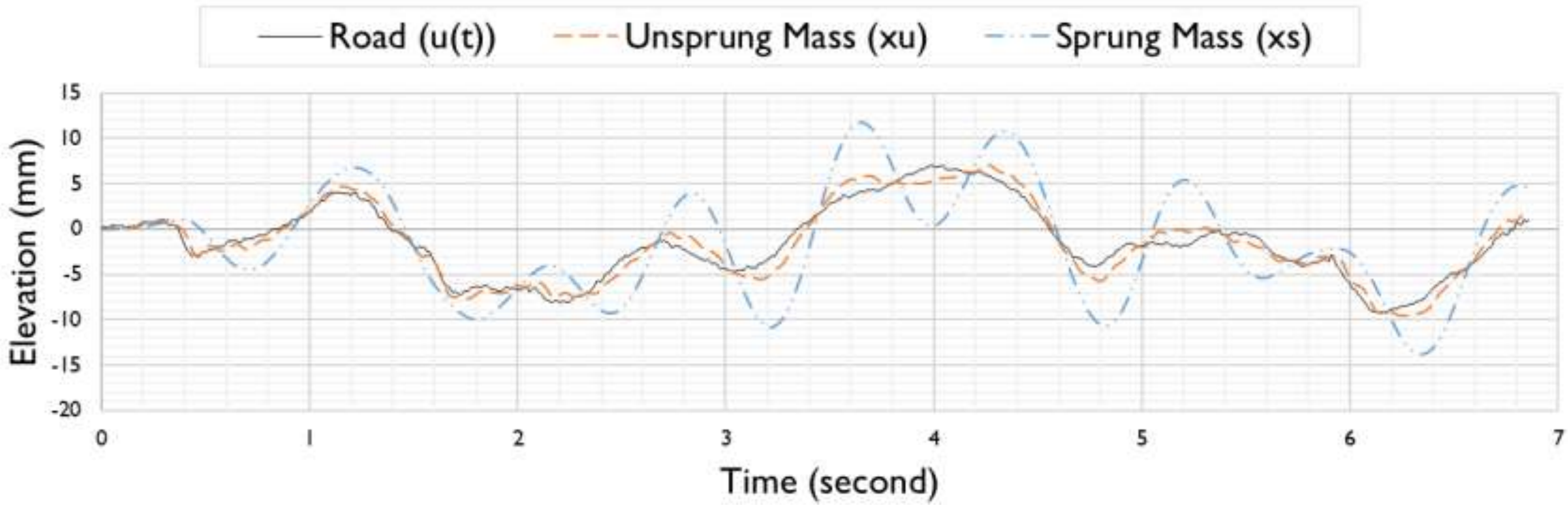
N_f = Number of repetitions to fatigue cracking
ε_t = Tensile strain at the critical location
E = Stiffness of the material
β_{f_1}, β_{f_2}, β_{f_3} =Calibration Parameters

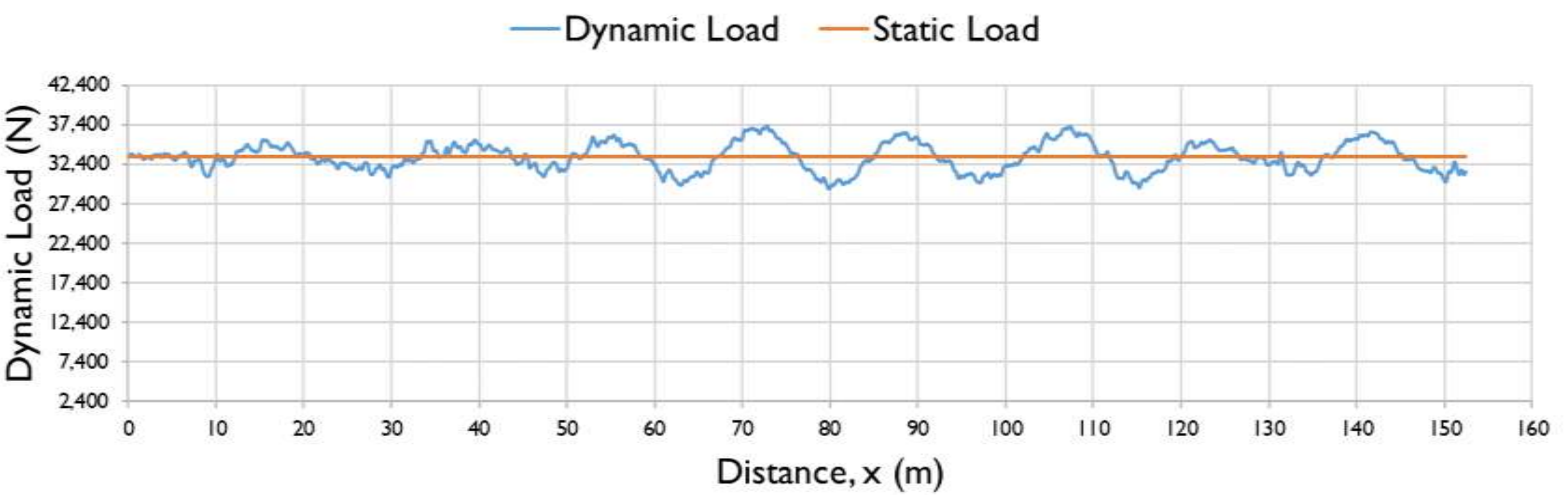
Pavement Structures



Road Profiles

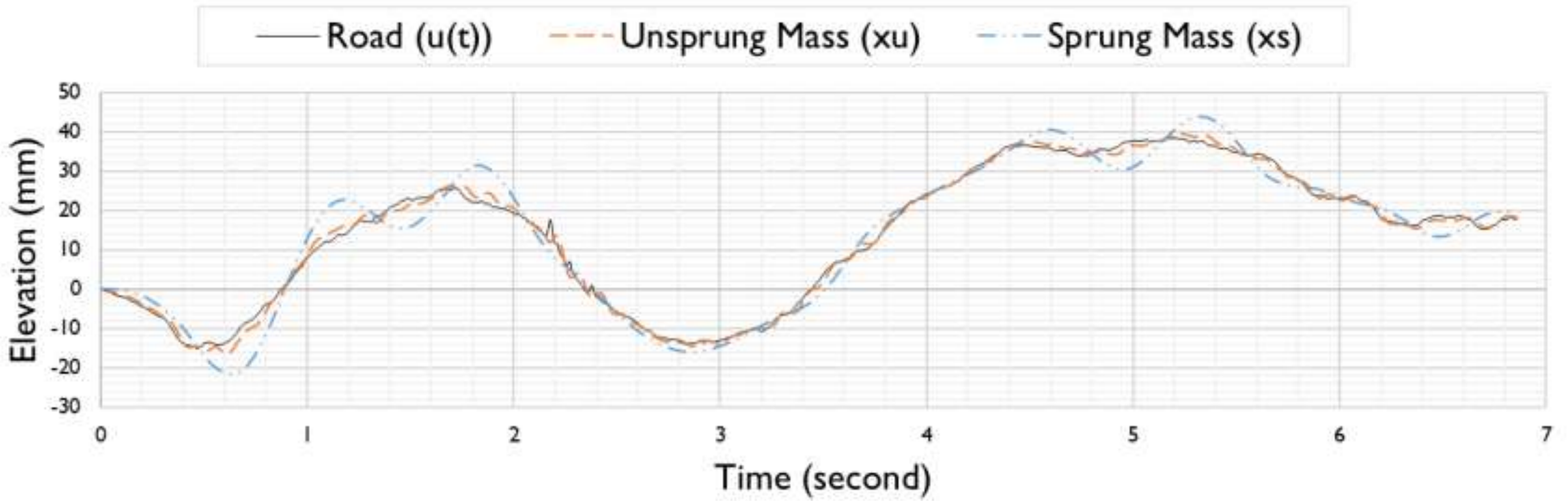
Profile #1: Very Smooth

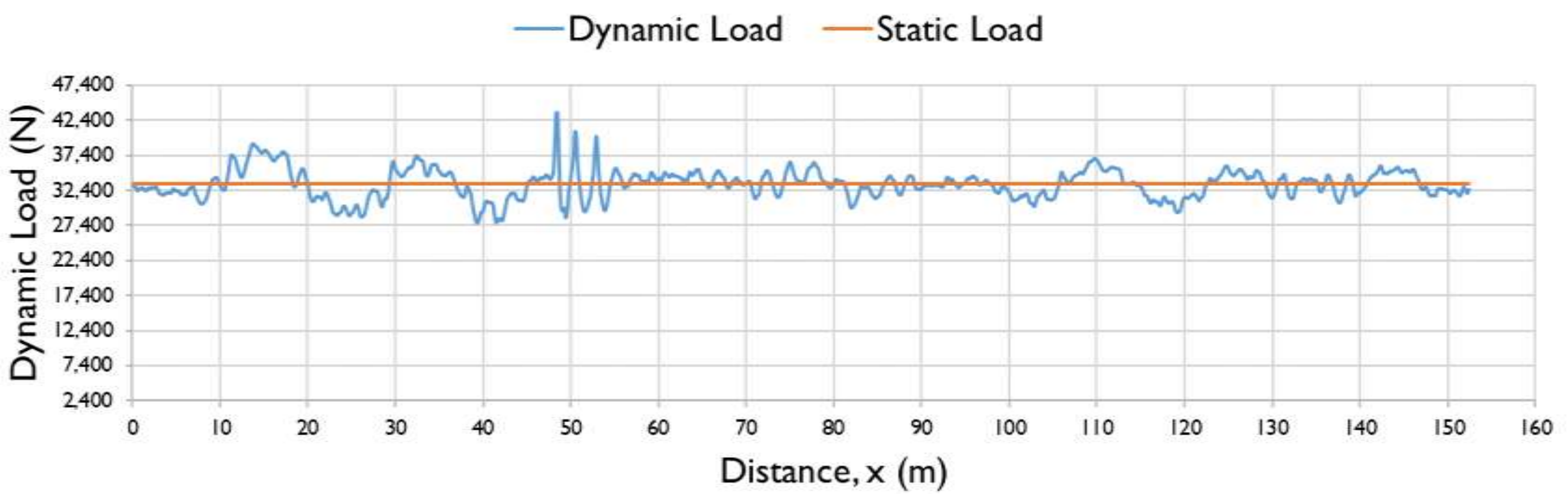




Road Profiles

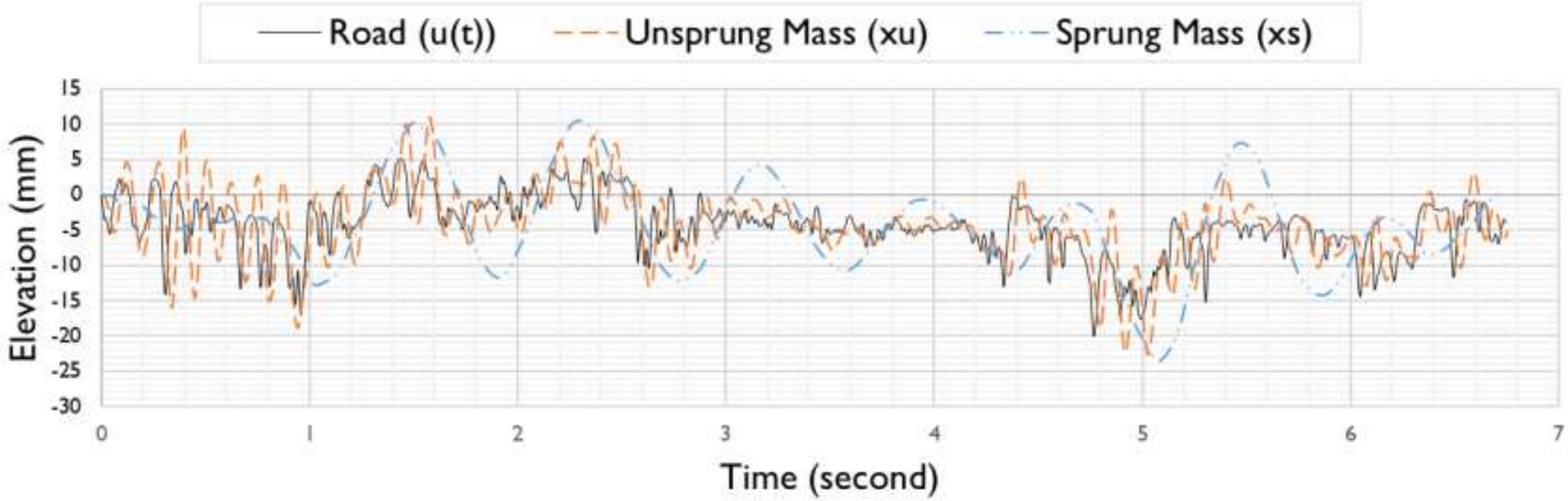
Profile #2: Smooth

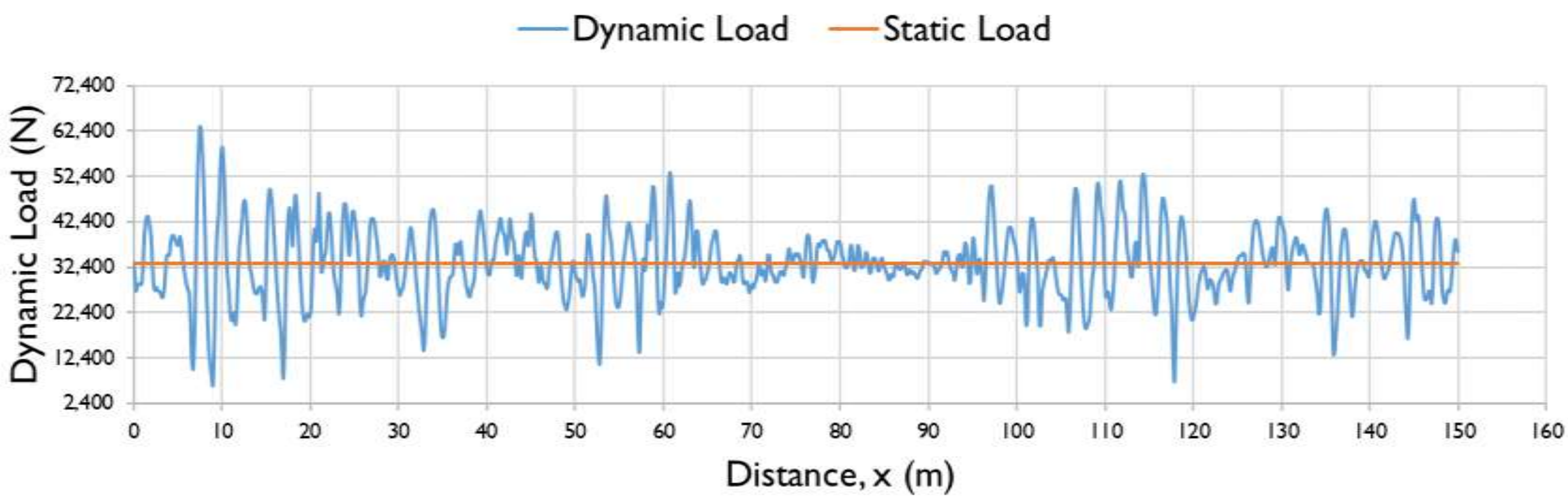




Road Profiles

Profile #3: Rough





Results

Quarter-Truck Simulation

Road Profile ID	IRI	IRI_{TRUCK}	Static Load	Maximum Dynamic Load	DLC	Impact Factor
1	0.499 m/km (31.6 in./mi)	1.017 m/km (64.43 in)		37,237 N (8,371 lbf)	5.2%	0.12
2	0.886 m/km (56.1 in./mi)	1.675 m/km (106.1 in./mi)	33,354 N (7,498 lbf)	43,561 N (9,793 lbf)	6.2%	0.31
3	3.606 m/km (228.5 in./mi)	6.536 m/km (414.1 in./mi)		63,211 N (14,210 lbf)	22.9%	0.90

Results

Pavement Structural Modeling

Road Profile ID	IRI	HMA Thickness	Speed	ε_t Static Load (μs)	ε_t DLC-based (μs)	ε_t IF-based (μs)
1	0.499 m/km (31.6 in./mi)	6 in. (15.2 cm)	50 mph (80 km/h)	132	139	155
		8 in. (20.3 cm)		87	92	102
		10 in. (25.4 cm)		58	61	68
2	0.886 m/km (56.1 in./mi)	6 in. (15.2 cm)		132	140	183
		8 in. (20.3 cm)		87	92	121
		10 in. (25.4 cm)		58	62	80
3	3.606 m/km (228.5 in./mi)	6 in. (15.2 cm)		132	162	307
		8 in. (20.3 cm)		87	107	203
		10 in. (25.4 cm)		58	71	135

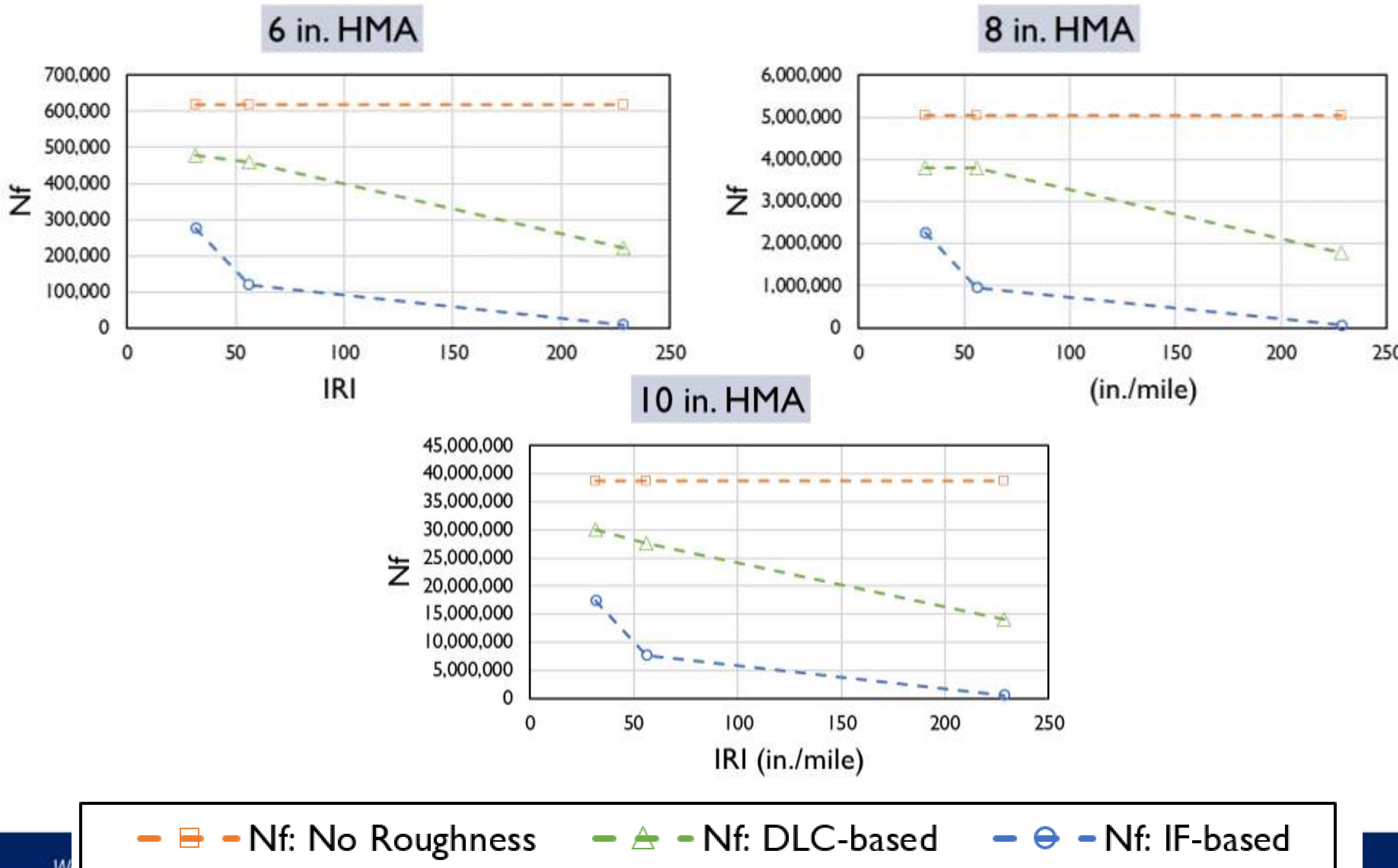
Results

Roughness-Induced Fatigue Life Reduction

Road Profile ID	HMA (in.)	Speed (mph)	N_f Static Load	N_f DLC-based	% N_f Red. DLC-based	N_f IF-based	% N_f Red. IF-based
1	6	50 mph (80 km/h)	619,364	477,644	23%	276,170	55%
1	8		5,039,198	3,804,778	24%	2,264,618	55%
1	10		38,709,605	30,039,141	22%	17,396,114	55%
2	6		619,364	460,734	26%	119,820	81%
2	8		5,039,198	3,804,778	24%	959,317	81%
2	10		38,709,605	27,680,739	28%	7,683,204	80%
3	6		619,364	221,164	64%	8,886	99%
3	8		5,039,198	1,780,273	65%	71,126	99%
3	10		38,709,605	14,001,436	64%	553,184	99%

Results

Fatigue Life vs. Road Roughness Level



Conclusions

- Roughness causes higher dynamic load, which in turn causes shorter fatigue life.
- DLC-based fatigue life analysis revealed ~25% reduction in fatigue life for high smooth and smooth pavements but a larger life reduction of ~65% for rough pavement.
- IF-based fatigue life analysis is very conservative and shows significant life reduction specifically for rough pavement. This may translated into local fatigue failures at locations with high dynamic loads.
- For the analyzed profiles, the reduction percentage in fatigue life due to road roughness is irrespective of pavement structure.

Future Work and Improvements

- Dynamic Models (3D-FAST)
- Effect of Speed and Temperature
- Monte-Carlo Simulations
- IRI model
- Random Profile
- Full-Truck Simulation and/or Miner's rule
- Air and rubber suspension
- Non-linear suspension modeling
- Considering damage accumulation

THANK YOU!

Questions