Impact of Electric Trucks on Flexible Pavement

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Introduction

- Heavy- and medium-duty vehicles were responsible for a 1/3 of GHG emissions in 2022[1]
- Electric trucks can achieve up to 86% reduction in global warming potential[2]
- E-trucks are key in the U.S. goals to reduce GHG emissions by 50% by 2030 to reach net zero by 2050.
- Incentives/ regulations are being provided
  - Federal EV tax credit
  - Climate and Equitable Jobs Act (Illinois)

1. BTS, 2023; 2. Zhou et al., 2023; 3. Harvey et al., 2020

Challenges of HDEVs[1]

- *Technological barriers*: limited range, charging time, and early state of development
- *Financial barriers*: High upfront cost, infrastructure investment, and uncertainty of total cost of ownership
- *Infrastructure limitations*: lack of widespread charging and refueling infrastructure
- *Operational Considerations*: payload constraints

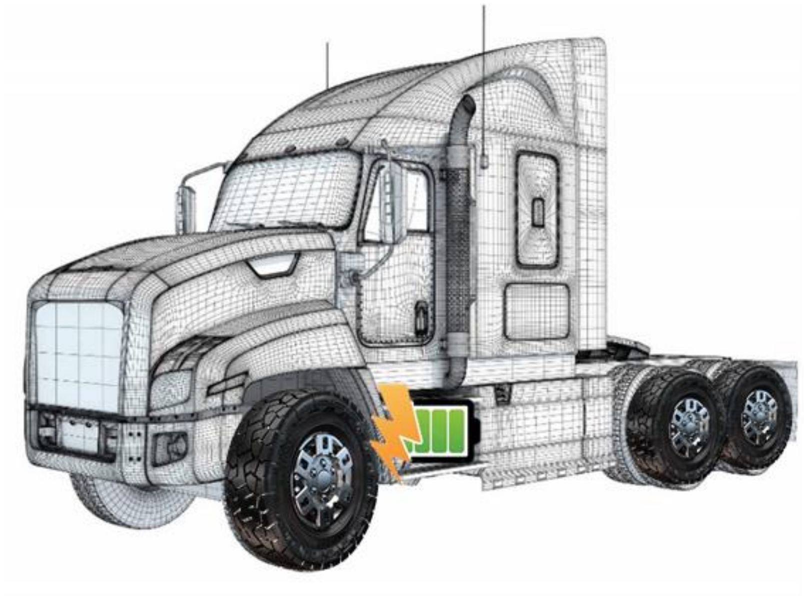
1. Moultak et al., 2017

Impact of HDEV on Pavements

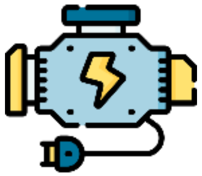
- Extra weight of batteries leads to minimal increase in pavement damage[1]
  - Additional weight of batteries: 2,000 lb
  - Same maximum axle load for EV and ICEV
  - Longitudinal contact stresses not considered
- Based on numerical simulations and AASHTOWare transfer functions, extra battery weight results in a slight difference in IRI projections[2]
- These studies did not include the effect of torque
  - Torque has shown to be relevant for rutting, showing, and near surface shear[3]

1. Harvey et al., 2020
2. Zhou et al., 2023
3. Ameri-Gaznon et al., 1989, Kandhal et al., 1998, Hajj et al., 2007

Heavy-Duty EV Impact on Pavements



Engine	~ 3,000 lb
Gas tank, exhaust, fuel	~ 1,600 lb



600 kWh battery at 250Wh/kg	~ 5,300 lb
for 900kWh @ 160Wh/kg	*~ 12,150 lb*
Electric engine, electronics	~ 1,400 lb
Net extra load for 600 kWh bat.	~ 2,000 lb
for 900 kWh	*~ 9,000 lb*

Objective

- Assess the impact of electric trucks on flexible pavements, focusing on potential changes in IDOT pavement design – asphalt mixture and structure – and management

Evaluate Impact of Torque and Weight of Electric Trucks on Contact Stresses

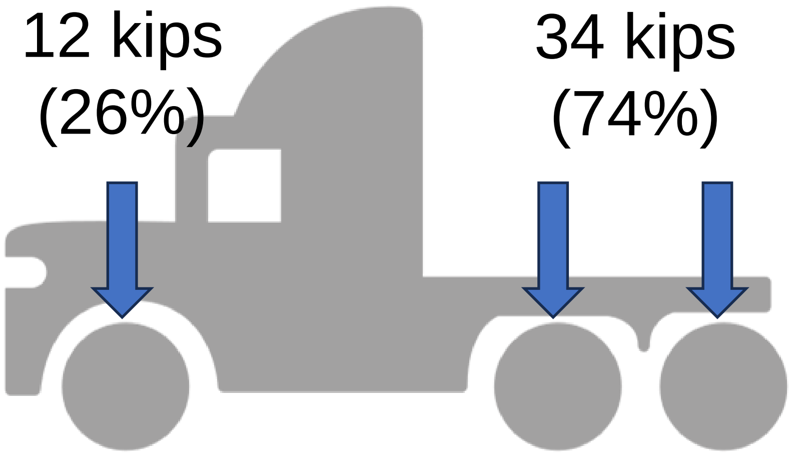
Optimize IDOT HMA Pavements and Develop Numerical Analysis for Flexible Pavements

Develop Guidelines for Potential Modifications of IDOT Pavement Design and Pavement Type Selection

Battery Location

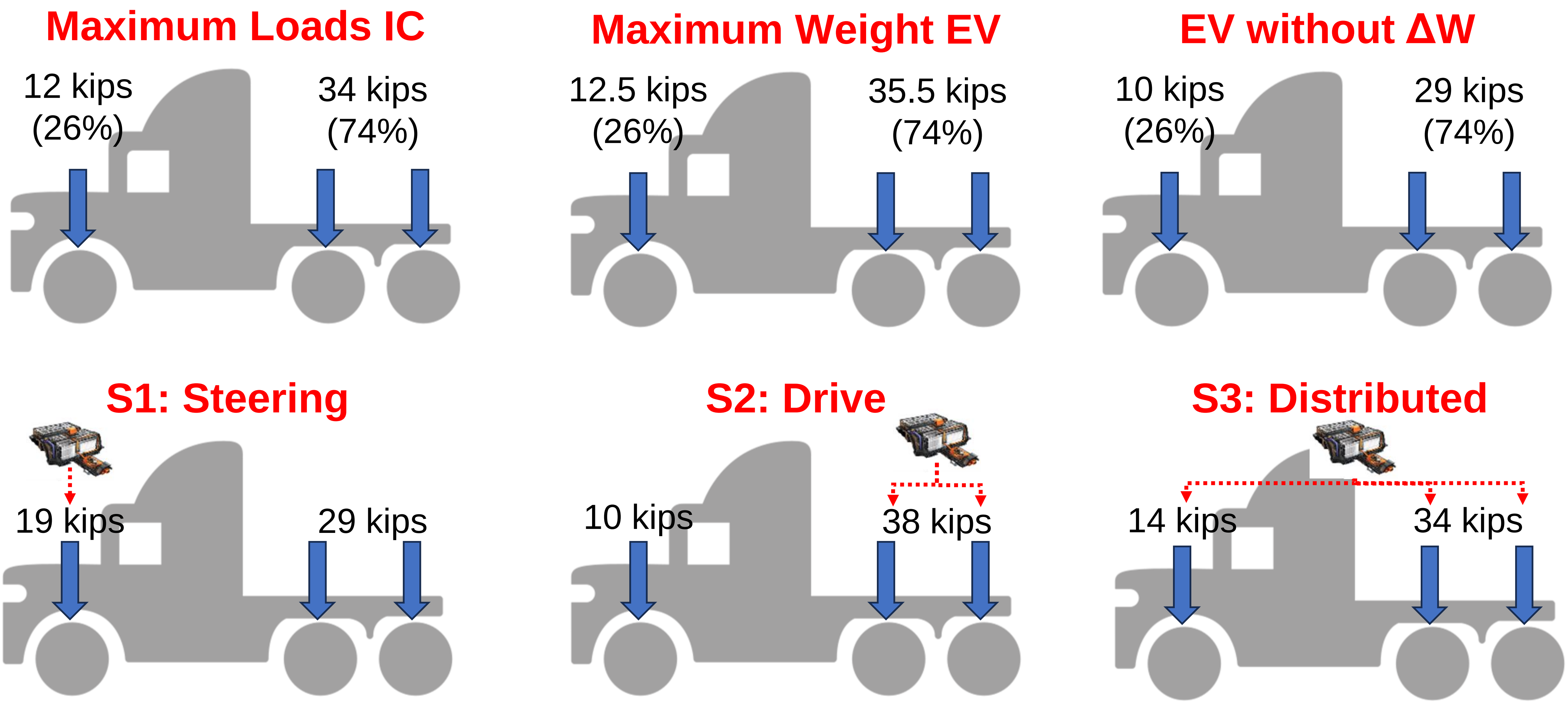
IC: Internal Combustion

Maximum Loads IC



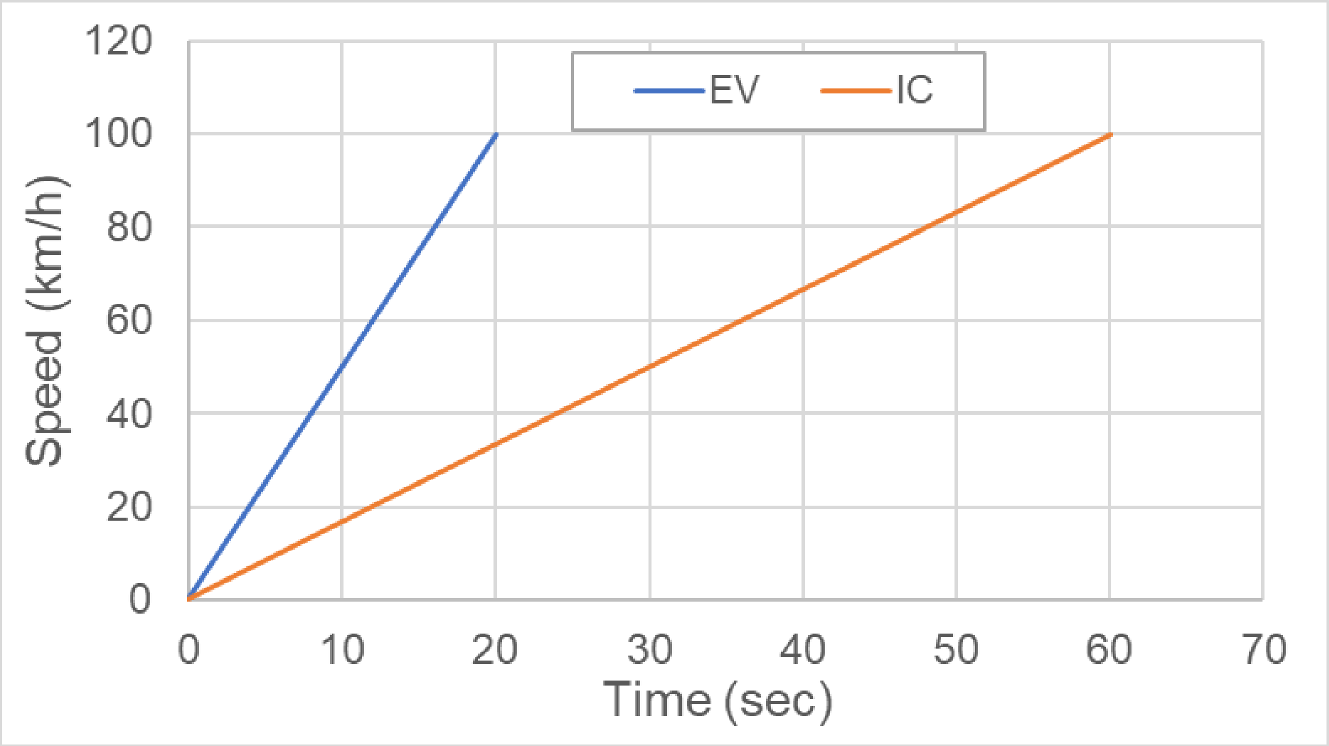
- Allowed extra weight in EV: 2.0 kips → Total tractor weight: 48 kips
- Added weight in EV: 9.0 kips (battery, electric engine, electronics, etc.)

Battery Location



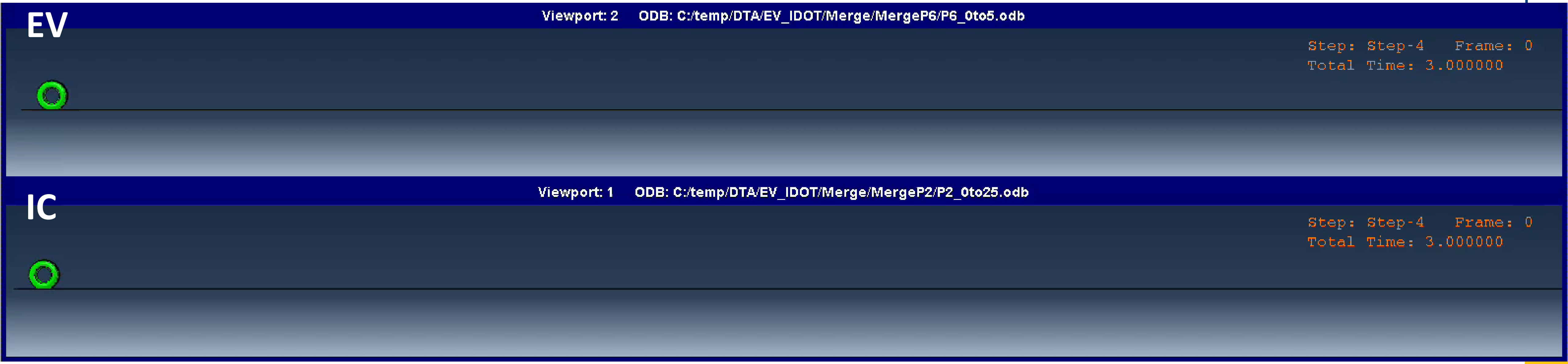
Larger Torque

- Shorter time from 0 to 100 km/h taken as a surrogate of a larger torque



Tire Model

- EV travels a longer distance during the same timespan



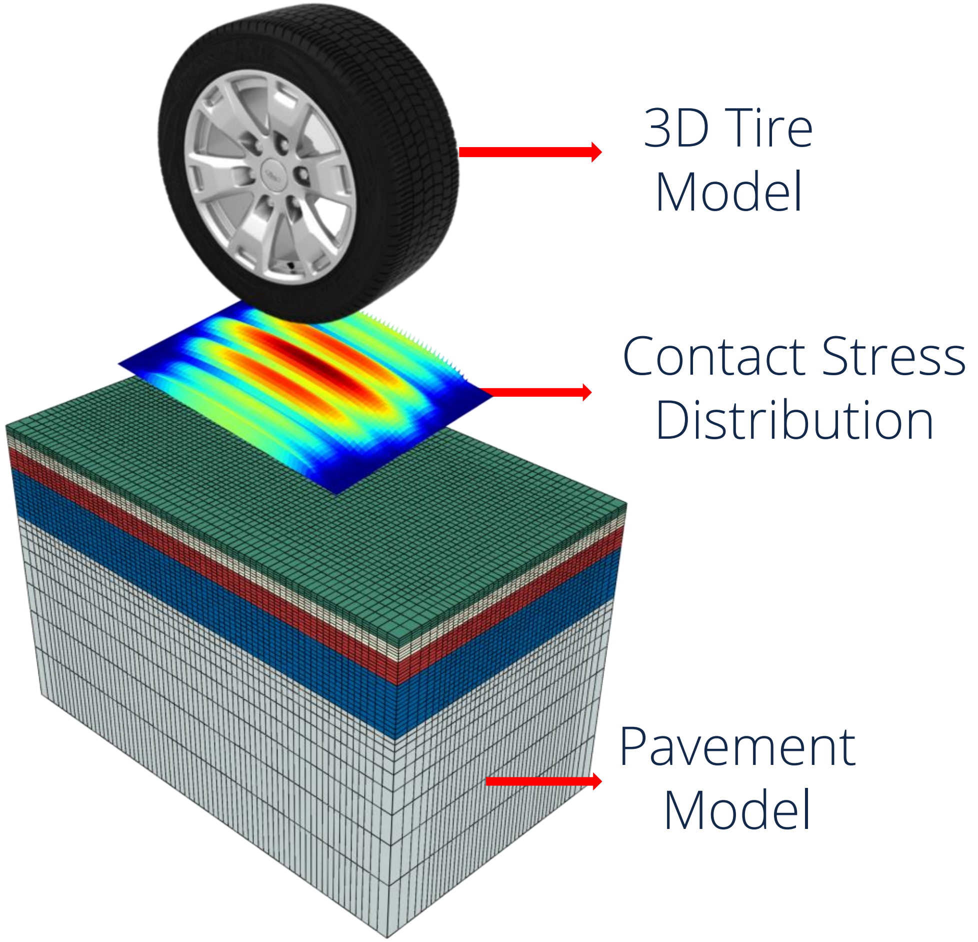
Contact Stresses

- FEM captured the larger torque in HDEV
- Contact stresses are affected by battery location, torque, and slip ratio

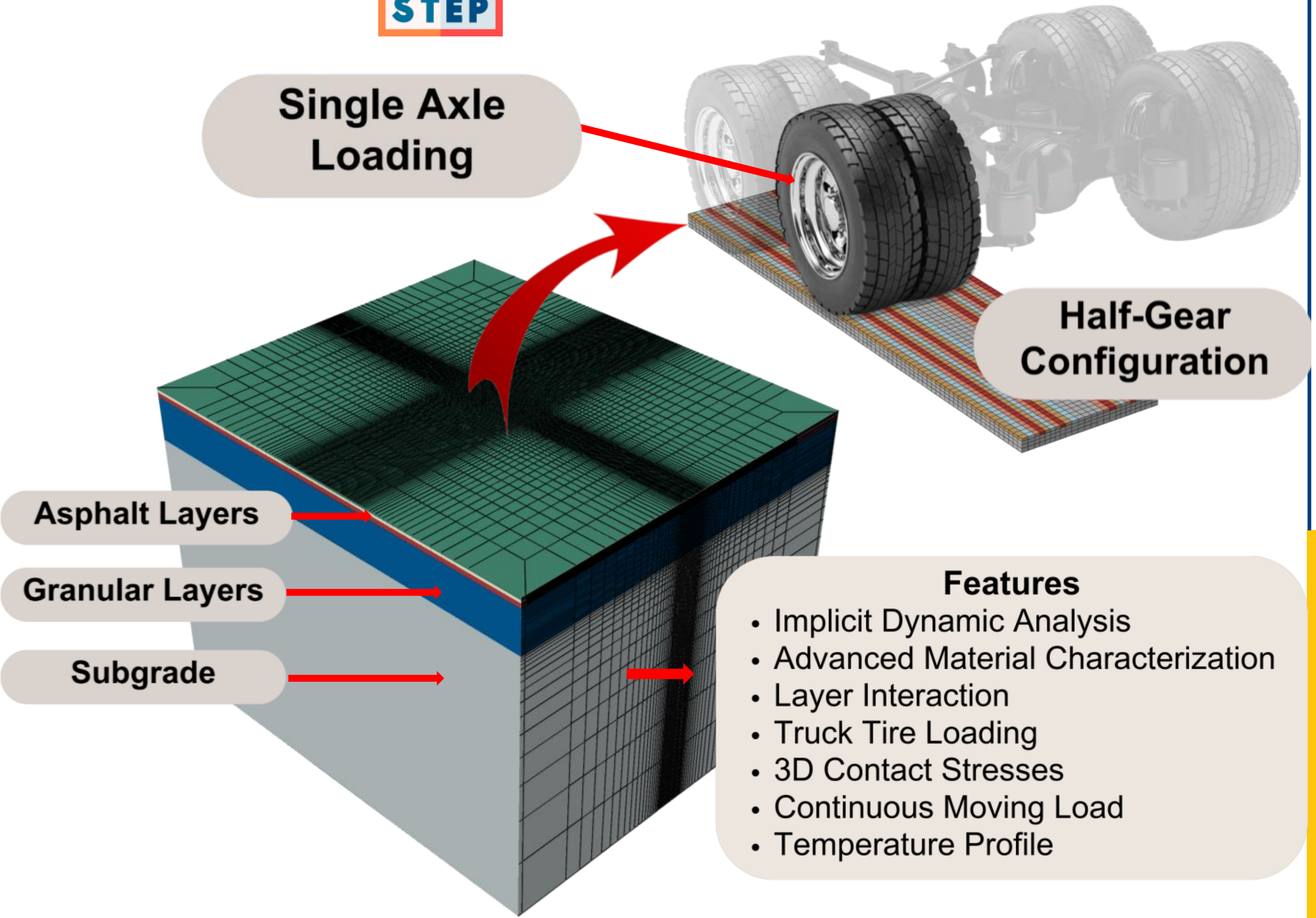
	Vertical	Longitudinal	Transverse
Tire Load (battery location)	↑↑↑	↑	↑↑
Slip ratio	↑	↑↑↑	↓

Pavement Model

1 STEP *Tire Loading Input*

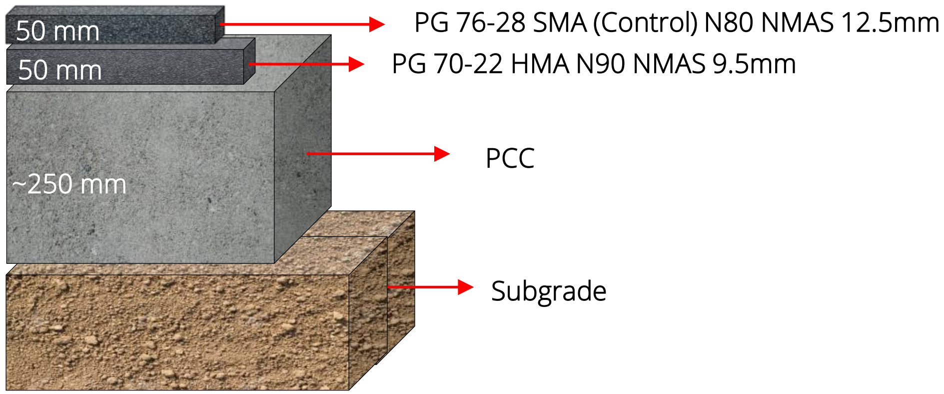


2 STEP *Pavement Model*

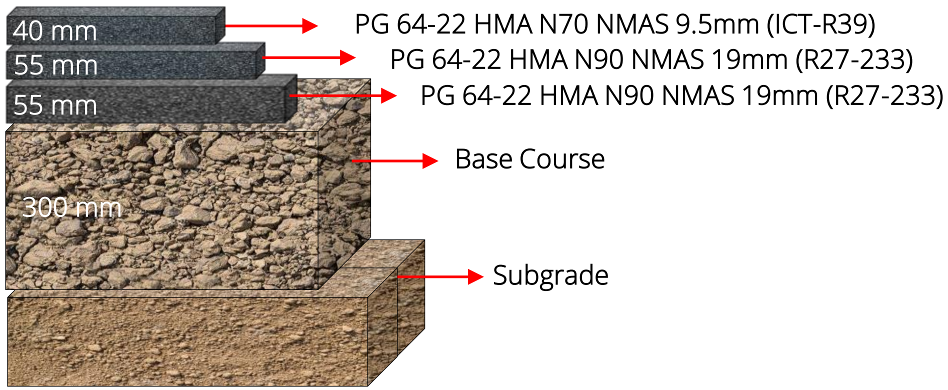


Pavement Sections

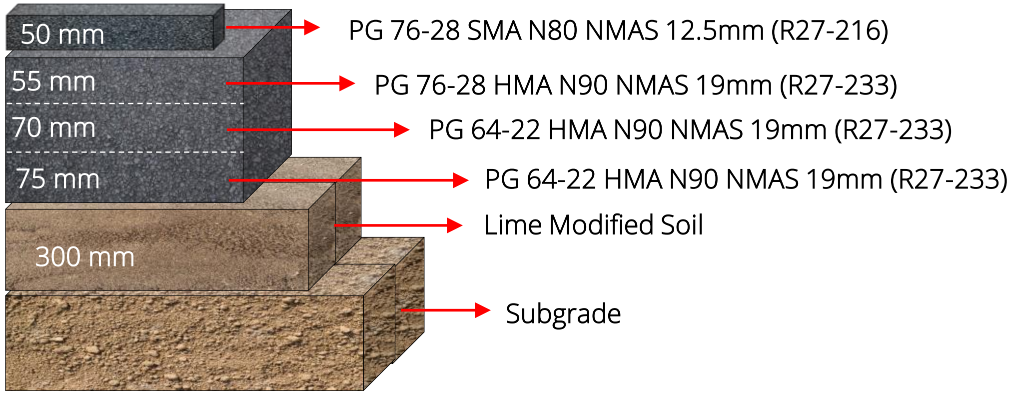
1 SMA Section



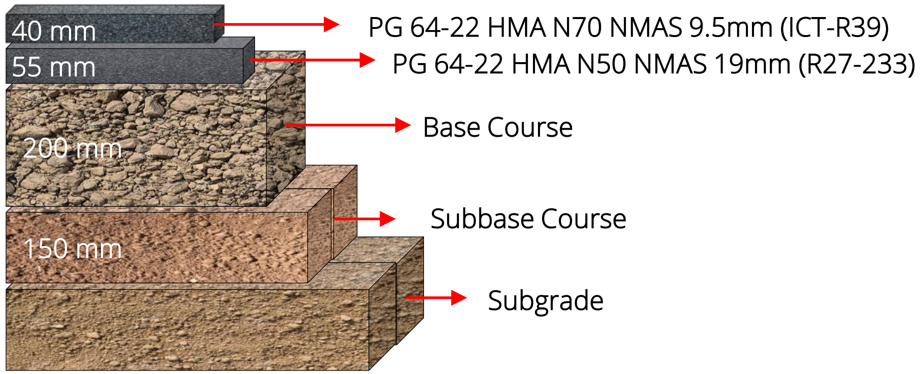
2 Typical "Thick" Section



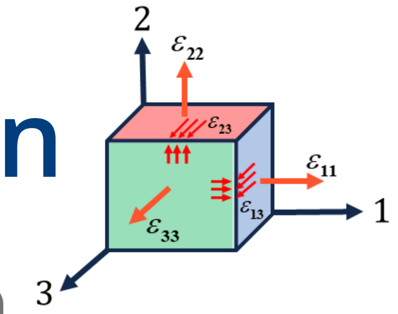
3 Full-depth Section

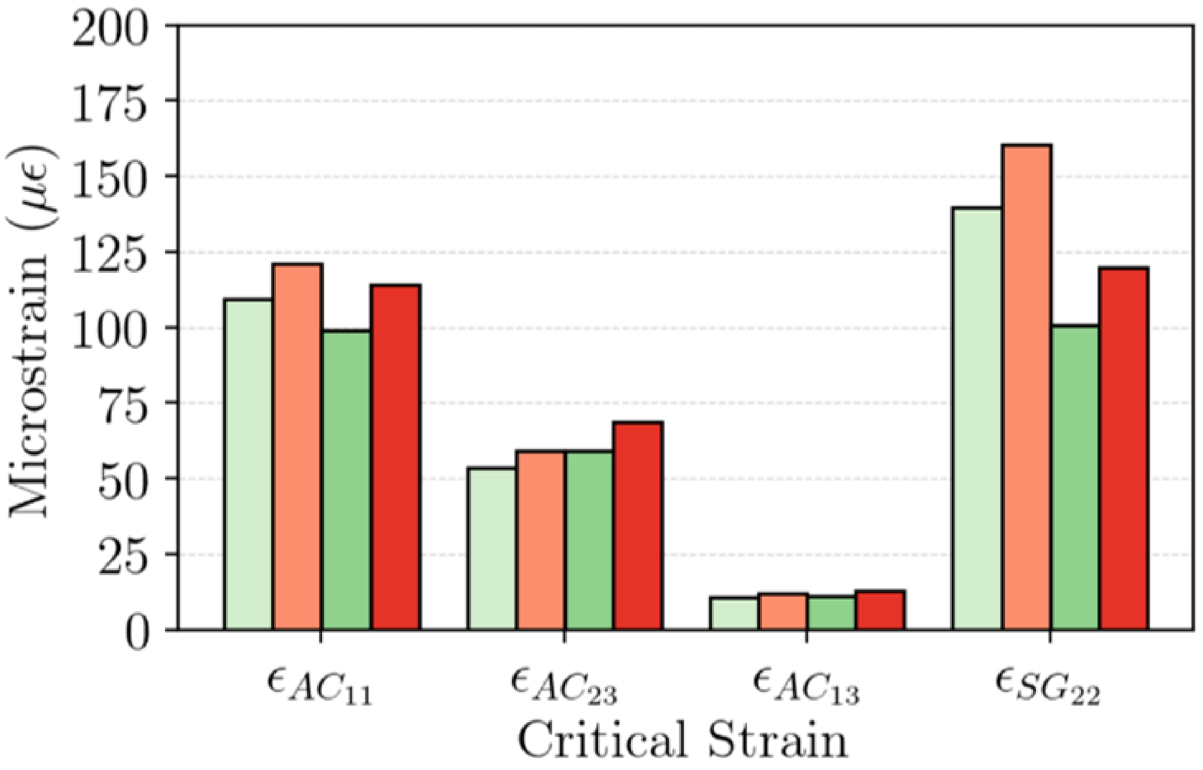


4 Low-volume Section



Pavement Strains – Typical Thick Section





Loading

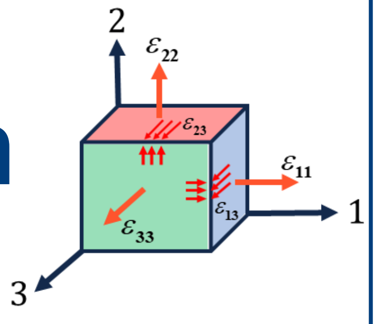
- DIC, 8.4 kips, 0%
- SIC, 6.0 kips, 0%
- DEV, 9.4 kips, 0%
- SEV, 7.0 kips, 0%

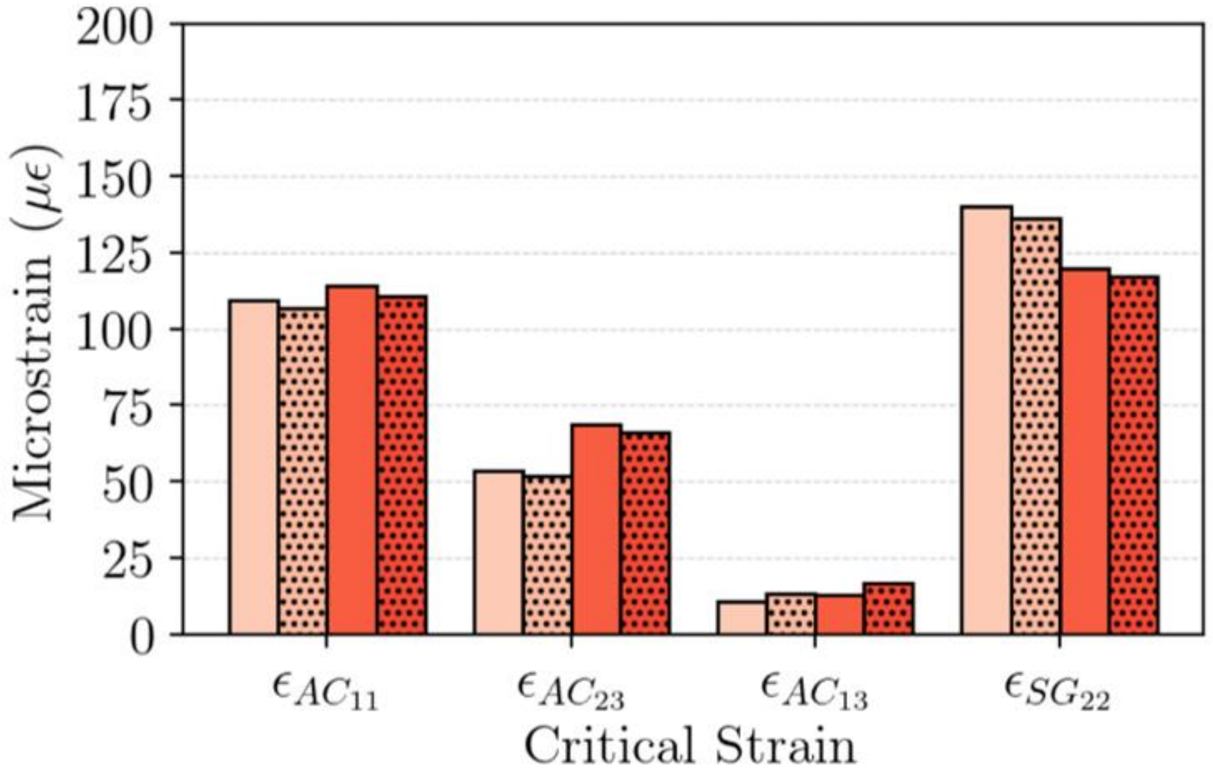
Legend

- S: steer, D: DTA
- IC: internal combustion, EV: electric vehicle

- Increasing the load increased all pavement responses
- Steer axle caused comparable strains to DTA

Pavement Strains – Typical Thick Section





Slip Ratio

- **DEV**, 8.4 kips, 0%
- **DEV,** 8.4 kips, 2%
- **SEV**, 7.0 kips, 0%
- **SEV,** 7.0 kips, 3%

Legend

- S: steer, D: DTA
- IC: internal combustion, EV: electric vehicle

- Slip ratio does not significantly affect most strains in the typical thick pavement section

Load and Slip Ratio Impact – Summary

	SMA Overlay	Typical Pavement	Full Depth	Low Volume
No Slip ratio Increased tire load	Tensile strain ε_{11} at bottom of AC			
	↑	↑↑	↑	↑↑
	Shear strain ε_{23} within AC			
	↑↑	↑	↑↑	↑
	Shear strain ε_{13} within AC			
	↑↑	↑	↑↑	↑
	Compressive strain at top of SG			
	↑	↑	↑	↑
Constant load Increased slip ratio	Tensile strain ε_{11} at bottom of AC			
	↔	↔	↔	↔
	Shear strain ε_{23} within AC			
	↓	↔	↔	↔
	Shear strain ε_{13} within AC			
	↑↑	↑	↑↑	↑
	Compressive strain at top of SG			
	↔	↔	↔	↔

Mechanistic-Empirical Design Approach

- *Transfer Functions*: relate critical pavement response, e.g., strain, to service life via the number of repetitions to failure
- *Number of Repetitions (N_f)*: number of load applications a pavement section can endure before a distress reaches a critical level

Bottom-Up Fatigue Cracking

$$N_{BUFC} = f(\varepsilon_{11_{HMA}})$$

Top-Down Fatigue Cracking

$$N_{TDS} = f(\varepsilon_{23_{AC}})$$

Near-Surface AC Shoving

$$N_{NSS} = f(\varepsilon_{13_{AC}})$$

AC Rutting

$$N_{RUT} = f(\varepsilon_{22_{AC}}, \varepsilon_{22_{BASE}}, \varepsilon_{22_{SG}})$$

Relative Distress Level

- *Distress Ratio (DW):* ratio of the number of repetitions to failure of a specific case to a reference case (DTA, 4.2 kips, 0% SL)

$$DW_{BUFC} = \frac{N_{BUFC}^{case}}{N_{BUFC}^{ref}} \qquad DW_{TDS} = \frac{N_{TDS}^{case}}{N_{TDS}^{ref}} \qquad DW_{RUT} = \frac{N_{RUT}^{case}}{N_{RUT}^{ref}} \qquad DW_{NSS} = \frac{N_{NSS}^{case}}{N_{NSS}^{ref}}$$

- *Cumulative Distress Ratio (CDW):*
  - Weighted combination of various distresses
  - Weights (a_i) are computed based on the inverse, logarithmically scaled N_f of each transfer function.

$$CDW = a_1 DW_{BU} + a_2 DW_{TDS} + a_3 DW_{RUT} + a_4 DW_{NSS}$$

$$a_i = \frac{\frac{1}{\log(N_t)}}{\sum_{j=1}^{5} \frac{1}{\log(N_j)}}$$

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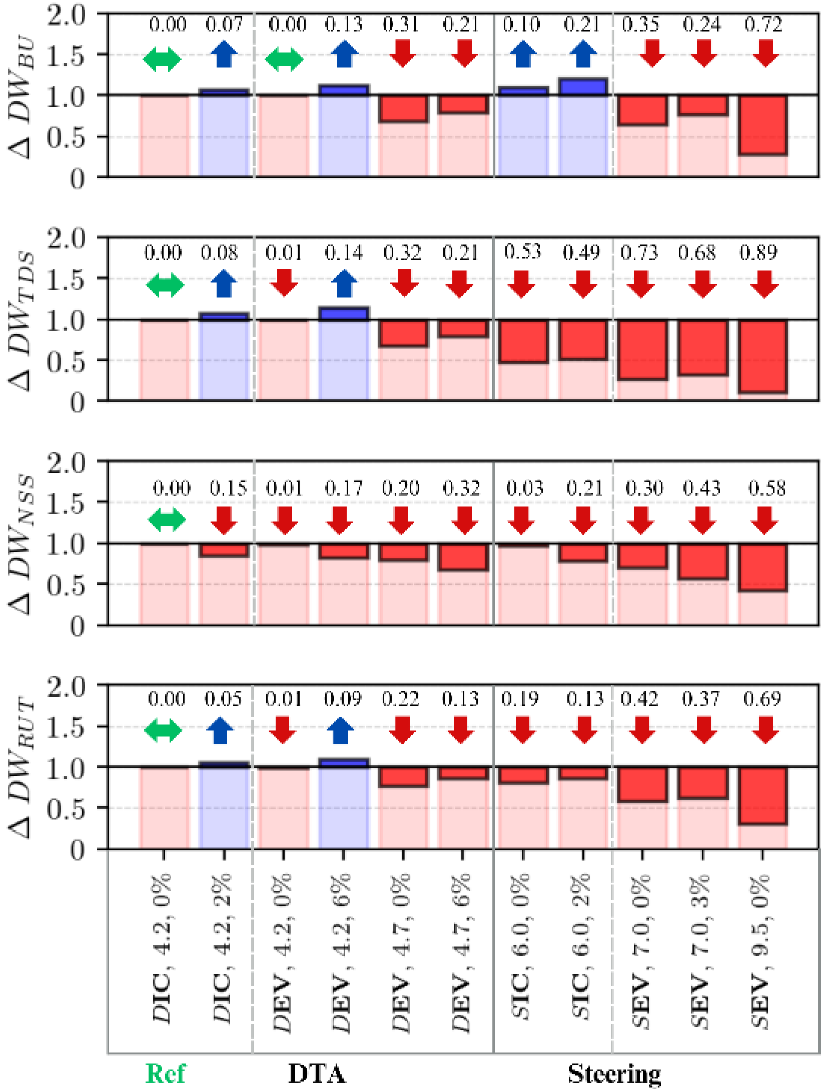
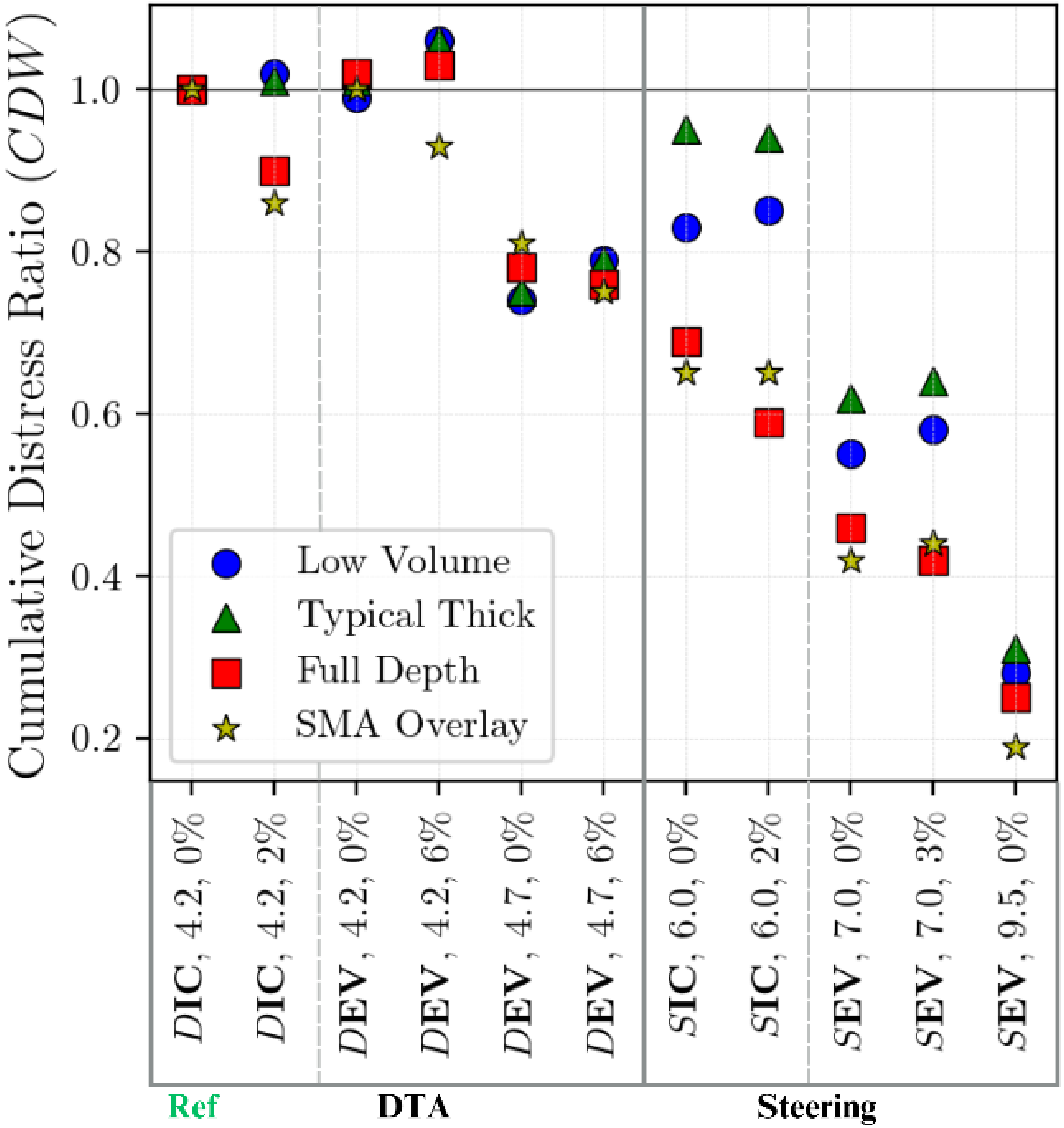
Relative Distress Evaluation - Low-Volume Roads



- Load magnitude governed low-volume pavement DWs
- As load increased, DW decreased
- As slip ratio increased, varied DW per pavement and had low impact in low-volume roads

CDW Summary

- CDW is reduced with increasing load and slip ratio
  - CDW < 1, the more damage
- Typical-thick and low-volume pavements were affected by load (low impact by slip ratio)
- SMA overlay on PCC and full-depth pavements were highly impacted by slip ratio



Final Remarks

- Tire and pavement modeling can successfully combine to study the impact of HDEV on flexible pavements
- The battery location controls the axle load, which is the most relevant factor
- Effect of acceleration is evident on near-surface shear strains
- Increase in shearing at near-surface may increase maintenance/rehab frequency or warrant using shear-resistant materials
- Steer axle induced highest cumulative distress, for all pavements, when battery load is evenly distributed on axles or solely placed on the steer axle

Thank you.

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