Increased Electric Vehicles Induced Damage on Flexible Pavement in Arid Climates

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ABSTRACT: The transition to Electric Vehicles (EVs), particularly in regions like the United Arab Emirates (UAE), presents both environmental benefits and unique challenges for transportation infrastructure. This study examines the impact of heavy-duty EV adoption on flexible pavements in the UAE, where increased axle loads from EV battery weights are expected to accelerate pavement deterioration. Using the Mechanistic-Empirical (ME) design method, the effects of partial replacement of Class 5 Internal Combustion Engine (ICE) vehicles with Class 5 EVs on pavement performance are analyzed. Results indicate that the increased load demands of EVs lead to premature fatigue cracking and a shorter pavement lifespan. Enhanced asphalt mixtures, such as high polymer and rubber-modified binders, were tested to improve pavement durability, showing that both options could extend service life with minimal additional thickness. Findings suggest that while polymer-modified materials provide significant durability improvements, cost-benefit analysis is necessary to optimize binder choice for long-term infrastructure sustainability.

1 INTRODUCTION

The global transition to sustainable transportation is growing, with Electric Vehicles (EVs) emerging as a pivotal alternative to reduce carbon emissions, improve air quality, and address the climate crisis. Many countries, including the United Arab Emirates (UAE), are integrating EVs into their transportation networks as part of broader environmental goals (International Energy Agency, 2023; Seitz et al., 2024). Recognized as a regional leader in e-mobility, the UAE has implemented ambitious strategies, including the UAE Energy Strategy 2050 and the Green Mobility Strategy 2030, to guide the nation toward a sustainable future. These frameworks aim to replace many ICE vehicles with EVs, setting goals for 50% of all vehicles to be electric or hybrid by 2050 (Maddren, 2024; Seitz et al., 2024).

The rapid adoption of EVs presents specific challenges for the UAE's infrastructure, particularly its flexible pavement roads, which are widely used due to their cost-effectiveness and ease of construction. EVs exert unique and often heavier loads on pavement surfaces due to the weight of their battery packs, which can weigh several hundred kilograms. Unlike ICE vehicles, where the load is distributed differently, EVs concentrate greater weight on specific pavement areas (Fares et al., 2024; Zhou et al., 2024). This additional stress can accelerate wear and tear, potentially leading to increased rutting, cracking, and a reduction in pavement lifespan—especially in hot climates like the UAE, where high temperatures exacerbate pavement deterioration (Fares et al., 2024; Seitz et al., 2024).

Given these challenges, it is essential to explore pavement design and material solutions tailored to the demands of EVs. Pavement materials and structural design play a critical role in determining the durability of roads under varying loads and environmental conditions. This study starts by investigating the effects of introducing EVs to the currently used pavement structures in the UAE. Next, solutions to mitigate EV-induced damage on flexible pavements, including using modified asphalt materials for the UAE's unique environment. Additionally, this paper concludes with policy recommendations and regulatory measures that could support the sustainable integration of EVs without compromising infrastructure longevity.

In sum, the UAE's journey toward a sustainable transport sector requires technological and policy advancements and proactive measures to ensure that infrastructure can withstand the evolving demands of EVs. By addressing these concerns, this study aims to contribute to the UAE's vision of a resilient and eco-friendly transportation network, ultimately fostering a sustainable future for the region.

2 METHODOLOGY AND MATERIALS

In this study, a typical pavement section commonly used for high-demand highways is investigated. The actual vehicle class distribution of the road segment (Fig. 1) showed that most vehicles belong to class 5 (Salameh, 2020). Although all classes of the current heavy ICE vehicle fleet are expected to be partially or fully replaced with EVs over time, it is reasonable to assume that significant effects will be noticed when corresponding Class 5 EVs replace Class 5 ICE vehicles. The analysis was performed by replacing a percentage of Class 5 ICE vehicles with the Volvo FL Electric (Volvo, 2024). A 45/55 weight split between the front and rear axles of the Volvo

FL was assumed in the analysis (Fares et al., 2024). Figure 2 represents the difference in weight between a typical Class 5 vehicle with two axles and the Volvo FL Electric.

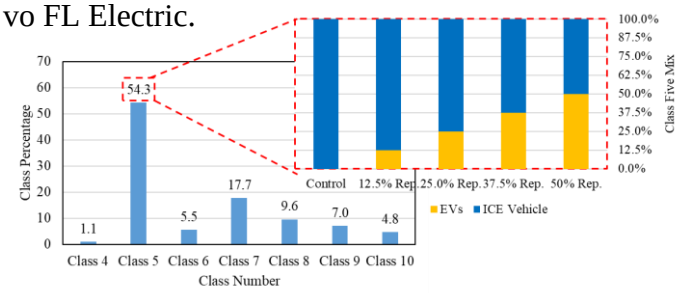

Figure 1. Typical vehicle class distribution in the UAE

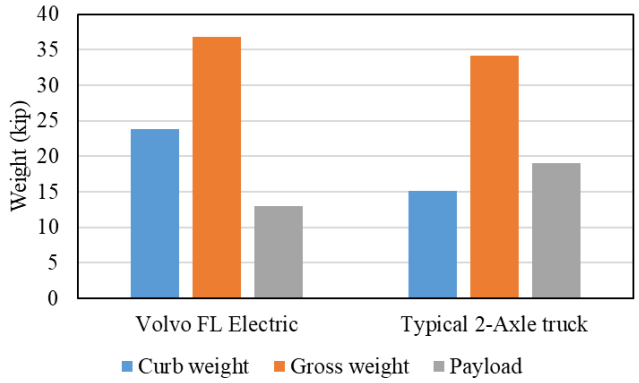

Figure 2. Estimated EVs' weights for Class 5 vehicles.

Table 1 shows the traffic inputs collected for the case study. The Average Annual Daily Truck Traffic (AADTT) is 21,211 vehicles (Salameh, 2020). In the design case, the following scenarios were evaluated:

- Control – All ICE vehicles.
- 12.5% Class 5 replacement: 12.5 % of the Class 5 ICE vehicles (54.3 % of the traffic mix) are replaced with Class 5 Volvo FL EVs.
- 25.0%, 37.5%, & 50.0% Class 5 replacement.

Figure 3 illustrates the cross-section of the pavement structure and the material properties used in the analysis. While the material type for the unbound base and subgrade layers are fixed, the HMA Wearing Course (WC) layer changes as the paper progresses. First, all the scenarios are evaluated using a Dense Graded HMA mixed with a 60/70 Neat Binder (DG-NB). This material is typical for flexible pavements in the UAE. Two more HMAs with the same gradation but different binders are evaluated. The first is a High Polymer Modified Binder (PMB), while the other is a Terminally Blended Rubberized Binder (TBRB) (Ibrahim et al., 2024). Both binders are produced in the UAE and are currently used in a limited number of projects with special performance requirements.

2.1 *NCHRP 1-37A mechanistic-empirical method*

The mechanistic-empirical analysis was conducted using the MEAPA (Mechanistic-Empirical Asphalt Pavement Analysis) web application using the climatic data of the UAE (Kutay & Lanotte, 2020). Asphalt Concrete (AC) rutting and bottom-up fatigue cracking were compared. All these flexible pavement-related distresses were evaluated using the mixture-specific calibration coefficients obtained by conducting Repeated Load Permanent Deformation (RLPD) Testing and Push-Pull (PP) Testing (AASHTO TP 79, 2012; Kutay & Lanotte, 2018). Additionally, the viscoelastic properties of the asphalt binders and mixtures were obtained from laboratory testing (AASHTO M 320-17, 2017; AASHTO TP 79, 2012). Table 2 presents the materials-specific coefficients alongside general inputs for the ME analysis.

Table 1. General traffic input values for the evaluated design case.

General Traffic Input	UAE Design Case
Two-way AADTT	21,211
Number of lanes	2
Trucks in design direction [%]	58
Trucks in design lane [%]	95
Operational speed [km/h]	100
Reliability [%]	95

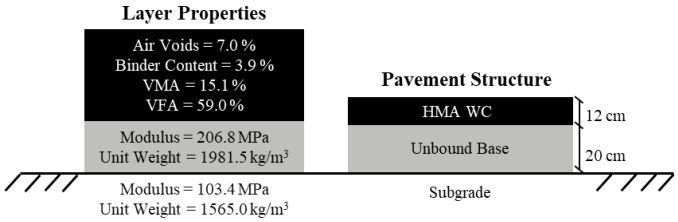

Figure 3. Pavement cross-section and layer properties

Table 2. MEAPA, analysis data input

Parameter	Mix ID		
	DG-NB	DG-TBRB	DG-PMB
Bottom-up fatigue coefficients (β_{r1}, β_{r2}, β_{r3})	(1.43E-5, 1.726, 1.877)	(1.02E-2, 1.671, 2.059)	(5.87E53, 1.749, 1.941)
AC Rutting (β_{r1}, β_{r2}, β_{r3})	(3.00E-3, 1.0, 0.616)	(6.54E-3, 1.0, 0.418)	(8.70E-3, 1.0, 0.357)
General Details	**Value**		
Analysis duration	20 years		
Groundwater table	30.48 meters		
MERRA2 Station Latitude	24.355003		
MERRA2 Station Longitude	54.579152		

3 RESULTS AND DISCUSSION

Figure 4 shows the number of Equivalent Single Axle Loads (ESALs) calculated for all the scenarios analyzed. The values from "All ICE vehicles" are obtained using the traffic information for the pave-

ment structures under evaluation. Hence, they represent the design traffic. The percent increase obtained by replacing 12.5% of Class 5 ICE vehicles with Class 5 EVs is more than 18%. As the replacement percentage increases, the difference can reach more than 70% of the original amount. The causes for this increase are related to the increase of the EV replacement percentage and the higher EV loading that concentrates more towards the front axle.

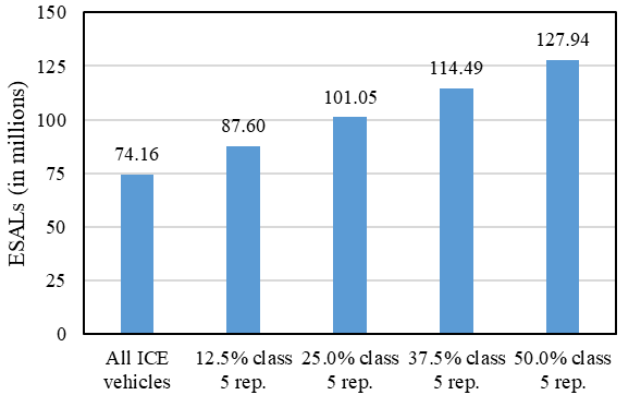

Figure 4. ESAL outcome for each scenario

The ME analysis showed that the leading distress is the bottom-up fatigue cracking (Fig. 5). The analysis indicated minimum rutting (>0.5 mm), which goes along with observations made in the field where design practices suggest the use of a low binder percentage (i.e., 3.9%) to account for the dominant arid climate in the UAE. Meanwhile, it can be noticed that with the "All ICE vehicles" scenario, the pavement structures (with DG-NB) fail within six years of service life. Moreover, the replacement of class 5 vehicles resulted in accelerated failure, with the pavement structure failing within 42 months for the 50% replacement case.

When the wearing course material was changed to PMB and TBRB, results showed that both materials performed significantly better than the currently employed low penetration grade binder (i.e., 60/70). Instead of failing within the first six years, the DG-PMB fails after 15 years, while the DG-TBRB fails after 16 years. This outcome shows that the DG-TBRB outperforms the DG-PMB, which is also reinforced as an outcome when comparing the 50% class 5 replacement, where the DG-TBRB service life extends to 131 months, and the DG-PMB fails within 123 months of service.

Even though using polymer-modified binders could enhance the performance of pavement structures and extend their service life, they have yet to meet a 20-year design life, and optimization of the pavement structure thickness is required.

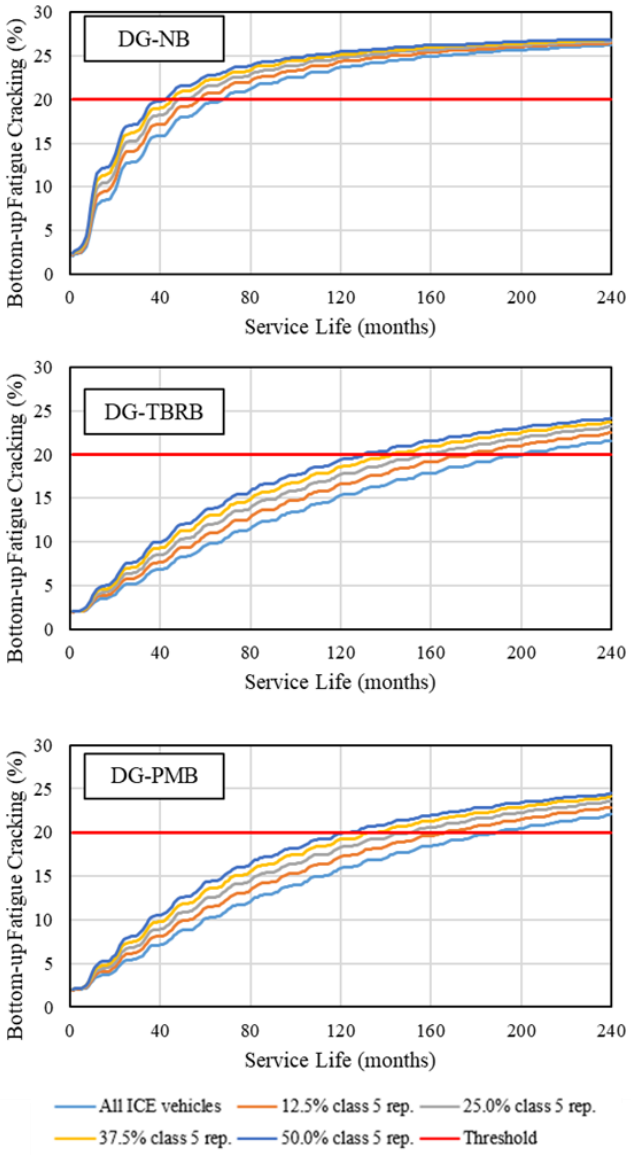

Figure 5. Results of the Mechanistic-Empirical Pavement Structural Analysis

Table 3 presents the pavement cross-section thicknesses for the control scenario and the 50% class 5 replacement.

The outcomes indicate that an increase of 2.5 cm (1 inch) is essential for the DG-NB WC to withstand the full design life, while both the DG-TBRB and -PMB require only an additional 0.5 cm to pass the 20 years of design life with the "All ICE vehicles" scenario. Moreover, for the 50% class 5 replacement, a 16 cm thick wearing course is needed using DG-NB, and 14.5 cm for modified materials. This change in thickness leads to additional costs. Table 3 shows the difference in the expected material cost if the polymer-modified binders are used instead of the neat binder. Due to their higher cost, it can be observed that the DG-PMB costs $1839 per lane per km in comparison to the DG-NB, while the DG-TBRB costs an additional $901 per lane per km. These costs are related to the material costs; however, to obtain a more complete picture, the cost of the

construction and maintenance should be factored into the analysis.

Table 3. Additional material cost due to the 50% class 5 replacement

	DG - NB	**DG - TBRB**	**DG - PMB**
Optimized cross-section thickness (All ICE vehicles) [cm]	14.5	12.5	12.5
Optimized cross-section thickness (50% class 5 rep.) [cm]	16	13.5	13.5
Difference in thickness [cm]	1.5	1.0	1.0
HMA density [kg/m^3]	2528	2513	2527
Mass per lane (3.6 m) per km [ton]	136.5	135.7	136.5
Unit price [$/ton]	60.0	67.0	73.5
Additional Material Cost [$]	8,191	9,092	10,030

4 CONCLUSION

This study evaluates the potential impact of light-duty EVs on road networks. Compared to traditional ICE vehicles, the findings reveal that the increased weight of EVs accelerates pavement deterioration.

The primary design method followed in the UAE is AASHTO 1993. However, previous studies showed the inadequacies of the technique in accurately designing pavement structures (Fares et al., 2024). The ME analysis results indicate that the pavement sections analyzed failed within the first six years for fatigue cracking, which is close to field observations (5 years, fatigue cracking as lead distress) (Marini & Lanotte, 2021).

Replacing class 5 ICE vehicles with class 5 EVs increases the traffic load on the structure. However, the growth is not as significant as in other case studies (e.g., Michigan, Fares et al., 2024) due to the dominant vehicle class being class 5 with lower gross vehicular weight.

The ME analysis showed that the dominant distress is bottom-up fatigue cracking with no asphalt concrete rutting occurring. A balanced mixed design could be used in the region to enhance the fatigue cracking performance but only slightly increase rutting potentials.

The use of PMBs and TBRBs can extend the service life of the pavement structure without changing the thickness of the wearing course layer. Of the two options evaluated, the TBRB is preferable since it slightly overperforms the PMB asphalt mixture.

The optimization of the pavement structure design to serve satisfactorily for 20 years with the EVs present showed that the change of thickness varies between 1.0-1.5 cm compared to the control scenario. The outcome showed that DG-NB would cost less than the other two binders from a material cost point of view, yet the addition of the construction and transportation costs could likely change the outcome where the DG-TBRB can be the best solution (Ibrahim et al., 2024).

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