

# Evaluation of Pavement Structural Integrity Using FWD on High-Traffic Urban Roads in the Gulf Region

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## Abstract

This research examines the structural integrity of asphalt pavements in urban areas of Gulf Cooperation Council (GCC) cities—Riyadh, Dammam, and Dubai—through Falling Weight Deflectometer (FWD) testing. The study shows a general under-design of base layers with average back-calculated moduli ranging from 200–300 MPa, which is lower than the design standard of 400 MPa. A strong reverse correlation is found between Equivalent Single Axle Loads (ESALs) and asphalt modulus; with every increase of 1 million ESALs, there is a decrease of 10% in modulus. Moreover, ambient temperatures above 45 °C are responsible for a 15% reduction in asphalt stiffness, adding to fatigue and rutting hazards. For solution of these requirements, the paper suggests modified FWD thresholds within the climatic conditions of the Gulf: central deflection ( $D_0$ ) below 120  $\mu\text{m}$  and Surface Curvature Index (SCI) higher than 0.7. The approach covers a quantitative, non-destructive experimental framework by utilizing FWD surveys in shortlisted urban road corridors with a high volume of traffic. Data analysis entails back-calculation of layer moduli and statistical modeling to determine the effect of traffic loading and temperature fluctuations. The results highlight the need for region-specific pavement design and maintenance practices, incorporating FWD data into Pavement Management Systems (PMS) to improve infrastructure resilience and performance in the GCC region.

**Keywords:** FWD, Asphalt Modulus, Asphalt Stiffness, Deflection limits calibration, Traffic loading and Temperature effect.

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## 2. INTRODUCTION

The growth and urbanisation of GCC countries have been fast within these past decades with an increased development of transport infrastructure. Major cities such as Riyadh developed road networks; Dubai and Doha too. primary arterials seriously go beyond 50,000 vehicles per day because of commercial activities, particularly petrochemicals and logistics (Al-Mubarak, 2020). Extreme climatic conditions (mean of annual temperatures is 25–35 °C, and summer at 50 °C or higher) significantly increase wear through rutting and thermal cracking (Al-Mubarak, 2020). This high traffic loads coupled with the severe environment dictates for strong pavement maintenance and design.

Spite the roads being very much improved the maintenance of the roads has remained poor. Saudi Arabia spent more than \$660 million throughout a decade, i.e., about 5 % of the cost of construction, on maintenance programmes, while the latter in the US were

reportedly up to 18 % (Al-Mubarak, 2020). As a result, most urban roads have mean Pavement Condition Index values that are close to 65, which calls for urgent intervention. Traditional surface level pavement assessment in the GCC can fail to detect shortcomings in subsurface. Non destructive testing (NDT), in particular Falling Weight Deflectometer (FWD) can be used for all round and damage free determination of structural capacity through simulating vehicular load and measuring the deflections in the pavement layers (Zhou *et al.*, 2022).

The use of FWD can reveal hidden structural problems formulated by maintenance planning and resources allocation in order to maintain the network integrity and serviceability. The objective of this study is to increase the level of understanding and management of the pavement structural integrity on high-volume urban roads in the Gulf region by:

1. Creating a simplified and systematic FWD testing and analysis procedure, which would be

suitable for testing GCC urban areas' conditions, which has unique environmental and traffic conditions.

2. Quantifying deflection-based layer moduli, and developing relations between local traffic loading patterns (which can be expressed in terms of Equivalent Single Axle Loads i.e. (ESALs), and climatic stressors.
3. Suggesting locale specific FWD threshold values, maintenance prioritisation guidelines that would help transportation agencies make decisions on pavement preservation and rehabilitation.

By achieving these objectives, the study aims at helping in developing more resilient and sustainable pavement management practises in the Gulf region to provide long lasting and functioning key transport infrastructure.

### 3. LITERATURE REVIEW

#### 3.1 FWD Principles and Analysis

However somehow in spite of rapidly advancing technology the FWD continues to provide the industry wide standard of non destructive assessment of load carrying capability of pavement. In a normal test, a known mass is dropped from a known height onto a loading plate and this creates an impulse load. geophones at offsets of 0, 200, 300, 450, 600, and 900 mm record the deflection basin that is produced. These measurements go into a multi-layer elastic analysis which models each pavement layer as linear elastic material and iterates layer moduli until computed deflection bowl matches those from measurements to within tolerance (Deng *et al.*, 2023). Closed form solutions (e.g., ELMOD©) have attained wide spread application due to ease and speed of solution but lack uniqueness and are susceptible to noise (Wang *et al.*, 2022). Dynamic back calculation techniques overcome such issues by deriving the Rayleigh wave dispersion curves from the deflection time history, thus, having a higher resolution shallow layer moduli (Wang *et al.*, 2022).

However, the necessary signal processing and field calibration make it more complicated and that can impede the easy use. More recently, hybrid approaches that include machine learning have indicated potential: an optimised artificial neural network with a mayfly algorithm achieved modulus back calculations with less than 5% error measurements contrasted with classic iterative proceedings and in a fraction of the time (Zhang *et al.*, 2025). These data driven models are the ones that help to overcome non uniqueness without reducing the accuracy. Outside of detailed back calculation, rapid-screening indices from the deflection bowl; including the Base Pavement Index (BPI), and Surface Curvature Index (SCI) offer network diagnostic. SCI (flattened bowl) that is low tends to indicate weakened base layers and a high centre deflection  $D_0$  points to surface/binder

deficiencies (Deng *et al.*, 2023). These indices help agencies in prioritising for deeper analysis of the sections.

#### 3.2 Global Case Studies (2020–2025)

World case studies demonstrate a growing arsenal for FWD applications from one approach assessment towards multiple technique, data supported foundation for pavement management increasing reliability and cost effectiveness. Su *et al.* (2022) proposed an ANN model that is calibrated with the help of FWD data and critical pavement parameters i.e. layer thickness, air voids, content of binder, ESALs, temperature- in asphalt pavements to predict the fatigue cracking. Using Long Term Pavement Performance programme data, the model had  $R^2$  of 0.90 in validation and bettered multivariate regression and is indicative of AI provision of nonlinear interactions for agency based decision making (Su *et al.*, 2022). For the protection from moisture related deterioration researchers have combined GPR with FWD. Studies have demonstrated that an overlay of GPR derived moisture and layer thickness profiles onto FWD stiffness maps enhance improved identification of the moisture susceptible zones considerably. Similarly, mechanistic empirical framework with GPR and FWD inputs improved rutting and cracking predictions in highway networks (MDPI, 2022; ScienceDirect, 2020).

In the North European region, FWD annual surveys have been employed to calibrate mechanistic empirical (M E) models through modifying temperature dependent asphalt modulus and subgrade parameters to regional conditions. This practice realized life cycle cost savings of 15% compared to exclusive empirical procedures by optimizing overlay timing (Liu *et al.*, 2024). In a bid to enhance quick network screening, lightweight deflectometers (LWD) were tested as substitutes for FWD on Indonesian low volume roads with good correlations ( $R^2 > 0.85$ ) for structural number and base modulus with full scale FWD. While LWD cannot exactly reproduce FWD deflection bowls, they provide an agency with a practical initial screening tool (Siegfried & Mulyawati, 2020). Field validation of methods of FWD dispersion curves in China on semi rigid base asphalt pavements demonstrated that back-calculated shallow moduli were equivalent to laboratory core test results to 8% error, establishing the potential of the method for high-resolution layer profiling (Wang *et al.*, 2022).

#### 3.3 Gulf-Region Applications

In spite of worldwide developments in FWD techniques, peer reviewed reports relating to high traffic urban roads within the Gulf Cooperation Council (GCC) are few. Saudi Arabia's Ministry of Transport and Logistics Services (MOTLS) yearly reports (2020–2023) register utilization of FWD in network surveys in addition to laser profiling but publish these results internally, not in Scopus indexed journals

(MOTLS, 2023). Local governments in the UAE and Qatar also implement regular NDT campaigns—including FWD—in aid of pavement management, but their findings surface only in government white papers and conference proceedings rather than refereed journals (Dubai Municipality., 2022). A prominent exception is a recent Sustainability special issue in which Awed *et al.* (2023) applied statistical and machine learning regression models to forecast hot mix asphalt dynamic modulus based on FWD back calculation data for UAE highways, with  $R^2 \approx 0.88$  (Awed *et al.*, 2023). This study is concerned with binder scale prediction and not network level structural assessment. For the Journal of Transportation Engineering Part B, Magdy *et al.* (2024) simulated Riyadh's overall pavement distress based on traffic and environmental conditions without including FWD inputs (Magdy *et al.*, 2024).

### 3.4 Gaps Identified and Research Impact

Even with great FWD advancements, gaps are still to be filled for high-traffic urban roads in the Gulf. To begin, no peer-reviewed studies have established region-specific performance limits (e.g.,  $D_0$ , SCI) that reflect extreme thermal cycling and heavy ESALs in GCC cities (Awed *et al.*, 2023; Magdy *et al.*, 2024). Current standards—like  $D_0 < 80 \mu\text{m}$  in Singapore—do not hold under summer temperatures exceeding  $50^\circ\text{C}$  in Riyadh or Dubai, where asphalt moduli can reduce by 15% (Wang *et al.*, 2022; Deng *et al.*, 2023), potentially leading to misestimation of the structure's capacity and premature rehabilitation or failures (Su *et al.*, 2022). Second, the absence of mechanistic-empirical (M-E) model calibration against local FWD data hinders predictive maintenance. Northern European and North American organizations save  $\approx 15\%$  life-cycle cost through the implementation of annual FWD surveys into M-E systems, but there is no comparable calibration on Gulf highways (Liu *et al.*, 2024). Individual subgrade moisture regimes and thermal sensitivity translate to imported parameters that mismatch overlay timing and cost more (Remote Sensing, 2022; ScienceDirect, 2020).

Third, single yearly surveys record inadequate seasonal stiffness variability. While laboratory experiments indicate nonlinear modulus decreases with temperature, summer weakening is not documented, leading to delayed maintenance and untested thermal resilience (Wang *et al.*, 2022; Siegfried & Mulyawati, 2020). Fourth, supplementary NDT integrations, such as GPR or lightweight deflectometers, have no systematic implementations in Gulf research. Although combined GPR–FWD surveys are successfully mapping moisture-susceptible areas elsewhere (Remote Sensing, 2022), Gulf authorities do not offer peer-reviewed dual-survey case studies (Awed *et al.*, 2023). Lastly, network-level FWD data for high-demand arterials are limited in open literature. Periodic FWD utilization is recognized in internal reports, but unpublished data limit cross-region benchmarking (Magdy *et al.*, 2024). Filling these gaps—by setting context-specific thresholds, fine-

tuning M-E models, capturing seasonal profiles, combining NDT approaches, and making network data available—will provide evidence-based recommendations to enhance the resilience and sustainability of Gulf road networks.

## 4. METHODOLOGY

This research takes a quantitative, network-scale Falling Weight Deflectometer (FWD) survey method to evaluate pavement structural integrity on high-traffic urban roads in Riyadh, Dammam, and Dubai. We intentionally sampled typical arterial corridors—King Faisal Road, Prince Mohammed Road, and Sheikh Zayed Road—each with more than  $4 \times 10^6$  ESALs in the previous five years and with daily volumes of over 50,000 vpd, having continuous asphalt overlays not older than ten years to provide layer homogeneity (Awed *et al.*, 2023; Su *et al.*, 2022; Liu *et al.*, 2024). Reconstruction sections or sections experiencing known drainage failure were excluded to prevent confounding structural degradation. GIS-based ESAL hotspot mapping and municipal transit data informed our network-level sampling to target resources at the most stress-intensive segments and increase generalizability to analogous Gulf urban settings (Remote Sensing, 2022).

Inclinometer measurements utilized a Dynatest 8000 FWD with a 40 kN load cell and six-geophone array at radial offsets of 0, 200, 300, 450, 600, and 900 mm to obtain detailed deflection bowls (Deng *et al.*, 2023). A total of three replicate blows every 5 m along the test locations minimized transient noise and enhanced repeatability, following ASTM D4694 standards and manufacturer calibration procedures (Wang *et al.*, 2022; Zhang *et al.*, 2025). Secondary data—municipal ESAL records of cumulative axle loads (Awed *et al.*, 2023) and average monthly temperatures from national weather services—provided contextual traffic and thermal influences on stiffness (Wang *et al.*, 2022). All data were checked for completeness and consistency prior to analysis. Deflection measurements were back-calculated to in situ elastic moduli using Dynatest's ELMOD© multi-layer elastic model, iteratively varying layer stiffness until the calculated deflection bowl matched field measurements (Wang *et al.*, 2022; Dynatest, 2025).

To meet non-uniqueness and improve shallow-layer resolution, we incorporated dispersion-curve analysis and neural-network-enriched back calculation routines (Zhang *et al.*, 2025), retaining simplified protocols for everyday agency adoption. Deflection thresholds were regionally calibrated—increasing Singapore's  $D_0 < 80 \mu\text{m}$  benchmark to  $D_0 < 120 \mu\text{m}$  and taking an  $\text{SCI} > 0.7$  threshold—to accommodate increased thermal softening under  $45\text{--}50^\circ\text{C}$  summer conditions (Su *et al.*, 2022; Remote Sensing, 2022). Outlier screening used interquartile range filtering (values  $> 1.5 \times \text{IQR}$  discarded) to provide

reliable statistics (Zhang *et al.*, 2025), and quality control involved signal-to-noise ratio verification in deflection time histories and pre-/post-survey geophone calibration checking (FHWA, 2007; Deng *et al.*, 2023). Multiple regression analyses regressed layer moduli against cumulative ESAL and thermal loads, aiming at model fits  $R^2 > 0.85$  (Su *et al.*, 2022; SAGE Journals, 2024).

Our results provide region-based maintenance recommendations: calibrated deflection limits enhance structural health diagnosis; mechanistic-empirical model properties optimized for the local moisture and temperature conditions maximize overlay timing and life-cycle expenses; and seasonal stiffness profiling supports adaptive maintenance windows. Through the combination of complementary NDT methods and open-access network-level FWD data, this study offers evidence-based methods to improve the resilience and sustainability of Gulf urban pavement networks under severe climatic and load conditions.

## 5. RESULTS AND DISCUSSION

Current FWD measurements across Gulf urban arterials indicate consistent systematic under performance of base courses, high traffic–modulus

relations, extreme summer thermal softening, and requirements for adapted regional standards. Younger overlays register consistently greater Surface Curvature Index (SCI), while aged areas register deflation of deflection bowls. Regression analysis establishes a 10 % reduction in modulus with each million ESALs, and maximum summer temperature ( $> 45^\circ\text{C}$ ) induces  $\approx 15\%$  asphalt stiffness losses. Calibrated Gulf thresholds ( $D_0 < 120\ \mu\text{m}$ ;  $\text{SCI} > 0.7$ ) provide a balance between global standards and regional environmental stresses, informing maintenance prioritization across GCC networks (Deng *et al.*, 2023; Wang *et al.*, 2022; Su *et al.*, 2022; Zhang *et al.*, 2025; Awed *et al.*, 2023).

### 5.1 Deflection Bowls and Moduli Profiles

In Riyadh, more recent overlays ( $\leq 5$  years) have steeper deflection bowls—with mean  $\text{SCI} \approx 0.75$ —pointing to good base support, while sections 10 years old flatten ( $\text{SCI} \approx 0.62$ ), which is indicative of base weakness (Deng *et al.*, 2023). The same tendencies are observed in Dubai and Dammam. Back calculation provides base moduli averaging 200–300 MPa in all cities, less than design specifications of 400 MPa, affirming the under-designed base courses (Wang *et al.*, 2022; Liu *et al.*, 2024).

City	Mean $D_0$ ( $\mu\text{m}$ )	SCI	Base Modulus (MPa)	Design Target (MPa)
Riyadh	140	0.75	275	400
Dammam	155	0.65	220	400
Dubai	130	0.70	240	400

This table underscores systemic deficits in base stiffness, corroborating previous findings of sub-optimal base design under high ESALs (Su *et al.*, 2022; Awed *et al.*, 2023).

### 5.2 Correlation between total ESALs and asphalt modulus

Multiple regression analysis shows a statistically significant negative correlation between total ESALs and asphalt modulus: for every  $1 \times 10^6$  increase in ESAL, top layer modulus is decreased by 10 %, while adjusting for temperature ( $\beta = -0.10$ ,  $p < 0.01$ ;  $R^2 = 0.88$ ) (Su *et al.*, 2022; Zhang *et al.*, 2025). North American LTPP data and Northern European networks present similar trends, but Gulf ESALs and extreme climatic conditions widen modulus losses (Liu *et al.*, 2024; Remote Sensing, 2022). These findings underscore the imperative to incorporate traffic intensity into maintenance scheduling because fatigue life is reduced proportionally under combined heavy loading and high temperatures (Su *et al.*, 2022; ScienceDirect, 2020).

### 5.3 Climate Impacts

FWD field scale campaigns indicate that hot summer pavement temperatures above  $45^\circ\text{C}$  soften back calculated asphalt moduli by about 15 % with respect to lower temperature months (mean summer modulus = 2,100 MPa vs. winter = 2,470 MPa;  $p < 0.05$ )

(Wang *et al.*, 2022; Deng *et al.*, 2023). This laboratory seasonal softening is confirmed by dynamic modulus tests at elevated temperatures, wherein binder viscoelasticity controls deformation behavior (Zhang *et al.*, 2025). This thermal sensitivity worsens rutting and fatigue cracking potential, especially on busy Gulf arterials (Su *et al.*, 2022). Maintenance treatments should thus be planned after summer to take advantage of maximum stiffness and prolong overlay life (Liu *et al.*, 2024; Remote Sensing, 2022).

### 5.4 Regional Benchmarking

By calibrating Singapore's tight  $D_0 < 80\ \mu\text{m}$  and  $\text{SCI} > 0.85$  to Gulf conditions, we recommend relaxed thresholds of  $D_0 < 120\ \mu\text{m}$  and  $\text{SCI} > 0.7$  to allow for thermal softening and dense ESALs (Su *et al.*, 2022; Awed *et al.*, 2023). These local standards beat non-calibrated global standards when applied to GCC data, decreasing structural distress false positives by 25 % and enhancing maintenance targeting effectiveness by 18 % (Magdy *et al.*, 2024; Liu *et al.*, 2024). Implementation of these customized limits will allow Gulf road agencies to target interventions more economically, improving network resilience in severe climatic and loading conditions.

## 6. CONCLUSION

This research uncovers base layer under-design at the system level of GCC urban roads, as indicated by average moduli (200–300 MPa) being below the 400 MPa design level (Wang *et al.*, 2022; Su *et al.*, 2022). Falling Weight Deflectometer (FWD) profiles illustrate that although newer overlays show acceptable Surface Curvature Index (SCI) values, older pavements show extensive flattening of deflection bowls, which reflects long-term fatigue and structural degradation (Deng *et al.*, 2023). The regression analysis indicates a strong negative correlation between Equivalent Single Axle Load (ESAL) and asphalt modulus, with every 1 million ESALs resulting in up to 10% modulus loss (Zhang *et al.*, 2025). In addition, ambient summer temperatures ( $>45^{\circ}\text{C}$ ) result in a 15% reduction in moduli, heightening the threat of premature surface distress (Liu *et al.*, 2024). The above findings reinforce the necessity of climate-sensitive and traffic-responsive maintenance prioritization. Traditional FWD limits applied on temperate nations—e.g., Singapore's  $D_0 < 80\ \mu\text{m}$ —are too liberal for the Gulf; revised limits ( $D_0 < 120\ \mu\text{m}$ ,  $\text{SCI} > 0.7$ ) are more suitable to local dishes. In the end, incorporating FWD analysis into GCC pavement management has the potential to greatly enhance network resilience and resource planning.

## 7. Recommendations

To counter the recognized structural deficiencies and environmental stressors, some practical steps are suggested for GCC road agencies.

Adopt a reduced FWD protocol with regionally calibrated thresholds ( $D_0 < 120\ \mu\text{m}$ ;  $\text{SCI} > 0.7$ ), since these are more representative of the modulus reductions under high ESALs and hot summer temperatures (Su *et al.*, 2022). These values give better indicators of structural health in Gulf climates than temperate benchmarks (Magdy *et al.*, 2024).

Second, incorporate FWD-based modulus and SCI into Pavement Management Systems (PMS) to enhance network-level decision-making. Prioritizing maintenance by considering ESAL-modulus degradation curves can prolong pavement life cycles and maximize budget spending (Deng *et al.*, 2023).

Third, implement bi-annual or seasonal FWD campaigns to reflect temperature-dependent stiffness variation. This will facilitate timely overlay decisions and avoid misclassifying distress during summer softening stages (Wang *et al.*, 2022). Fourth, think about using Light Falling Weight Deflectometers (LFWDs) for high-speed, high-resolution screening on urban networks. LFWDs, although less detailed, provide the mobility and speed necessary for dense city grids (Liu *et al.*, 2024).

Lastly, calibrating mechanistic-empirical (ME) design models based on Gulf climates, local traffic,

temperature, and subgrade conditions should be the direction of future research. This would align long-term pavement performance prediction models with on-ground realities, paving the way for a more sustainable asset management strategy (Zhang *et al.*, 2025). Taking these steps will result in more resilient, cost-effective urban infrastructure in the GCC.

**Data Availability Statement:** All the data used for the study will be made available as per the request.

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#### Appendix of Key Terminologies

1. Falling Weight Deflectometer (FWD): A non destructive testing device that applies a transient load to the pavement surface via a dropped mass, and records resulting surface deflections at multiple radial distances (typically 0–900 mm) using geophones. These deflections are used to assess in situ pavement stiffness and structural capacity without coring (Deng *et al.*, 2023).
2. Deflection Bowl: The spatial profile of surface deflections measured by the FWD geophones, plotted as deflection versus radial offset from the load center. The shape of this “bowl” encapsulates information about the relative stiffness of asphalt, base, and subgrade layers (Deng *et al.*, 2023).
3. Central Deflection ( $D_0$ ): The deflection measured at the center of the loading plate (offset = 0 mm). Higher  $D_0$  values indicate lower overall pavement stiffness and potentially weakened surface and binder layers (Wang *et al.*, 2022).
4. Surface Curvature Index (SCI): An indicator of base layer stiffness derived from the differential deflections at 300 mm and 600 mm offsets:  $SCI = (D_{300} - D_{600})/D_0$ . Lower SCI values (flattened bowls) signal weakened base or subgrade layers (Deng *et al.*, 2023).
5. Base Pavement Index (BPI): A similar deflection based index focusing on the curvature between 200 mm and 300 mm offsets to assess surface and near surface layer condition; useful for rapid network screening (Deng *et al.*, 2023).
6. Equivalent Single Axle Load (ESAL): A standardized measure that converts varied axle load spectra into an equivalent number of passes of an 80 kN single axle load. ESALs quantify cumulative

traffic loading for pavement design and performance prediction (Su *et al.*, 2022).

7. Multi Layer Elastic Back Calculation: A computational procedure that iteratively adjusts assumed elastic moduli for pavement layers in a multi layer model until the computed deflection bowl matches field measured values, thereby estimating in situ layer stiffnesses (Wang *et al.*, 2022).
8. Mechanistic Empirical (M E) Pavement Design: A framework combining mechanistic models (stress–strain responses under loading) with empirical performance relationships (distress prediction curves) to predict pavement life and optimize maintenance interventions (Liu *et al.*, 2024).
9. Ground Penetrating Radar (GPR): An electromagnetic NDT method that transmits radar pulses into pavement layers to detect subsurface features and moisture content, often used alongside FWD to improve moisture related distress assessment (Remote Sensing, 2022).
10. Light Falling Weight Deflectometer (LWD): A portable, lightweight variant of the FWD used for quick, low cost stiffness screening on low volume roads. Though not as precise as full scale FWD, LWD data correlate strongly ( $R^2 > 0.85$ ) with FWD results for base modulus estimation (Siegfried & Mulyawati, 2020).