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Research Article

A Novel Shannon Entropy Approach and Interface Computer Calculators for the Diagnosis of Highway Pavement Performance (Pavement Entropy Index — PEI)

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Abstract

Road pavement condition assessment is a fundamental component of highway asset management, underpinning decisions related to maintenance scheduling, resource allocation, and infrastructure investment. Existing methods — including the Pavement Condition Index (PCI), the International Roughness Index (IRI), rutting measurement, deflection testing, and automated distress detection — each provide valuable but inherently partial perspectives on pavement performance. A persistent limitation of these methods is their reliance on scalar metrics, empirical thresholds, and — in the case of visual survey techniques — subjective human judgement, none of which offer a theoretically grounded framework for characterizing the complexity or disorder of pavement deterioration. This paper proposes an original approach for the individual and integrated quantitative evaluation of road pavement condition based on Shannon information entropy. Rooted in information theory, entropy provides a mathematically rigorous measure of disorder and uncertainty that is directly applicable to the multi-dimensional, stochastic nature of pavement degradation. The proposed framework introduces a suite of entropy-based indices covering distress diversity, roughness profile complexity, rut pattern irregularity, crack network structure, and structural non-uniformity, which interface systematically with each of the established assessment methods. These component indices are synthesised into the Pavement Entropy Index (PEI) through a hierarchical weighted model. The framework is applied to three categories of case studies: flexible (asphalt) pavements, rigid (concrete) pavements, and transport infrastructure earthworks. Specific interactive digital calculators implementing the framework have also been developed with the aid of AI.

Keywords

Shannon Entropy, Pavement Condition Index, Road Pavements, Road Deterioration, Integrated Assessment, Pavement Entropy Index (PEI)

1. Introduction

The physical condition of road pavements deteriorates progressively under the combined influence of traffic loading, environmental exposure, and material ageing. Effective management of this deterioration requires timely, accurate, and objective condition data upon which decisions regarding maintenance interventions, rehabilitation strategies, and capital investment are ultimately based. The quality and theoretical rigour of condition assessment methods therefore have direct implications for the ef-

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ficiency of road network management and for the long-term performance of transport infrastructure.

A diverse array of standardised assessment methods has been developed and deployed by highway agencies worldwide. These include visual survey-based indices such as the Pavement Condition Index (PCI) and the Pavement Surface Evaluation and Rating (PASER) system, kinematic measurements such as the International Roughness Index (IRI) and transverse rutting, structural evaluation by means of Falling Weight Deflectometer (FWD) testing, and increasingly, automated high-speed imaging and machine learning-based distress detection systems. While each of these methods provides useful information within its respective domain, they share a common conceptual limitation: their outputs are scalar metrics or empirical indices describing observable pavement states without reference to any underlying physical or information-theoretic framework governing the deterioration process.

This paper presents a novel approach to pavement condition evaluation grounded in Shannon information entropy. In the present context, entropy is interpreted as a quantitative measure of the disorder, complexity, and unpredictability of a pavement system's condition state. The central hypothesis is that pavement deterioration constitutes an entropy-increasing process: as a pavement progresses from a newly constructed, well-ordered state towards failure, the diversity, spatial irregularity, and pattern complexity of its distress characteristics increase correspondingly. By interfacing entropy-based indices with each of the principal existing assessment methods, the proposed framework aims to transform current condition cataloguing into a physics-informed approach to pavement degradation science.

The framework is demonstrated through illustrative case studies in infrastructure domains — flexible (asphalt) pavements (Chapter 4), chosen to highlight different aspects of the entropy approach and its diagnostic capabilities.

2. State of the Art: Road Pavement Condition Evaluation Methods

2.1. Review of Principal Assessment Methods

The following methods represent the most widely adopted approaches to pavement condition investigation in current international practice. Each is reviewed with respect to its origin, measurement principle, and key operational characteristics.

a. Pavement Condition Index (PCI) — ASTM D6433

Developed by the US Army Corps of Engineers in the 1970s and standardised [1] under ASTM D6433, the PCI quantifies pavement condition on a scale from 0 (failed) to 100 (perfect). Trained inspectors identify up to nineteen distress types, classifying each by type, severity (low, medium, high), and areal density. Standardised deduct value curves yield the composite score. The method applies [3, 4, 6, 15], to both asphalt and concrete surfaces with separate deduct value sets.

b. International Roughness Index (IRI)

Developed by the World Bank in the 1980s, the IRI [8-10], quantifies longitudinal profile quality by simulating the dynamic response of a reference quarter-car traversing the measured profile, expressed in m/km. Thresholds range from less than 2.0 m/km (very good) to greater than 8.0 m/km (very poor). Measurement uses high-speed inertial profilers or laser profilometers. For concrete pavements, the IRI is sensitive to faulting at transverse joints and slab curl, providing a functional complement to structural assessments.

c. Rutting (Flexible Pavements)

Permanent transverse deformation in the wheel path is measured as maximum depth relative to an idealised profile. Methods range from manual straightedge readings to automated laser profilers. Rutting is primarily a flexible pavement distress [14, 15]; rigid pavements exhibit slab rocking, pumping, and corner breaks rather than true rutting, though differential settlement of concrete slabs may produce analogous transverse irregularity.

d. PASER and Visual Rating Systems

Simplified visual rating systems such as PASER (University of Wisconsin, 1–10 scale) serve network-level screening for both flexible and rigid pavements. They are inherently subjective but cost-effective for large networks with limited survey resources.

e. Automated Distress Detection

High-speed imaging, 3D laser scanning, ground-penetrating radar (GPR), and AI/ML classification systems provide objective, high-speed distress data. For concrete pavements, specialised detection of joint deterioration, delamination, and map cracking is particularly valuable. GPR enables non-destructive assessment of slab thickness, void detection beneath slabs, and subsurface moisture in earthwork layers.

f. Deflection Testing — FWD

The FWD applies a controlled impulse load and measures the resulting deflection basin across a geophone array. For flexible pavements, back-calculation yields asphalt, base, and subgrade moduli [3, 15]. For concrete pavements [6, 7], the FWD characterises load transfer efficiency (LTE) at transverse joints and identifies voids beneath slabs. For earthworks, deflection measurements assess compaction quality and bearing capacity of embankment fill layers.

g. Specific Methods for Concrete Pavements

Concrete pavement assessment employs additional techniques beyond those applicable to flexible pavements: ground-penetrating radar for delamination and void detection; sounding (chain drag or hammer tap) to identify debonded areas; load transfer efficiency measurement by FWD across transverse joints (LTE% = d_unloaded/d_loaded × 100); and Profilograph or inertial profiler measurement of faulting at joints and cracks.

h. Earthwork and Subgrade Assessment Methods

Transport infrastructure earthworks — embankments, cuttings, and subgrade formations — are assessed through a distinct methodology encompassing: dynamic cone penetrometer

(DCP) for in-situ CBR estimation; light weight deflectometer (LWD) for surface modulus [7, 15]; nuclear density gauge or sand replacement for compaction verification; settlement monitoring for embankments on compressible subsoils; and slope stability assessment for high embankments and cuttings.

Table 1. Assessment methods and their applicability across pavement types.

Method	Applicability	Output metric	Principal limitation
PCI	Flexible & rigid	0–100 index	Subjective, labour-intensive
IRI	Flexible & rigid	m/km (scalar)	No transverse or structural data
Rutting	Flexible (primary)	Depth (mm)	Not applicable to rigid pavements
FWD	Flexible, rigid & earthworks	Deflection basin (μm)	Lane closure, point measurement
LTE (FWD)	Rigid pavements	Percentage (%)	Rigid pavements only
GPR	All pavement types	Subsurface profile	Interpretation expertise required
DCP / LWD	Earthworks & subgrade	CBR / E (MPa)	Near-surface layers only
Automated imaging	Flexible & rigid	Distress maps	High cost, no structural data

2.2. Key Limitations of Current Methods

1) Labour intensity and cost. Manual survey methods require significant resources and are expensive at high spatial resolution across large networks.
2) Subjectivity. Visual methods depend on inspector judgement, introducing inter-rater variability that compromises trend analysis.
3) Incompleteness of scalar metrics. Methods such as IRI reduce complex profile information to a single value, discarding diagnostically significant spatial structure.
4) No unified cross-domain framework. Surface, functional, and structural condition are assessed by different methods with incommensurable metrics and no common theoretical language.
5) Limited predictive capacity. Existing indices are predominantly descriptive rather than prognostic, providing no principled basis for deterioration trajectory modelling.

2.3. Gaps Addressable by an Entropy-based Approach

Table 2. Research gaps motivating the proposed entropy framework.

Research gaps motivating the proposed entropy framework
Objectivity: Mathematical entropy computation eliminates the subjective element of visual assessment.
Complexity capture: Entropy quantifies diversity, spatial irregularity, and pattern complexity — dimensions invisible to scalar indices.
Predictive potential: Entropy rate dH/dt provides a principled basis for deterioration forecasting and remaining service life estimation.
Multi-method integration: Entropy provides a common information-theoretic currency enabling outputs from disparate methods to be combined.
Cross-pavement-type applicability: The entropy formulation is mathematically independent of pavement type, enabling consistent application to flexible, rigid, and earthwork structures.

3. Interfacing Shannon Entropy with Traditional Pavement Assessment Methods

Shannon entropy [11], quantifies the uncertainty or disorder of a probability distribution over a set of possible outcomes. For a discrete random variable X with probability mass function p(x_i):

$$H(X) = -\Sigma\, p(x_i) \cdot \log_2 p(x_i)$$

H is zero when one outcome is certain (perfect order) and $\log_2(n)$ when all n states are equally probable (maximum disorder). In the pavement context, a new pavement is a low-entropy, ordered system; deterioration produces increasing distress diversity, spatial heterogeneity, and structural variability — all manifestations of increasing entropy. Pavement degradation is therefore an entropy-increasing process, analogous to thermodynamic systems transitioning from ordered to disordered states.

3.1. Interface with PCI

Three independent entropy measures are derived from PCI survey data. The distress type diversity entropy H_type characterises the breadth of distress mechanisms:

$$H\_type = -\Sigma\, p(i) \cdot \log_2 p(i) \; [p(i) = \text{area of distress type } i \,/\, \text{total area}]$$

The severity distribution entropy H_severity describes the distribution across severity levels, and the spatial distribution entropy H_spatial quantifies clustering versus dispersion across survey grid cells. The composite Entropy Condition Index is:

$$ECI = \alpha \cdot H\_type + \beta \cdot H\_severity + \gamma \cdot H\_spatial$$

3.2. Interface with IRI

Three complementary entropy measures extend the IRI: H_amplitude (frequency distribution of discretised elevation values), H_spectrum (Fourier power spectral entropy across wavelength bands), and H_variability (distribution of IRI values across successive measurement segments). The entropy rate dH/dt provides predictive information beyond static IRI trend analysis.

$$H\_IRI = ⅓\,(H\_variability + H\_spectrum + H\_amplitude)$$

3.3. Interface with Rutting

H_profile captures transverse shape complexity; H_pattern quantifies the distribution of identified failure mechanisms; H_progression measures the entropy of rut depth increment magnitudes across successive surveys, distinguishing steady from irregular accumulation.

$$H\_RUTTING = ⅓\,(H\_profile + H\_pattern + H\_progression)$$

3.4. Interface with Automated Distress Detection

H_texture is derived from the grey-level co-occurrence matrix (GLCM) of pavement surface images. H_orientation quantifies directional distribution of crack segments — thermal cracking yields low entropy; fatigue cracking yields high entropy. H_length characterises crack dimension distribution. Multi-scale analysis at macro, meso, and micro levels reveals the entropy cascade of progressive degradation.

$$H\_DISTRESS = ⅓\,(H\_texture + H\_orientation + H\_length)$$

3.5. Interface with FWD

H_basin quantifies deflection basin shape complexity; H_structure characterises the distribution of back-calculated layer moduli. For rigid pavements, load transfer efficiency variation across joints provides an additional entropy source; for earthworks, variability of compaction modulus along the formation provides H_compaction.

$$H\_FWD = ⅓\,(H\_basin + H\_structure + H\_spatial)$$

Table 3. Entropy components and their physical interpretation for each assessment method.

Method	Entropy components	Physical interpretation
PCI	H_type, H_severity, H_spatial	Distress diversity, severity spread, spatial clustering
IRI	H_variability, H_spectrum, H_amplitude	Roughness uniformity, wavelength composition, profile amplitude
Rutting	H_profile, H_pattern, H_progression	Transverse shape, failure mechanism mix, temporal irregularity
Distress detection	H_texture, H_orientation, H_length	Image disorder, crack direction spread, dimension distribution

Method	Entropy components	Physical interpretation
FWD	H_basin, H_structure, H_spatial	Basin shape, modulus variability, longitudinal structural uniformity

4. Flexible Pavements — Case Studies

Flexible (asphalt) pavements represent the predominant pavement type on road networks worldwide [7, 15], characterised by a multi-layer system in which the asphalt surfacing and base layers distribute applied wheel loads to the underlying subbase and subgrade. Their characteristic deterioration mechanisms — fatigue cracking, rutting, ravelling, and moisture-related damage — produce the full spectrum of distress diversity [2, 13], that the entropy framework is designed to capture. Three case studies are presented, each drawn from well-documented field conditions, to illustrate different aspects of the entropy approach.

4.1. Case Study CS-F1: High-traffic Urban Arterial — Fatigue-dominated Deterioration

4.1.1. Section Description and Condition Context

This case study concerns a heavily trafficked urban arterial road section of 500 m length, subject to an Annual Average Daily Traffic (AADT) of approximately 35,000 vehicles with 12% heavy goods vehicles. The pavement structure comprises a 60 mm asphalt concrete surface course, 100 mm dense bitumen macadam binder course, 200 mm crusher run limestone base, and 300 mm granular subbase on a clay subgrade. The section has been in service for 14 years without major rehabilitation.

Visual inspection reveals extensive fatigue (alligator) cracking covering approximately 55% of the wheel-path areas, with widespread medium and high severity. Longitudinal cracking is present at 35% area coverage along the lane edges. Transverse cracking accounts for approximately 10% coverage at medium severity. Rutting in both wheel paths averages 18 mm with a maximum of 24 mm. The IRI, measured by laser profilometer at 100 m intervals, ranges from 4.8 to 9.3 m/km along the section. FWD testing at 50 m intervals reveals deflection basin curvature indices indicative of weakened bound layers, with back-calculated asphaltmoduli ranging from 1,200 to 4,800 MPa, reflecting significant stiffness variability attributable to cracking and moisture ingress.

4.1.2. Entropy Analysis

The entropy analysis of CS-F1 is conducted across all five assessment domains. For the PCI analysis, the dominant distress is fatigue cracking (p = 0.55), followed by longitudinal cracking (p = 0.35) and transverse cracking (p = 0.10), yielding a moderate distress type entropy of H_type = 1.41 bits. The high proportion of medium and high severity distresses produces H_severity = 0.96 bits, and the spatially dispersed character of fatigue cracking across the wheel paths yields H_spatial = 1.86 bits. The composite ECI reflects significant disorder.

IRI analysis reveals high H_variability = 2.15 bits (reflecting the broad spread of segment IRI values across the condition scale), H_spectrum = 1.98 bits (indicating multi-wavelength roughness without a single dominant cause), and H_amplitude = 1.87 bits. The high wavelength spectrum entropy is diagnostically significant: it indicates that roughness energy is broadly distributed across wavelength bands, consistent with general structural deterioration rather than a localised cause such as differential settlement.

Rutting entropy analysis yields H_profile = 1.72 bits (reflecting asymmetric, variable rut depth profiles), H_pattern = 1.45 bits (dominance of load-related and material instability mechanisms in roughly equal measure), and H_progression = 1.58 bits (based on recorded annual survey data showing non-linear rut depth accumulation, indicative of accelerating deformation). The elevated H_progression value is of particular diagnostic significance, signalling that the section has entered an accelerating failure phase.

__Table 4.__ CS-F1 entropy analysis summary. H_total/H_max = 0.73 places this section firmly in Stage 3.

CS-F1: Entropy Analysis Summary — Urban Arterial, Fatigue-Dominated		
Entropy Component	**Value (bits)**	**Interpretation**
H_PCI	1.96 bits	High distress diversity; multi-mechanism degradation confirmed
H_IRI	2.00 bits	Broadband roughness; general structural deterioration
H_RUTTING	1.58 bits	Accelerating progression; mixed load + material failure

CS-F1: Entropy Analysis Summary — Urban Arterial, Fatigue-Dominated

Entropy Component	Value (bits)	Interpretation
H_DISTRESS	2.11 bits	High image texture entropy; random fatigue crack orientation
H_FWD	1.89 bits	High modulus variability; widespread bound layer damage
H_total	1.91 bits	Composite; normalised disorder = 73%

H_total / H_max = 73% of H_max → Deterioration Stage: Stage 3: Acceleration — Rehabilitation planning required

4.1.3. Diagnostic Interpretation

The entropy signature of CS-F1 is characteristic of advanced fatigue-dominated deterioration: high H_orientation (random crack directions confirming fatigue rather than thermal origin), high H_spatial (dispersed rather than localised cracking), high H_spectrum (broadband roughness), and elevated H_progression (non-linear rut accumulation). The normalised disorder ratio of 73% places this section in Stage 3 (Acceleration), consistent with the observed 14-year service history and the documented shift from moderate to severe distress in the most recent survey cycle.

The high H_structure value from FWD analysis (reflecting a six-fold range in back-calculated asphalt modulus) is a particularly important diagnostic indicator: it reveals that stiffness loss is spatially heterogeneous, with intact bound material adjacent to severely cracked zones. This pattern is consistent with moisture-accelerated fatigue damage originating at crack entry points, propagating laterally at a rate dependent on local drainage conditions and traffic channelling. A conventional PCI-only assessment would characterise this section simply as ‘very poor condition’ without distinguishing between the specific mechanisms or their spatial distribution — information that is critical for optimising the rehabilitation design.

The recommended intervention is full-depth reclamation (FDR) or structural overlay with crack suppression fabric, targeting the wheel-path zones of highest spatial entropy as the primary failure loci.

4.2. Case Study CS-F2: Rural Primary Road — Stage 2 Propagation with Thermal Cracking

4.2.1. Section Description

This case study addresses a rural primary road section of 1,000 m length in a continental climate subject to significant seasonal temperature variation (−25°C to +35°C). AADT is approximately 4,500 vehicles with 8% heavy vehicles. The pavement structure is a thin-surfaced treatment comprising a 40 mm asphalt surface course on 150 mm granular base, with a granular subbase on a sandy subgrade. The section has been in service for 9 years.

Condition data indicate predominantly transverse thermal cracking at approximately 5 m intervals (medium severity), with some longitudinal cracking along the centreline. Total cracking area coverage is approximately 22%. IRI ranges from 2.8 to 5.4 m/km. Rutting averages 7 mm. FWD testing indicates generally consistent structural behaviour with some variability at crack locations.

4.2.2. Entropy Analysis and Interpretation

Table 5. *CS-F2 entropy analysis summary. H_total/H_max = 0.39 indicates Stage 2 with identified thermal cracking mechanism.*

CS-F2: Entropy Analysis Summary — Rural Road, Thermal Cracking

Entropy Component	Value (bits)	Interpretation
H_PCI	1.14 bits	Low-moderate diversity; single dominant mechanism (thermal)
H_IRI	1.21 bits	Relatively uniform roughness; low wavelength entropy
H_RUTTING	0.78 bits	Low: shallow symmetric ruts, steady progression
H_DISTRESS	0.91 bits	Low H_orientation (0.68): confirms thermal origin
H_FWD	1.08 bits	Moderate: some stiffness variability at crack positions
H_total	1.02 bits	Composite; normalised disorder = 39%

CS-F2: Entropy Analysis Summary — Rural Road, Thermal Cracking

Entropy Component	Value (bits)	Interpretation
H_total / H_max = 39% of H_max → Deterioration Stage: Stage 2: Propagation — Corrective maintenance effective		

The entropy signature of CS-F2 is distinctly different from CS-F1. H_orientation is low (0.68 bits), reflecting the strongly preferential transverse crack orientation characteristic of thermal cracking. H_type is moderate (1.12 bits) with cracking dominating. H_spatial is low (1.04 bits), reflecting the regular, approximately periodic spacing of thermal cracks rather than random dispersion. H_variability for IRI is low (0.94 bits), consistent with relatively uniform roughness along the section.

The low orientation entropy (H_orientation = 0.68 bits) is the key diagnostic indicator distinguishing this thermal cracking case from fatigue cracking. A crack sealing treatment targeting the regular transverse crack pattern is the appropriate intervention, informed directly by the entropy signature. The relatively low H_total confirms that intervention at this stage — before entropy escalates into Stage 3 — is cost-effective and structurally appropriate.

4.3. Case Study CS-F3: Post-rehabilitation Assessment — Entropy as a Treatment Effectiveness Metric

4.3.1. Context and Rationale

This case study demonstrates the application of entropy as a quantitative metric for assessing the effectiveness of pavement rehabilitation treatments. A 600 m section of urban distributor road, previously assessed at H_total/H_max = 0.71 (Stage 3), received a 60 mm hot-mix asphalt mill-and-fill rehabilitation treatment, followed by post-treatment assessment using the same entropy framework.

4.3.2. Pre- and Post-treatment Entropy Comparison

The rehabilitation treatment produced measurable reductions across all entropy components. The entropy reductions are summarised in Table 6 below. The most significant reductions are in H_IRI (reflecting the elimination of roughness through the new smooth surface) and H_DISTRESS (reflecting the elimination of visible surface cracking). The more modest reduction in H_FWD reflects the fact that the mill-and-fill treatment did not address structural deficiency at the base and subgrade levels.

The post-treatment H_total/H_max = 0.23 (Stage 1: Initiation) confirms successful rehabilitation of the surface and functional layers. However, the relatively high residual H_FWD = 1.41 bits (compared to a theoretical maximum of approximately 2.58 bits for this configuration) is a critical finding: it indicates that structural variability in the base and subgrade layers has not been addressed by the surface treatment. This entropy-based diagnostic provides a quantitative basis for the recommendation of a full structural assessment prior to the next major treatment cycle, targeting specifically the zones of highest H_structure along the section.

$$H\_TLS = -\Sigma\, p(\Delta z\_bin) \cdot \log_2 p(\Delta z\_bin)\ [\Delta z = \text{annual TLS surface change}]$$

For CS-E2, H_displacement = 1.89 bits over the eight-year monitoring period, reflecting episodic rather than steady movement. H_TLS = 2.24 bits, reflecting a spatially heterogeneous slope face with multiple zones of different displacement magnitude and character. The drainage condition entropy H_drainage = 1.98 bits, computed from the distribution of drainage condition ratings across survey points, reflects severely deteriorated drainage infrastructure contributing to elevated pore pressures.

Table 6. *CS-F3 pre- and post-rehabilitation entropy comparison. The residual H_FWD indicates unresolved structural risk.*

Entropy component	Pre-treatment (bits)	Post-treatment (bits)	Reduction	Interpretation
H_PCI	1.88	0.42	−77%	New surface eliminates visible distress diversity
H_IRI	1.96	0.31	−84%	New surface restores uniform roughness profile
H_RUTTING	1.52	0.55	−64%	Mill removes surface deformation; base variability remains
H_DISTRESS	2.03	0.28	−86%	All cracking removed from new surface layer

Entropy component	Pre-treatment (bits)	Post-treatment (bits)	Reduction	Interpretation
H_FWD	1.74	1.41	−19%	Structural variability partially remains in lower layers
H_total	1.83	0.59	−68%	Overall disorder reduced from 70% to 23% of H_max

5. Hierarchical Model for a Unified Entropy-based Framework

The individual entropy components developed in Chapter 3 and demonstrated through the case studies of Chapters 4–6 are integrated within a hierarchical model yielding the Total Pavement Entropy H_total as a weighted sum of the principal entropy sub-indices:

$$H_{total} = w_s \cdot H_{surface} + w_f \cdot H_{functional} + w_s \cdot H_{structural} + w_t \cdot H_{temporal} + w_n \cdot H_{spatial}$$

where H_surface encompasses the surface distress entropy from PCI and automated distress detection, H_functional encompasses roughness and rutting entropy, H_structural encompasses FWD deflection and modulus entropy, H_temporal encompasses deterioration rate and seasonal entropy, and H_spatial encompasses network-level and section-level variability entropy. The case studies demonstrate that the weighting coefficients w_i should reflect not only the relative importance of each entropy domain in a given assessment context, but also the infrastructure type: for embankment sections, H_temporal and H_structural carry greater weight; for JPCP sections, the joint-specific entropy components (H_LTE, H_spacing) should be incorporated.

The normalised disorder ratio H_total / H_max pro-vides a dimensionless index enabling cross-infrastructure comparison and network-level prioriti-sation. The four-stage deterioration classification — Initiation (≤0.25), Propagation (0.25–0.50), Acceleration (0.50–0.75), and Failure (≥0.75) — applies consistently across all case study types, as demonstrated in Table 7.

***Table 7**. Deterioration stage classification applied to case study outcomes.*

Stage	Designation	H/H_max range	Observed in case studies	Recommended management action
1	Initiation	< 0.25	CS-F3 (post-rehab)	Preventive maintenance; monitor H_FWD
2	Propagation	0.25–0.50	CS-F2 (thermal cracking)	Corrective maintenance; crack sealing
3	Acceleration	0.50–0.75	CS-F1, CS-R1, CS-R2, CS-E3	Rehabilitation planning; structural assessment
4	Failure	> 0.75	CS-E1 (settlement), CS-E2 (slope)	Structural reconstruction; geotechnical intervention

6. Practical Implementation Strategy

The proposed entropy framework is designed for implementation using existing pavement condition data without requiring new survey equipment. A four-phase programme is envisaged:

Phase 1 — Data Preparation

Existing PCI, IRI, rutting, FWD, automated imaging, and where applicable earthwork monitoring datasets are compiled and spatially referenced along a common network coordinate system [5, 12], For earthwork sections, geotechnical monitoring data (settlement surveys, inclinometers, DCP, piezometers) are integrated using the same spatial referencing framework.

Phase 2 — Entropy Computation

Probability distributions are derived from discretised measurement data for each entropy component. The six interactive calculators documented in Appendices A–G implement this computation for all five assessment domains and the unified hierarchical model. For seasonal entropy analysis (relevant to frost-susceptible subgrades), quarterly or monthly survey data are required as input.

Phase 3 — Calibration and Validation

Entropy thresholds corresponding to defined condition states are established by correlation with known pavement conditions and maintenance histories. The case studies presented in Chapters 4–6 provide initial empirical anchors for this calibration. Predictive accuracy is validated against independent longitudinal performance data.

Phase 4 — Operational Integration

The calibrated model is incorporated into PMS workflows. Entropy-based maintenance trigger points replace or supplement existing composite indices. The entropy production rate dH/dt drives prioritisation for network-level maintenance programming. Separate weighting profiles are defined for flexible pavements, rigid pavements, and earthwork structures, reflecting the different diagnostic emphases demonstrated in the case studies.

7. Novel Diagnostic Capabilities Enabled by the Entropy Framework

Failure Mode Identification Across Infrastructure Types

The case studies confirm that the entropy signature — the characteristic pattern of component entropy values — enables objective discrimination between failure modes across all pavement types and infrastructure domains. Fatigue cracking (high H_orientation, high H_spatial), thermal cracking (low H_orientation), joint faulting (low H_spectrum, high H_LTE), punchout risk (high H_spacing), settlement-driven roughness (high H_settlement, high H_rate), and seasonal structural weakness (high H_seasonal) each produce distinctive signatures that are recoverable from measured data and interpretable without subjective engineering judgement.

a. Deterioration Stage Classification

The four-stage classification model applies consistently across all six case studies, providing an objective, reproducible basis for condition state assignment that is independent of pavement type. The normalised entropy ratio H/H_max serves as a universal condition descriptor that enables comparison between flexible and rigid pavements, and between pavement sections and earthwork structures, within a single management framework.

b. Treatment Effectiveness and Residual Risk

Case study CS-F3 demonstrates the application of entropy as a treatment effectiveness metric: the post-rehabilitation entropy profile identifies residual structural disorder (H_FWD = 1.41 bits) not visible in surface or functional measures, providing a quantitative basis for predicting the next intervention requirement. This capability transforms post-treatment assessment from a pass/fail exercise into a probabilistic remaining life assessment.

8. Research Questions and Future Development

The development of the proposed framework to full operational maturity requires investigation of the following research questions, informed by the case study findings:

1) Discretisation methodology. What are the optimal bin widths for converting continuous measurement data into probability distributions across different pavement types and climatic environments?
2) Weighting scheme calibration. How should the weighting coefficients w_i be determined for different pavement types, traffic categories, and infrastructure domains? The case studies suggest that earthwork-dominated sections require substantially different weighting profiles from surface-dominated flexible pavement sections.
3) Entropy production rate. What are the characteristic dH/dt values for different pavement and infrastructure types? The CS-F1 case illustrates that entropy production accelerates non-linearly as Stage 3 is entered.
4) Critical entropy thresholds. What entropy values correspond to operationally meaningful trigger points for each infrastructure type? The case studies suggest that the Stage 3/4 boundary at H/H_max = 0.75 may warrant adjustment for earthwork structures, where Stage 4 onset may occur at lower disorder ratios due to the catastrophic nature of geotechnical failure.
5) Seasonal entropy integration. How should seasonal entropy measures be integrated with spatial entropy measures in the unified H_total for frost-susceptible subgrades and seasonal climates?
6) Remaining service life estimation. Can remaining service life be reliably estimated from entropy trajectory analysis? The CS-F1 and CS-E1 case studies suggest that the entropy production rate acceleration observed in Stage 3 provides a basis for non-linear remaining life models.
7) Network-level optimisation. Can maintenance programming be formulated as an entropy minimisation problem subject to budget constraints, and how does such a formulation compare with conventional priority-ranking approaches across a mixed network of flexible, rigid, and earthwork infrastructure?
8) CRCP-specific entropy extensions. Can the crack spacing entropy H_spacing be calibrated as a reliable early indicator of punchout risk across a range of CRCP design standards and climate conditions?

9. Conclusions

This paper has proposed, developed, and demonstrated through eight case studies a theoretically grounded, mathematically rigorous framework for the integrated quantitative evaluation of road pavement and transport infrastructure condition based on Shannon information entropy. The framework systematically interfaces with the principal established assessment methods — PCI, IRI, rutting measurement, automated distress detection, and FWD — and extends naturally to earthwork-specific assessment data, deriving entropy-based indices from the probabilistic structure of measurement data in each domain and integrating them into the Pavement Entropy Index (PEI).

The case studies demonstrate five key findings. First, the entropy signature — the pattern of component entropy values — enables objective discrimination between failure modes that conventional composite indices conflate: fatigue and thermal cracking, faulting and structural distress in concrete pavements, and pavement-layer versus geotechnical-origin deterioration are reliably distinguishable from their entropy profiles. Second, the entropy framework applies consistently across flexible pavements, rigid pavements, and earthwork structures, using the same mathematical formulation with domain-appropriate input distributions. Third, the entropy rate dH/dt and its acceleration provide a principled basis for deterioration stage classification and remaining service life estimation. Fourth, the treatment effectiveness analysis (CS-F3) demonstrates that entropy reveals residual disorder not detectable by surface assessment alone, supporting risk-informed post-treatment management. Fifth, seasonal entropy (H_seasonal, CS-E3) provides a novel metric for quantifying frost-induced structural vulnerability that has no equivalent in existing assessment frameworks.

The framework does not replace existing methods but synthesises their outputs within a unified information-theoretic language, enhancing their collective diagnostic and predictive power. Six interactive calculators have been developed with the aid of AI in order to operationalise the framework for immediate use in research and practice. The research programme outlined herein — encompassing calibration, longitudinal validation, and network-level optimisation — is proposed as the basis for establishing the Pavement Entropy Index as a standard for integrated, physics-informed infrastructure condition evaluation across all pavement types and geotechnical domains.

In the author’s opinion, the scientific unswers for all these research questions could be obtained, by initiating a common international research, under the framework of a future proposed COST Action, at European level, involving specialists from road research institutes and highway agencies from various countries of the world, in order to undertake full operational maturity investigations and appropriate case studies, in various geographic climates and traffic conditions, capable to validate this new proposed concept of Pavement Entropy Index.

Abbreviations

PEI	Pavement Entropy Index
ASTM	American Standards for Testing Methods
GPR	Ground Penetrating Radar
CBR	Californian Bearing Ratio
DCP	Dynamic Cone Penetrometer
LTE	Load Transfer Efficiency
PCI	Pavement Condition Index
IRI	International Roughness Index
LWD	Light Weight Deflectometer
PASER	Pavement Surface Evalation Rating
BS	British Standard

Author Contributions

Radu Andrei: Conceptualization, Methodology, Resources, Software, Validation, Writing – original draft, Writing – review & editing

Conflicts of Interest

The author declares no conflicts of interest.

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