

Research Article

Network-Level Pavement Bearing Capacity Assessment Using the Curviameter Mechanical Index (CMI)

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Abstract: Bearing capacity assessment of asphalt pavement networks is a fundamental task in pavement asset management. This paper presents the Curviameter Mechanical Index (CMI), a composite indicator derived from continuous moving-load deflection measurements for network-level structural condition assesment. The CMI integrates three physically meaningful quantities: the global dynamic stiffness ratio, an energy ratio characterising viscoelastic asymmetry, and the logarithmically scaled effective range reflecting viscoelastic memory. The paper establishes the theoretical basis for the distinction between Falling Weight Deflectometer (FWD) and Curviameter measurements, demonstrating that direct numeric conversion between the two is theoretically unfounded. Instead, CMI is functionally aligned with deflection-based bearing capacity rating frameworks through empirical calibration, without claiming mechanistic equivalence. A proposed five-class structural condition scheme is presented, with threshold values determined by co-located FWD and Curviameter surveys. A pilot measurement campaign on three motorway sections confirms the physical validity and discriminatory power of the index. The role of CMI in pavement management systems is discussed, including the handling of temperature and moisture effects. The framework positions Curviameter and FWD as complementary tools: the former for network-level assesment, the latter for project-level mechanistic design.

Keywords: *curviameter; deflection measurement; bearing capacity; pavement management; network-level assesment*

I. INTRODUCTION

Bearing capacity assessment of asphalt pavement networks is a fundamental task in pavement asset management, directly influencing traffic safety, maintenance expenditure, and the timing of rehabilitation interventions [1]. At the network level, the objective is not to carry out detailed mechanistic analysis of individual structural elements, but reliable comparison of road sections, identification of structurally deficient segments, and prioritisation of interventions.

Falling Weight Deflectometer (FWD) measurements provide detailed, localised structural information based on impulse-load deflection response. However, network-scale deployment is constrained by the low sampling rate and traffic management requirements [1]. In recent years, continuous deflection measurement devices — most notably the Curviameter — have gained wider

adoption for high-speed network monitoring on motorway and primary road networks [2]. Their main advantage is high sampling rate and continuous spatial coverage. However, the interpretation of the deflection recorded under moving load differs in principle from that of the locally measured deflection bowl produced by FWD. Similar indicator-based approaches have been adopted internationally for continuous deflection devices, including the Traffic Speed Deflectometer (TSD) [3].

Consequently, direct numerical conversion between Curviameter and FWD outputs is not feasible on theoretical grounds. The challenge is to derive robust, network-level indicators from the Curviameter dynamic response that characterise pavement structural condition in a manner functionally consistent with established bearing capacity rating categories — without claiming mechanistic equivalence. This paper introduces the

Curviameter Mechanical Index (CMI) as such a composite structural indicator and explicitly delimits its scope from project-level mechanistic analyses.

II. HISTORICAL AND METHODOLOGICAL BACKGROUND

1. Evolution of Network Deflection Measurement

Systematic deflection measurement for pavement structural evaluation dates back to the early 1960s, when the Benkelman Beam enabled rapid, non-destructive estimation of elastic deformation under dual truck tyre loads [4]. In the subsequent decades Lacroix-type deflectographs and the Falling Weight Deflectometer (FWD) were introduced. They offered controlled load application and multi-sensor deflection bowl measurement. FWD measurements made back-calculation of layer moduli possible [5]. More recently high-speed, continuous deflection measurement devices have enabled network-scale condition assesment at traffic speed, revealing structural variability along entire corridors without lane closure.

2. Deflection-Based Rating Frameworks

Several countries have developed national bearing capacity rating systems anchored to FWD measurements. These systems define threshold-based structural condition classes linked to estimated residual service life [1], [6], [7]. The principle of such systems is that they define *decision categories* rather than continuous mechanistic outputs. This means that a non-FWD tool can be integrated through functional equivalence rather than numeric substitution — provided it reliably ranks sections consistently with the established categories.

III. COMPARISON OF FWD AND CURVIAMETER MEASUREMENT PRINCIPLES

1. Load Type and Measurement Geometry

The stationary FWD applies an impulse load at a fixed point while an array of sensors simultaneously records the deflection bowl at defined radial offsets. The Curviameter records pavement response to a moving load at a single longitudinal point while travelling at constant speed. The resulting signal is a time-domain deflection record, transformable to a quasi-spatial profile via the known vehicle speed, but fundamentally distinct from the FWD bowl [7].

2. Deflection Bowl Concept: Key Differences

For the FWD, the deflection bowl is a symmetric spatial deformation pattern at a single instant; different sensor offsets are sensitive to different

depth ranges [8]. For the Curviameter, the “bowl” is a derived quasi-spatial representation of the time-dependent response, characteristically asymmetric, incorporating viscoelastic lag effects that depend on load speed, asphalt temperature, and layer bonding quality [9].

3. Implications for Data Interpretation

Differences in load duration, travel speed, and frequency-dependent viscoelastic behaviour mean that FWD and Curviameter deflection magnitudes can differ substantially for identical pavement structures. Direct numeric conversion is theoretically unfounded [10]. Table 1 summarises the principal differences between the two systems.

Table 1. Comparison of FWD and Curviameter measurement principles

<i>Aspect</i>	<i>FWD</i>	<i>Curviameter</i>
Load type	Impulse, stationary	Moving, quasi-continuous
Measurement points	Multiple, fixed offsets	Single point / line
Bowl type	Direct spatial	Quasi-spatial, time-derived
Symmetry	Symmetric	Asymmetric
Primary application	Project-level	Network-level
Direct conversion	—	Not applicable

IV. PRE-PROCESSING OF THE CURVIAMETER DEFLECTION PROFILE

1. Time-to-Space Transformation

The Curviameter sensor records vertical deflection as a continuous time-domain signal $w(t)$ at a fixed point on the vehicle, while the vehicle travels at constant survey speed v (typically 18 km/h). To obtain a spatially interpretable deflection profile $w(x)$, the time axis is transformed using Equation (1), where v is the measurement speed and t_0 is the time instant at which the maximum deflection is observed [3]. The transformation is valid under the assumption of uniform travel speed and negligible vehicle acceleration over the measurement window. Speed is measured directly by the Curviameter inertial system and verified against GPS records. Typical speed variation is below ± 1 km/h over a 4 m window, introducing negligible distortion. The resulting spatial profile $w(x)$ spans approximately -2 m to $+4$ m relative to the load centre, but only the ± 1000 mm window is used for indicator computation after the subsequent pre-processing steps.

$$x = v(t - t_0) \quad (1)$$

2. Axis Registration and Windowing

Raw Curviameter records require three systematic pre-processing steps before structural indicators can be computed reliably. Each step is illustrated in Fig. 1, which shows a representative deflection profile recorded at motorway speed.

Step 1 — Axis registration. The raw time-domain record is first converted to a spatial profile using Equation (1), yielding a coordinate axis in millimetres relative to the vehicle position. Because vehicle positioning is subject to timing uncertainty of the order of ± 50 – 100 ms, the spatial origin does not automatically coincide with the deflection maximum. The axis registration step identifies the location of the global minimum (maximum downward deflection) within a ± 200 mm search window centred on the nominal vehicle axle position, and resets the spatial origin to that point. This ensures that D_0 (peak central deflection), ER (energy ratio), and TL_{10} (10%-effective range) are always evaluated relative to the true load centre, eliminating systematic bias in all subsequent calculations.

Step 2 — Baseline removal. Even after axis registration, a small non-zero far-field offset typically remains in the signal. This offset originates from sensor drift, electronic bias, and road surface macrotexture. It is quantified as the mean deflection measured in the far-field zone ($|x| > 900$ mm), where the structural influence of the rolling load is negligible. Subtracting this constant baseline ensures that the profile asymptotically approaches zero deflection at large distances, which is a physical requirement for a pavement responding elastically at the surface. Without this correction, the energy ratio ER and the influence length TL_{10} would be systematically distorted.

Step 3 — Uniform windowing. The analysis window is restricted to $x \in [-1000 \text{ mm}, +1000 \text{ mm}]$. The lower bound excludes the approach zone where sensor noise and vehicle vibration distort the pre-load signal; the upper bound excludes the far-field region beyond the structural influence of the deflection bowl. Uniform windowing is essential for comparability: because TL_{10} and ER are defined as integrals and ratios over fixed spatial intervals, any variability in window limits would propagate directly into the CMI value. Restricting all surveys to the same window converts CMI into a strictly comparable network indicator. The width of ± 1000 mm was chosen to capture the full viscoelastic recovery tail observable at typical Curviameter survey speeds (18 km/h).

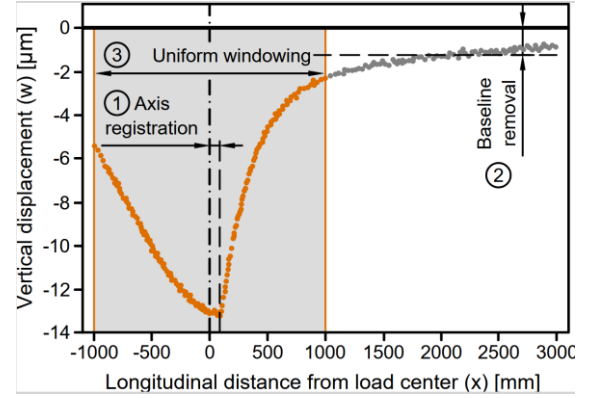


Figure 1. Representative Curviameter deflection profile illustrating the three pre-processing steps: (1) axis registration — the spatial coordinate is shifted so that the deflection maximum coincides with $x = 0$; (2) baseline removal — the far-field mean offset (dashed line) is subtracted; (3) uniform windowing — analysis is restricted to $x \in [-1000, +1000]$ mm (vertical lines). The characteristic asymmetry of the profile and the extended viscoelastic recovery tail on the right-hand side are visible.

V. DEFINITION AND PHYSICAL INTERPRETATION OF THE CMI

1. Mathematical Formulation

The **Curviameter Mechanical Index (CMI)** is defined by Equation (2), where P is the static axle/tyre load [kN], D_0 is the maximum central deflection [μm], ER is the dimensionless energy ratio, and TL_{10} is the effective range to 10% of maximum deflection [mm]. Equation (2) was developed specifically for this study, combining established deflection-based parameters (P/D_0 , ER , TL_{10}) into a single composite index.

$$CMI = \frac{P}{D_0} \cdot ER \cdot \left(1 + \ln \left(\frac{TL_{10}}{1000} \right) \right) \quad (2)$$

2. Physical Meaning of Each Term

The ratio P/D_0 expresses global dynamic stiffness, analogous to central stiffness from FWD but not numerically equivalent [11]. The energy ratio ER , formed from leading and trailing integrals of the deflection profile, quantifies viscoelastic energy dissipation and imperfections in layer connections. $ER \approx 1$ means that the response of the pavement is near-symmetrical, indicating quasi-elastic behaviour. $ER > 1$ indicates significant energy dissipation, longer recovery time and increased viscoelastic effects [12]. TL_{10} represents the viscoelastic memory of the pavement. It is the positive distance from $x=0$ where the deflection value reaches the 10% of the maximal deflection. It is affected by the viscoelastic time constants, the temperature of the asphalt layer, and the quality of

the interlayer bond between pavement layers. $\frac{TL_{10}}{1000}$ makes the parameter dimensionless, $\ln()$ transformation is necessary to express the nonlinearity of the range, while the “+1” shift ensures positivity of the expression for typical Curviameter measurements. [13],[14].

3. CMI as a Composite Dynamic Condition Indicator

The CMI integrates maximum deflection, energetic asymmetry, and viscoelastic memory into a single indicator. It is not an FWD-equivalent output but can be calibrated against FWD-derived stiffness and bowl-shape indicators [3]. Its primary domain of application is network-level comparative ranking, not absolute mechanistic characterisation.

VI. CMI INTERPRETATION WITHIN A DEFLECTION-BASED RATING FRAMEWORK

1. Indicator-Based Alignment

Deflection-based pavement rating systems define structural condition through decision categories linked to residual service life estimates. Integration requires functional correspondence rather than numeric substitution [6], [15]. Table 2 presents the proposed classification framework. Thresholds T_1 – T_4 should be determined through co-located Curviameter and FWD surveys on representative sections for each assessed network and measurement condition

Table 2. Proposed structural condition classes based on CMI values

Class	CMI Range	Recommended Action	Remaining Service Life
5 – Very poor	$CMI < T_1$	Immediate intervention	≤ 1 yr
4 – Poor	$T_1 \leq CMI < T_2$	Scheduled rehabilitation	1–5 yr
3 – Moderate	$T_2 \leq CMI < T_3$	Monitoring, targeted repair	5–10 yr
2 – Good	$T_3 \leq CMI < T_4$	Preventive maintenance	10–15 yr
1 – Very good	$CMI \geq T_4$	No bearing capacity risk	≥ 15 yr

2. CMI in the Pavement Management System Workflow

The primary operational context for CMI is the network-level Pavement Management System (PMS) [16]. CMI serves four functions: (i) rapid screening of structurally deficient sections; (ii) network-wide ranking for intervention prioritisation; (iii) longitudinal monitoring of condition trends; and (iv) targeted FWD designation for sections requiring mechanistic, project-level assessment.

VII. MECHANISTIC INTERPRETATION AND FWD CALIBRATION

1. Limits of Mechanistic Interpretation

Project-level structural assessment requires knowledge of displacements and strains – especially the tensile strain at the bottom of the asphalt layer (ϵ_t) – to determine remaining service life. These quantities require back-calculation from FWD measurements using structural pavement models that contains layer structure and material parameters explicitly [17]. Curviameter data does not allow direct determination of layer-level strains as it only records surface responses. The Curviameter signal is the resultant of a coupled vehicle–road interaction system across multiple time scales, which current mechanistic models can only approximately reproduce [18]. CMI is therefore an integrated surface indicator of the pavement condition.

2. FWD as the Calibration Reference and Pilot Results

An empirical CMI– ϵ_t relationship is achievable through co-located measurements [19]. As a first-order approximation under consistent conditions, Equation (3) provides an indicative estimate of critical tensile strain. The proportionality constant is not universal and must not be used for stand-alone project-level design.

$$\epsilon_t \approx \frac{3000}{CMI} \quad (3)$$

Equation (3) provides only a robust first-stage screening estimate. In order to develop a relationship applicable in practice, Curviameter and FWD measurements were carried out on a representative set of road sections covering different CMI ranges, under identical temperature and environmental conditions.

Based on the layer moduli backcalculated from the FWD data and using a mechanistic pavement model, the critical tensile strain (ϵ_t) was determined. The resulting ϵ_t values were then statistically related to the corresponding CMI values [20].

A pilot survey on three motorway sections (13 profiles) confirmed the physical validity of the index

by resulting in inverse proportionality between D_0 and CMI (Table 3). M3 motorway profiles show significantly lower CMI (≈ 450 MN/m), indicating moderate condition and the need for intervention in the medium-term. M4 motorway sections are uniformly excellent (avg. CMI ≈ 1508 MN/m). M85 motorway exhibits high variability (607–1863 MN/m), warranting targeted FWD follow-up.

Table 3. Pilot survey results: CMI (Curviameter-derived) and D_0 (FWD-derived) values for 13 motorway profiles

Profile ID	D_0 (FWD) [μm]	CMI [MN/m]	Condition
M85 T1 M1	180	607	Good
M85 T1 M2	170	634	Good
M85 T2 M1	60	1863	Excellent
M85 T2 M2	70	1534	Excellent
M3 T1 M1	250	432	Moderate
M3 T1 M2	250	434	Moderate
M3 T2 M1	220	478	Moderate
M3 T2 M2	240	447	Moderate
M4 T9 M1	80	1399	Excellent
M4 T9 M2	80	1337	Excellent
M4 T10 M3	70	1484	Excellent
M4 T11 M4	70	1537	Excellent
M4 T12 M5	60	1782	Excellent

VIII. ENVIRONMENTAL EFFECTS AND THEIR MANAGEMENT

Bituminous pavement deflection response is strongly temperature-dependent. Rising temperature reduces layer stiffness, increasing D_0 and modifying ER and TL_{10} . Effects are more pronounced in moving-load measurements than in FWD [21]. The CMI framework restricts surveys to a narrow temperature range (e.g., 15–25°C) for robustness. Elevated subgrade moisture amplifies viscoelastic tail length [22], creating a challenge of separating permanent structural deterioration from transient environmental weakening. The following operational principles are recommended:

- Schedule survey campaigns under comparable environmental conditions from year to year;
- Average CMI over homogeneous segments (100–200 m) to suppress transient localised effects;
- Analyse temporal trends rather than absolute values in year-on-year comparisons;

- Flag environmentally sensitive sections for targeted project-level investigation.

IX. CONCLUSIONS AND FUTURE RESEARCH

This paper has demonstrated that the CMI provides a viable basis for network-level pavement bearing capacity assessment. FWD and Curviameter outputs cannot be converted directly, but CMI can be functionally aligned with deflection-based rating frameworks through empirical calibration, confirmed by the pilot survey results. The CMI framework reflects the emerging paradigm of differentiated measurement resource use: Curviameter for network screening, FWD for project-level design [23].

Future research should address: (i) statistically robust CMI– ϵ_t calibration across pavement types, temperatures, and speeds; (ii) separation of structural deterioration from transient environmental effects via seasonal campaigns; (iii) CMI formulation refinement including alternative energy metrics; and (iv) integration with multi-indicator PMS decision models combining CMI with surface distress indices [24], [25].

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AUTHOR CONTRIBUTIONS

Cs. Tóth: Conceptualization, Methodology, Writing – original draft.

D. Koch: Data curation, Validation, Writing – review and editing.

P. Primusz: Data curation, Validation, Writing – review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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