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Review Article

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A Standardized Grade Point Average (sGPA) Framework for Urban Pavement Systems: A Scalable Index for Infrastructure Economics and GIS-Based City Evaluation

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Abstract
Urban infrastructure condition is typically measured using engineering indices such as the ASTM D6433 Pavement Condition Index (PCI), which, while precise at the segment level, lacks interpretability and comparability at the city scale. This paper develops a standardized, bounded 4.3-point infrastructure grading system (sGPA) that transforms PCI into a unified scalar metric analogous to academic GPA systems. The proposed framework aggregates road condition using length- and function-weighted methods, producing a city-level index suitable for econometric modeling, GIS mapping, and capital planning. We demonstrate that the sGPA is compatible with nonlinear urban welfare functions and enables direct integration into urban productivity models. Conceptual application to mid-sized cities such as Saint John illustrates its utility for infrastructure benchmarking and spatial inequality measurement.

1. Introduction

Urban infrastructure systems are foundational to productivity, accessibility, and long-run economic growth. However, existing pavement condition measures suffer from three key limitations:

- **Non-aggregability** (segment-level scores do not scale well)

- **Low interpretability** for policy makers

- **Weak integration** into economic utility functions

To address these issues, we introduce the standardized Grade Point Average (sGPA), a transformation of PCI into a bounded, intuitive 4.3-scale system.

The objective is to unify:
- Engineering condition measurement
- Spatial aggregation
- Economic valuation

into a single framework.

2. Literature Review

2.1. Pavement Condition Measurement

The dominant framework is the ASTM D6433 Pavement Condition Index, which evaluates distress type, severity, and density on a 0–100 scale.

Alternative systems include:
- IRI (International Roughness Index)
- PASER visual ratings
- municipal asset management scoring systems

However, none provide:
- Cross-city comparability
- Bounded scalar interpretation
- Direct economic embedding

2.2. Urban Infrastructure Economics

Urban models typically link infrastructure to:
- Transport cost reduction
- Agglomeration effects
- Property value gradients

But infrastructure inputs are rarely normalized into a single interpretable scalar variable, limiting empirical comparability.

3. Methodology

3.1. PCI-to-sGPA Transformation

We define:

$$sGPA_i = f(PCI_i)$$

where f is a monotonic piecewise mapping:

$$sGPA_i \in [0,4.3]$$

Calibration:
- 97–100 → 4.3
- 93–96 → 4.0
- 90–92 → 3.7
- 87–89 → 3.3
- 83–86 → 3.0
- 80–82 → 2.7
- 77–79 → 2.3
- 73–76 → 2.0
- 70–72 → 1.7
- 65–69 → 1.3
- 60–64 → 1.0
- 55–59 → 0.7
- <55 → 0.0

This preserves ordinal structure while enabling cardinal interpretation.

3.2. City-Level Aggregation

We define city infrastructure quality as:

$$sGPA_{city} = \frac{\sum_{i=1}^{n} sGPA_i \cdot L_i}{\sum_{i=1}^{n} L_i}$$

Where:
- L_i: lane-kilometres of segment i

This yields a **length-weighted expected infrastructure grade.**

3.3.Functional Weighting Extension

To incorporate network hierarchy:

$$sGPA_{adj} = \frac{\sum(sGPA_i \cdot L_i \cdot W_i)}{\sum(L_i \cdot W_i)}$$

Where:
- Arterials: W=1.5
- Collectors: W=1.2
- Local roads: W=1.0

3.4. Econometric Framework

We embed sGPA into a standard urban outcome model:

$$Y_{it} = \beta_0 + \beta_1 sGPA_{it} + \beta_2 \ln(Pop_{it}) + \beta_3 Density_{it} + \epsilon_{it}$$

Where Y may represent:
- Property values
- Congestion delay
- Vehicle operating costs
- Productivity per km²

Expected sign:

$$\beta_1 > 0$$

3.5. Nonlinear Urban Welfare Function

We propose diminishing returns in infrastructure quality:

$$NB = a\ln(sGPA) - b(sGPA)^2$$

Implications:
- Increasing returns at low infrastructure levels
- saturation beyond optimal sGPA*
- convex investment trade-offs

Optimal condition:

$$sGPA^* = \frac{a}{2b}$$

3.6. GIS Implementation

Each road segment contains:

Variable	Meaning
PCI	distress score
sGPA	transformed grade
L	segment length
W	functional weight
Weighted score	$sGPA \cdot L \cdot W$

This enables:

- Continuous heat maps of infrastructure quality
- Spatial inequality decomposition
- Corridor prioritization models

3.7. Empirical Design (Multi-City Framework)

A comparative design is proposed:

City	Type
Toronto	high-density monocentric
Los Angeles	polycentric auto-dependent
Saint John	mid-sized port-industrial

Each yields:

$$sGPA_{city}, sGPA_{core}, sGPA_{suburbs}$$

allowing decomposition of infrastructure inequality.

3.8. Conceptual Case: Saint John

In Saint John, infrastructure exhibits:

- Historic core concentration
- Industrial corridor loading
- Suburban expansion gradients

Thus:

$$sGPA_{SJ} = \frac{\sum sGPA_i L_i W_i}{\sum L_i W_i}$$

becomes a spatial inequality metric of urban capital stock.

4. Results (Simulated Calibration Table)

City	Estimated sGPA	Interpretation
Toronto	3.1–3.4	stable
Los Angeles	2.6–3.0	mixed condition
Saint John	2.1–2.5	maintenance deficit

5. Discussion

The sGPA framework contributes:

- **Measurement innovation:** Transforms engineering PCI into bounded scalar index

- **Economic integration:** Direct inclusion in regression and welfare models

- **Policy usability:** “City GPA” is intuitive for governments and public reporting

- **Spatial economics linkage:** Compatible with GIS-based inequality and clustering models

5.1. Limitations

- Requires calibration across jurisdictions

- Sensitive to weighting scheme selection
- Does not capture underground utilities or structural base failure unless included in PCI inputs

6. Conclusion

This paper introduces a unified infrastructure metric (sGPA) that converts pavement condition data into a standardized 4.3-point system. The framework bridges engineering measurement, GIS spatial analysis, and urban economic modeling, enabling consistent cross-city evaluation of infrastructure quality and investment needs [1-21].

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