

Analysis of Road Damage Handling Priorities Using the Analytical Hierarchy Process (AHP) Method in Bandung City

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Abstract:

Urban road authorities in rapidly motorizing cities must allocate scarce maintenance budgets across competing segments under multi-criteria pressure. This study develops an objective, multi-expert, risk-informed prioritization model for the 36 national road segments of Bandung City, Indonesia, using the Analytic Hierarchy Process (AHP) with geometric-mean aggregation across a seven-expert panel drawn from government, academia, and practice. Five decision criteria are evaluated: International Roughness Index (IRI), Annual Average Daily Traffic (AADT), Road Function, a composite Safety Risk (operationalized as the interaction of normalized IRI and AADT), and a length-based Rehabilitation Cost proxy. The aggregated pairwise-comparison matrix attains a Consistency Ratio of 0.036, a 58.6% improvement over the single-expert benchmark (0.087), confirming the methodological superiority of group-based AHP. The aggregated weights place Safety Risk first (0.467), followed by IRI (0.234), AADT (0.187), Cost (0.068), and Function (0.044). Applied through weighted-linear synthesis, the model identifies three Critical segments warranting immediate rehabilitation; their designation is robust across five sensitivity scenarios. A key analytical finding is that the most physically damaged segment (Bts. Cileunyi–Nagreg I, IRI = 8.0 m/km) ranks seventh because its lowest network AADT reduces composite risk exposure, demonstrating that risk-informed multi-criteria prioritization produces materially different rankings from condition-only approaches.

Keywords: Analytical Hierarchy Process, Composite Safety Risk, Geometric-Mean Aggregation, Multi-Criteria Decision Analysis, Road Maintenance Prioritization, Sensitivity Analysis.

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1. INTRODUCTION

Roads function not merely as physical pathways but as integrated strategic assets underpinning the distribution of goods and services, access to public facilities, and overall quality of life. As urbanisation intensifies and city populations grow, pressure on road infrastructure escalates correspondingly (Mhana, 2024). Rising vehicle volumes, frequently outpacing road-capacity expansion and maintenance investment, cause pavement degradation in periods shorter than the intended design life. High traffic loads, the prevalence of heavy vehicles, and intensive utilisation accelerate damage modes such as alligator cracking, potholes, rutting, and surface deformation, each progressively reducing the road level of service (Priyanto, 2023).

Local governments face chronic insufficiency of maintenance budgets relative to network needs, making structured prioritisation unavoidable. Yet in practice, road damage management decisions are frequently reactive, driven by visible damage or public complaints rather than grounded in comprehensive, reproducible multi-criteria analysis (Tosulpa, 2026; Wubuli, 2025). This reactive paradigm is not merely inefficient; it is potentially unsafe, since the most hazardous segments are not necessarily those with the most visually obvious damage.

Among multi-criteria decision-analysis (MCDA) methods, the Analytical Hierarchy Process (AHP) developed by Saaty (1980) is the most extensively validated for infrastructure prioritisation, accommodating both quantitative indicators (IRI, AADT) and qualitative assessments (road function), and providing the Consistency Ratio as a transparent audit of judgment quality (Mvondo, 2026; Akbar, 2025). However, the methodological literature reveals two persistent gaps. First, most published studies rely on a single expert's judgment, embedding unquantified individual bias. Second, safety criteria are commonly omitted or approximated because segment-level accident records are unavailable in developing-country contexts.

In Bandung City, a high-density metropolitan area with one of the highest AADT values on its national-road corridors in West Java, these methodological choices are both practically motivated and theoretically significant (Zuhri, 2025). The present study therefore pursues four operational objectives: (i) to identify and operationalise five prioritisation criteria, including a composite Safety Risk; (ii) to derive representative criteria weights through multi-expert AHP with geometric-mean aggregation; (iii) to produce a complete, validated 36-segment priority ranking; and (iv) to characterise ranking robustness through systematic sensitivity analysis. Beyond these objectives, the study makes three theoretical contributions: empirical validation of a composite Safety Risk criterion as a methodological solution to the accident-data gap; empirical evidence that geometric-mean aggregation produces substantially more consistent AHP weights than single-expert assessment; and the first demonstration that risk-informed multi-criteria prioritization produces materially different rankings from condition-only approaches on Bandung City's national road network.

2. MATERIALS AND METHODS

2.1 Study area and data

The study covers 36 national road segments within the administrative boundary of Bandung City, West Java, managed by the Directorate General of Highways through BPJN West Java, totalling 72.51 km. Secondary data were obtained from the Integrated Road Management System (IRMS), specifically the road-link master table (segment ID, name, length, functional class, geometric reference) and the sub-link condition table (AADT, IRI, surface distress, structural indicators). Because long administrative links are surveyed as several homogeneous sub-sections, each sub-link record is treated as a distinct evaluation segment. Across the 36 segments, IRI values range from 2.7 to 8.0 m/km and AADT from 33,506 to 48,055 vehicles per day. Thirty-five segments are arterials (functional score 1.00), and one is a collector (0.75).

Primary data comprise structured pairwise-comparison judgments collected from a seven-expert panel spanning government road authorities (E1, E2, E7), academia and research (E3, E4), and consulting practice (E5, E6). Each expert completed the ten pairwise comparisons among the five criteria using Saaty's 1–9 ratio scale following a standardized briefing that defined every criterion and the normalization approach.

2.2 The analytical hierarchy process

AHP decomposes a multi-criteria problem into the objective (Level 1), criteria (Level 2), and alternatives (Level 3). Pairwise judgments populate an $n \times n$ reciprocal matrix A (Eq. 1). Criterion weights are the principal eigenvector of A , approximated by the row-normalised geometric mean (Eq. 2). The maximum eigenvalue $\lambda_{\max}$ (Eq. 3) drives the Consistency Index and Ratio (Eq. 4), with $RI(n=5) = 1.12$ and the AHP threshold $CR \leq 0.10$ (Saaty, 1980; Canco, 2021).

$$a_{ij} > 0, \quad a_{ji} = 1/a_{ij}, \quad a_{ii} = 1 \quad (1)$$

$$w_i = GM_i / \sum_k GM_k, \quad GM_i = (\prod_j a_{ij})^{1/n} \quad (2)$$

$$\lambda_{\max} = (1/n) \sum_i v_i/w_i, \quad v_i = \sum_j a_{ij} w_j \quad (3)$$

$$CI = (\lambda_{\max} - n)/(n - 1); \quad CR = CI/RI \quad (4)$$

2.3 Geometric-mean aggregation

Individual expert matrices are aggregated pairwise by the geometric mean (Eq. 5), which preserves the reciprocal property and attenuates extreme individual judgments. The aggregation consistently yields lower CR than individual matrices because inconsistencies from one expert are partially cancelled by others' more moderate judgments (Macchiaroli, 2023).

$$a_{ij}(\text{agg}) = (a_{ij}(E1) \cdot a_{ij}(E2) \cdot \dots \cdot a_{ij}(E7))^{1/7} \quad (5)$$

2.4 Criteria operationalization

Five criteria are evaluated. (i) Physical Road Condition is the IRI (m/km), min-max normalized. (ii) Traffic Volume is AADT (veh/day), min-max normalized. (iii) Composite

Safety Risk is operationalized as the product of normalized IRI and AADT (Eq. 6), capturing the interaction of hazard intensity and exposure and avoiding the need for accident records, which are unavailable at the segment level in Indonesian contexts. (iv) Rehabilitation Cost is a quantity-by-intensity proxy, $Cost_i = Length_i \times IRI_i$, min-max normalised and inverted (Eq. 7-8; Al-Omari and Darter, 1995). (v) Road Function: Arterial = 1.00, Collector = 0.75. Global priority scores are computed using weighted linear synthesis (Eq. 9), and segments are classified as Critical (≥ 0.840), High (0.600–0.839), Medium (0.450–0.599), or Low (< 0.450).

$$SRI = IRI_{i,norm} \times AADT_{i,norm} \quad (6)$$

$$Cost_i = Length_i \times IRI_i \quad (7)$$

$$Cost_{i,norm} = (Cost_{max} - Cost_i) / (Cost_{max} - Cost_{min}) \quad (8)$$

$$P_i = \sum_k w_k \times score_{i,k} \quad (9)$$

2.5 Sensitivity analysis

Five weighting scenarios are evaluated to characterize ranking robustness: So (base, multi-expert aggregated weights); S1 (IRI-dominant, $w_{IRI} = 0.380$); S2 (Safety-elevated, $w_{SR} = 0.580$); S3 (AADT-dominant, $w_{AADT} = 0.380$); and S4 (equal weights, $w = 0.200$ each). The perturbations span the plausible range of expert disagreement and are bounded by the consistency tolerance of AHP (Triantaphyllou and Sánchez, 1997). All scenario weight vectors are renormalized to sum to unity before scoring, so scores remain comparable across scenarios. A complementary one-at-a-time ($\pm 20\%$) local check is also conducted, with the remaining four weights proportionally renormalized on each variation.

3. RESULTS AND DISCUSSION

3.1 Aggregated pairwise-comparison matrix and consistency

Table 1 presents the seven-expert geometric-mean aggregated pairwise-comparison matrix together with the derived criteria weights. The consistency parameters of the aggregated matrix are $\lambda_{max} = 5.162$, $CI = 0.0405$, $RI(n=5) = 1.12$, and $CR = 0.036$. This is well below the AHP threshold of 0.10 and represents a 58.6% improvement over the single-expert reference value of $CR = 0.087$. The improvement is a direct mathematical consequence of geometric-mean aggregation: extreme individual judgments are dampened by more moderate judgments from other experts, yielding a composite matrix with substantially higher internal coherence than any individual matrix. All seven individual matrices satisfied $CR \leq 0.10$ prior to aggregation.

Table 1. Geometric-mean aggregated pairwise comparison matrix and derived criteria weights (w).

	IRI	AADT	Func	SR	Cost	w
IRI	1.000	1.292	5.822	0.381	4.401	0.234
AADT	0.774	1.000	4.787	0.307	3.536	0.187
Func	0.172	0.209	1.000	0.140	0.472	0.044
SR	2.627	3.257	7.163	1.000	6.365	0.467
Cost	0.227	0.283	2.119	0.157	1.000	0.068

3.2 Derived criteria weights and convergence with single-expert results

Table 2 compares the aggregated weights across multiple experts with the single-expert reference. Three findings emerge. First, the rank order of all five criteria is identical in both derivations, confirming that the reference expert's preference structure is directionally representative of the panel consensus. Second, the absolute weight differences are small (maximum 0.006), reflecting careful expert selection. Third, the CR drops from 0.087 to 0.03; multi-expert aggregation produces not just more representative weights but a more mathematically coherent judgment structure.

The multi-expert weights confirm a risk-performance interpretation of the decision model. Safety Risk (0.467) dominates; together with IRI (0.234) and AADT (0.187), the three criteria account for 88.8% of the total decision weight. Cost (0.068) and Function (0.044) act as supporting modifiers. Safety-Risk dominance is substantively justified: national road segments in Bandung City carry up to 48,055 vehicles per day, meaning that pavement deterioration creates risk exposure for tens of thousands of daily users.

The composite SR criterion captures this exposure effect, so a segment with moderate IRI on a maximum-AADT corridor presents higher aggregate risk than one with maximum IRI on the minimum-AADT corridor.

Table 2. Criteria priority weights: multi-expert vs single-expert.

Criterion	Multi-Expert	Single-Expert	Diff. / Rank
Safety Risk (SR)	0.467 (1st)	0.471 (1st)	+0.004 / same
Physical Cond. (IRI)	0.234 (2nd)	0.235 (2nd)	+0.001 / same
Traffic Vol. (AADT)	0.187 (3rd)	0.181 (3rd)	+0.006 / same
Rehabilitation Cost	0.068 (4th)	0.067 (4th)	+0.001 / same
Road Function	0.044 (5th)	0.046 (5th)	+0.002 / same
Consistency Ratio (CR)	0.036	0.087	58.6% improv.

3.3 Complete priority ranking and the Cileunyi–Nagreg paradox

Weighted-linear synthesis applied to the 36 segments yields three Critical (≥ 0.840), five High (0.600-0.839), sixteen Medium (0.450-0.599), and twelve Low (< 0.450) segments. The top twelve are reported in Table 3. The three Critical segments, Jln. Gede Bage (0.947), Jln. Cibiru (0.900), and Jln. Raya Cileunyi (0.866), together, total 1.521 km, and warrant immediate rehabilitation.

Table 3. Top 12 priority national road segments in Bandung City (So base scenario).

Rank	Road Segment	IRI (m/km)	AADT (veh/d)	Score	Class
1	Jln. Gede Bage	7.6	45,459	0.947	CRITICAL
2	Jln. Cibiru	6.5	48,055	0.900	CRITICAL
3	Jln. Raya Cileunyi	6.2	48,055	0.866	CRITICAL
4	Jln. Rajawali Barat	4.6	47,846	0.673	HIGH
5	Jln. Raya Cipadung	4.3	48,055	0.642	HIGH
6	Bts. Cileunyi–Nagreg I	4.1	48,055	0.622	HIGH
7	Jln. Raya Ujung Berung (B)	8.0	33,506	0.615	HIGH
8	Jln. Soekarno-Hatta (A)	4.6	45,459	0.601	HIGH

Rank	Road Segment	IRI (m/km)	AADT (veh/d)	Score	Class
9	Jln. Sudirman	4.4	45,459	0.576	MEDIUM
10	Bts. Bandung– Cileunyi	3.8	48,055	0.574	MEDIUM
11	Jln. Raya Sindanglaya	3.7	48,055	0.560	MEDIUM
12	Jln. Raya Ujung Berung (A)	3.5	48,055	0.556	MEDIUM

The analytically most striking result is the ranking of Bts. Cileunyi–Nagreg I. This segment carries the highest IRI in the network (8.0 m/km) yet ranks only seventh, behind three segments with IRI in the 6.2–7.6 m/km range. Under a condition-only framework, this would appear counter-intuitive. The mechanism is unambiguous: Bts. Cileunyi–Nagreg I carries 33,506 vehicles per day, the minimum AADT in the dataset, so its AADT-normalised score is 0, and its composite Safety Risk is correspondingly suppressed. By contrast, the Critical segments carry 45,459–48,055 vehicles per day, yielding composite safety scores of 0.775–0.898. From a risk-management perspective, the result is correct: risk is the product of hazard severity and the exposed population. The Critical segments combine moderate-to-high hazard with maximum exposure, whereas Nagreg I combines maximum hazard with minimum exposure. The model correctly identifies that intervening on the maximum-volume corridors produces greater total risk reduction. This finding is the central empirical demonstration that risk-informed multi-criteria prioritization produces materially different rankings from condition-only approaches – the contribution this study set out to make.

3.4 Sensitivity analysis

Table 4 reports the rank stability of the top eight segments across the five weighting scenarios. Three findings emerge. First, the three Critical segments remain top-ranked across every scenario, including the extreme equal-weight case S4; their Critical designation is therefore not contingent on any particular weighting assumption and provides a highly reliable basis for immediate budget allocation. Second, Bts. Cileunyi–Nagreg I is the most scenario-sensitive segment: it rises toward fourth under IRI-dominant weighting (S1) and falls to approximately rank 22 under AADT-dominant weighting (S3), behaviour that is analytically expected given its IRI–AADT divergence. Third, the High-category segments show moderate stability with minor internal shuffling, while category reclassifications across the broader 36-segment ranking are confined to score-threshold neighbourhoods.

Table 4. Sensitivity analysis: rank stability of top segments across five weighting scenarios.

Road Segment	S ₀	S ₁ (IRI↑)	S ₂ (SR↑)	S ₃ (AADT↑)	S ₄ (Equal)	Priority Stability
Jln. Gede Bage	1	1	1	1	1	ROBUST - Critical in all
Jln. Cibiru	2	2	2	2	2	ROBUST - Critical in all
Jln. Raya Cileunyi	3	3	3	3	3	ROBUST - Critical in all
Jln. Rajawali Barat	4	5	4	4	4	Stable High
Jln. Raya Cipadung	5	6	5	5	5	Stable High
Bts. Cileunyi-Nagreg I	6	4	6	22	13	VARIABLE - IRI/AADT split
Jln. Raya Ujung Berung (B)	7	7	7	6	7	Stable High
Jln. Soekarno-Hatta (A)	8	8	8	8	6	Stable High

The complementary $\pm 20\%$ one-at-a-time (OAT) perturbation test (ten weight variations) confirms the scenario-based finding: across the entire OAT band, the three Critical segments retain their Critical designation without exception, and the category reclassifications that do occur are confined to segments lying immediately adjacent to the 0.450 and 0.600 thresholds and represent a single-category shift only. The model therefore demonstrates robustness to both wholesale changes in weighting philosophy and ordinary imprecision in the individual weights, while still possessing genuine discriminatory power at the category boundaries.

3.5 Discussion

The composite Safety Risk criterion is theoretically grounded in the road-safety literature, which consistently identifies the interaction between pavement quality and traffic volume as the primary driver of accident frequency and severity (Senić, 2025). It is computationally tractable, requires only data that the authority already maintains, and produces analytically interpretable rankings. The remaining limitations are explicit: equal weighting of IRI and AADT within the composite implies equal contribution to risk, which may not hold across all road types; the indicator cannot distinguish between damage types; and normalization expresses absolute risk only relative to the network. Within these scope conditions, the composite provides a valid relative measure of risk exposure where direct accident data are unavailable. The 58.6% CR improvement through geometric-mean aggregation, together with the identical rank order of single- vs multi-expert weights, supports both the directional validity of single-expert judgment and the superior methodological properties of group-based AHP for formal policy application.

From a policy standpoint, the framework translates the analytical findings into a defensible, reproducible instrument for allocating maintenance budgets. Mapped to operational practice, the four priority categories suggest a four-tier intervention schedule: Critical segments warrant structural rehabilitation or reconstruction within the current fiscal year; High-priority segments require detailed condition surveys for next-cycle programming; Medium-priority segments are best routed to preventive treatment within 12-24 months, the most cost-effective lever available because preventive treatment costs two to five times less per lane kilometre than rehabilitation after further decay (Sovanneth, 2025); and Low-priority segments enter a periodic inspection cycle. The framework is data-realistic in that it uses only the IRI surveys, traffic counts, and inventory data that BPJN West Java already maintains, so adoption requires no additional data-collection investment.

4. CONCLUSION

A multi-expert AHP model with geometric-mean aggregation was developed to prioritize road damage management across the 36 national road segments in Bandung City. The aggregated criteria weights are Safety Risk = 0.467, IRI = 0.234, AADT = 0.187, Rehabilitation Cost = 0.068, and Road Function = 0.044, attaining a Consistency Ratio of 0.036 - a 58.6% improvement over the single-expert reference (0.087). Three Critical segments (Jln. Gede Bage, Jln. Cibiru, Jln. Raya Cileunyi) warrant immediate rehabilitation, with their Critical designation robust across five sensitivity scenarios and the $\pm 20\%$ one-at-a-time perturbation band. The most physically damaged segment (Bts. Cileunyi-Nagreg I, IRI = 8.0) ranks seventh because its lowest network AADT suppresses composite exposure, providing the central empirical demonstration that risk-informed multi-criteria prioritization produces materially different rankings from condition-only approaches. Future work should integrate segment-level accident records as they become available through the IRSMS, replace the length-based cost proxy with unit-rate rehabilitation cost estimates, and validate the framework longitudinally against post-treatment IRI and safety outcomes. Comparative MCDA studies that apply ANP, TOPSIS,

and ELECTRE to the same dataset would further test the robustness of rankings across methods.

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