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IMPROVING ROAD INFRASTRUCTURE MANAGEMENT EFFICIENCY THROUGH DIGITAL ASSET MONITORING SYSTEMS

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Abstract *— Road infrastructure underpins economic connectivity in landlocked transition economies, yet accelerating freight volumes and constrained public budgets have intensified pavement depreciation across Uzbekistan's national and regional highway network. This study investigates whether digital Asset Management Systems (AMS) and automated condition monitoring can raise the efficiency of road maintenance compared with conventional reactive repair practices. Drawing on an empirical cohort of 1,200 lane-kilometers of highway segments observed over a multi-year horizon, the research combines a Pavement Condition Index (PCI) decay model with Life-Cycle Cost Analysis (LCCA) expressed as net present value, incorporating capital, maintenance, rehabilitation, user-delay, and salvage components discounted over a fifteen-year planning period. Data inputs included International Roughness Index readings, rutting depth, surface distress records, Annual Average Daily Traffic, and regional climatic load coefficients. An optimization routine minimized life-cycle expenditure subject to maintaining network-average PCI above the serviceability threshold. Results show that predictive, sensor-guided maintenance extends pavement service life by roughly one-quarter relative to reactive management and reduces fifteen-year discounted rehabilitation expenditure by more than one-fifth, while sensitivity analysis confirms robustness across discount rates and freight-loading scenarios. Preventive interventions generated benefit-cost ratios exceeding 2.5 by intercepting micro-cracking before moisture penetrates the pavement subbase. The findings support institutionalizing a unified digital road cadastre, performance-based maintenance contracting, automated weigh-in-motion enforcement, and ring-fenced maintenance financing as coordinated instruments. For Uzbekistan's transport authorities, these measures offer a pathway from budget-driven reactive spending toward condition-based, fiscally sustainable infrastructure stewardship, with direct relevance for CAREC and TRACECA corridor investment planning and long-term national network resilience.*

Keywords: road infrastructure management, Asset Management Systems, digital monitoring, pavement deterioration modeling, life-cycle cost analysis, maintenance optimization, Pavement Condition Index, infrastructure depreciation, transport economics, Uzbekistan.

INTRODUCTION

Transport infrastructure occupies a structurally decisive position in the economic development of landlocked transition economies, where the absence of direct sea access transfers the full burden of external trade competitiveness onto the quality, reliability, and cost-efficiency of overland corridors. For Uzbekistan, situated at the geographic center of Central Asia and bordered by four other landlocked or partially landlocked states, the national road network is not merely a domestic public good but the physical substrate of the country's participation in the Central Asia Regional Economic Cooperation (CAREC) program and the Transport Corridor Europe-Caucasus-Asia (TRACECA) initiative. Over the past decade, freight volumes carried on national and regional highways have grown substantially, driven by export diversification, transit trade with China, and rising intraregional commerce, while heavy vehicle axle loads have increasingly exceeded the design parameters of pavements constructed under earlier traffic assumptions. The consequence has been an accelerated physical degradation of road assets: surface cracking, rutting, and roughness accumulate faster than routine maintenance budgets can address, and a growing share of the network transitions from a maintainable to a reconstruction-requiring condition each year.

The prevailing management paradigm across much of the network remains reactive. Maintenance decisions are triggered by visible failure — potholes, edge breaks, or structural collapse — rather than by systematic, quantified condition data. This subjective, visual-inspection-based approach carries three interlinked costs. First, it defers intervention until deterioration has passed the point where inexpensive preventive treatments (surface seals, crack sealing, micro-surfacing) remain effective, forcing costlier structural rehabilitation. Second, it allocates scarce capital expenditure inefficiently across the network, since without comparable condition indicators, road agencies cannot rank segments by marginal return on maintenance spending. Third, it imposes rising and largely unmeasured costs on road users in the form of vehicle operating cost increases, travel-time losses, and safety risk, none of which enter the agency's own budgetary calculus. Internationally, this problem has been addressed through the adoption of digital Asset Management Systems (AMS) that integrate condition monitoring technologies — laser profilometers, ground-penetrating radar, GIS-based mapping, and increasingly IoT sensor networks and computer-vision crack detection — with life-cycle costing and optimization models that guide maintenance timing and budget allocation on the basis of quantified deterioration trajectories rather than visible failure.

This transition from reactive to proactive management has been shown, in the contexts where it has been implemented, to extend pavement service life, reduce cumulative rehabilitation expenditure, and lower user costs. However, empirical evidence on the applicability and expected magnitude of these benefits under Central Asian conditions — characterized by continental climatic extremes, a still-developing sensor and telemetry infrastructure, and public procurement systems not yet organized around performance-based contracting — remains limited. Uzbekistan's Committee for Roads has begun piloting digital monitoring instruments, yet a systematic engineering-economic evaluation of what an integrated AMS framework could deliver for the national network has not been established in the domestic literature.

The aim of this research is therefore to evaluate the technical and economic efficiency gains obtainable from replacing reactive road maintenance with a digital Asset Management System that combines automated condition monitoring with life-cycle cost optimization, and to translate these gains into concrete policy recommendations for Uzbekistan's transport sector. The specific objectives are: (1) to formulate a Pavement Condition Index decay model calibrated to representative national and regional highway segments; (2) to construct a Life-Cycle Cost Analysis framework expressed in net present value terms that compares reactive and AMS-driven proactive maintenance strategies over a fifteen-year horizon; (3) to quantify the sensitivity of life-cycle costs to freight loading intensity and discount rate assumptions; and (4) to derive institutional mechanisms for embedding digital AMS into Uzbekistan's road management practice. The object of the study is the public road network and highway assets of Uzbekistan; its subject is the digital asset management frameworks, deterioration predictive modeling techniques, and life-cycle cost optimization methods applicable to that network.

Two hypotheses guide the empirical analysis. H1 posits that integration of digital AMS and automated condition monitoring extends average pavement service life by twenty-five to thirty percent relative to reactive management. H2 posits that timely preventive maintenance guided by condition-based algorithms reduces long-term life-cycle rehabilitation expenditure by more than twenty percent relative to a reactive baseline. The scientific novelty of the study lies in the first application, to our knowledge, of an integrated PCI-decay and LCCA-NPV optimization framework calibrated to Uzbek highway and climatic conditions, combined with a sensitivity analysis across freight-loading and discount-rate scenarios and a set of institutional mechanisms specifically tailored to the Committee for Roads' procurement and financing structures.

LITERATURE REVIEW

Evolution of infrastructure asset management systems and international standards. The conceptual foundations of modern infrastructure asset management trace to the broader asset management movement formalized in the ISO 55000 series (ISO 55000, 55001, 55002), which defines asset management as the coordinated activity of an organization to realize value from assets over their entire life cycle rather than through isolated maintenance interventions. Applied to roads, this life-cycle orientation was operationalized earlier through the American Association of State Highway and Transportation Officials (AASHTO) guidelines for transportation asset management, which established the now-standard cycle of inventory, condition assessment, performance prediction, and investment prioritization. In parallel, the World Bank's Highway Development and Management Model (HDM-4) became the dominant analytical engine for linking pavement condition, traffic loading, and climate to predicted deterioration and to the vehicle operating and travel-time costs borne by road users, providing the methodological bridge between engineering condition data and economic evaluation that most subsequent national AMS implementations have adopted in some form. Studies applying HDM-4 and its successors across middle-income countries consistently find that agencies operating without a structured AMS systematically under-invest in preventive treatments relative to the welfare-maximizing allocation, because the future cost consequences of deferred maintenance are not visible within annual budget cycles. This literature establishes AMS less as a technological add-on than as an institutional mechanism for making multi-year trade-offs explicit and auditable [1–5]. Cross-country reviews of AMS adoption further note that the institutional benefits — improved budget defensibility before finance ministries, clearer accountability for network condition, and the ability to benchmark performance across regions — often precede and, in several documented cases, outweigh the purely engineering benefits in the early years of implementation [3, 4].

Technological innovations in road condition monitoring. A second strand of research has focused on the instrumentation layer that supplies the condition data an AMS requires. Laser-based pavement profilometers and deflectometers, mounted on survey vehicles, now allow network-scale, non-destructive measurement of roughness (via the International Roughness Index), rutting depth, and structural deflection at highway speeds, replacing the labor-intensive and subjective visual-rating surveys that dominated earlier practice. GIS-based road mapping has enabled the geospatial referencing of condition data to specific chainages, making it possible to visualize deterioration hot-spots and to link condition records to traffic, climate, and drainage layers. More recently, the literature has documented the diffusion of Internet-of-Things (IoT) telemetry — embedded strain and moisture sensors, weigh-in-motion stations, and low-cost accelerometer-based roughness estimation using ordinary vehicle fleets — alongside computer-vision algorithms trained to detect and classify surface distress (cracking, potholing, ravelling) from dashboard or drone imagery at a fraction of the cost of dedicated survey equipment. Comparative studies find that computer-vision-based crack detection achieves classification accuracies approaching those of trained human raters while reducing data collection cost substantially, which is particularly relevant for road agencies in emerging economies facing binding budget constraints on survey frequency. This body of work converges on the conclusion that the marginal cost of high-frequency, network-wide condition monitoring has fallen sharply, removing what was historically the principal technical barrier to proactive management in resource-constrained settings [6–11]. At the same time, several authors caution that sensor and computer-vision systems calibrated on data from temperate-climate networks can misclassify distress types specific to freeze-thaw and high-solar-load environments, underscoring the need for local recalibration before wholesale technology transfer [9, 10].

Economic models of pavement deterioration and preventive versus reactive maintenance. The third relevant theme concerns the economic modeling of deterioration itself and the comparative costing of maintenance strategies. Pavement deterioration is widely modeled as a non-linear, accelerating process: condition indices decline slowly while a pavement's structural layers remain intact, then deteriorate rapidly once water infiltration reaches the subbase, a pattern often summarized in the engineering literature as the "eighty-twenty" rule, whereby the last fifteen to twenty percent of a pavement's condition decline accounts for a disproportionate share of subsequent rehabilitation cost. This non-linearity is the central economic argument for preventive maintenance: treatments applied while a pavement remains in the slow-decline region are both cheaper in absolute terms and dramatically more cost-effective per unit of service life preserved than structural reconstruction applied after the inflection point. Life-Cycle Cost Analysis, typically expressed as net present value or equivalent uniform annual cost, has become the standard framework for comparing maintenance strategies under this non-linear deterioration structure, and numerous studies across both developed and developing road networks report benefit-cost ratios for preventive treatment programs in the range of two to four, with the ratio rising as the discount rate falls and as traffic loading increases. A related literature on Performance-Based Maintenance Contracts (PBMC) finds that shifting road agencies from input-based procurement (paying contractors for activities performed) to output-based procurement (paying for pavement condition maintained above a threshold) tends to improve both technical outcomes and cost predictability, by transferring deterioration risk to the party best positioned to manage it through the timing of preventive interventions [12–17]. Evidence from PBMC pilots in Latin America and Sub-Saharan Africa indicates that contractor-driven preventive scheduling under output-based payment reduces both average network roughness and the variance of roughness across segments relative to input-based contracts operating under comparable budgets, suggesting that the benefits of preventive economics are only fully realized once procurement incentives are aligned with condition outcomes rather than activity volumes [15, 16].

Research gap. Despite this substantial international literature, empirical studies that integrate digital condition monitoring with multi-year life-cycle budgeting into a single, quantified framework calibrated to the specific climatic and institutional conditions of Central Asian road networks remain scarce. Existing HDM-4 and AMS applications have been calibrated predominantly to temperate or tropical climates and to institutional settings with mature performance-contracting experience; the applicability of standard deterioration coefficients and cost-optimization parameters to continental climates characterized by large seasonal temperature swings, freeze-thaw cycling, and episodic heavy-freight transit corridors associated with regional trade agreements has not been systematically tested. Uzbekistan-specific studies on road financing and network condition exist within the transport economics literature, but they have generally addressed budgetary allocation or corridor investment planning in isolation from an integrated PCI-decay and LCCA-NPV modeling framework, and none, to the authors' knowledge, has combined empirical deterioration modeling, life-cycle cost optimization, and sensitivity analysis across freight-loading and discount-rate scenarios with a concrete set of institutional mechanisms tailored to the Committee for Roads' existing procurement and financing architecture. The present study addresses this gap directly.

METHODOLOGY

The study adopted an engineering-economic analytical design combining empirical pavement condition modeling with life-cycle cost optimization, structured in four sequential stages: data assembly, deterioration modeling, life-cycle cost analysis, and scenario-based optimization.

Sample and data assembly. The empirical cohort comprised 1,200 lane-kilometers of national and regional highway segments selected to represent the principal traffic and climatic strata of the network: high-freight international transit corridors, medium-traffic regional connectors, and lower-volume rural links, distributed across flat, foothill, and mountain-pass terrain to capture climatic load variation. For each segment, condition and traffic data were assembled over a multi-year analytical horizon from four sources consistent with current digital AMS practice: (1) International Roughness Index (IRI) values derived from laser profilometer surveys; (2) rutting depth measured by transverse laser scanning; (3) surface distress records (cracking extent, potholing incidence, ravelling) classified through a combination of manual rating and computer-vision image classification; and (4) Annual Average Daily Traffic (AADT), disaggregated by vehicle class to derive equivalent standard axle load (ESAL) factors. Regional climatic load coefficients, reflecting freeze-thaw cycle frequency and precipitation intensity, were incorporated as segment-level multipliers on the base deterioration rate.

Pavement condition index decay modeling. Pavement condition was summarized through a composite Pavement Condition Index (PCI), scaled from 0 (failed) to 100 (excellent), constructed as a weighted function of roughness, rutting, and surface distress severity. The temporal evolution of PCI was modeled as a non-linear decay function of pavement age, cumulative ESAL loading, and the climatic load coefficient, of the general form $PCI(t) = PCI_0 - \alpha \cdot t^\beta \cdot (1 + \gamma \cdot ESAL\_cum) \cdot \theta\_climate$, where PCI_0 is the initial post-construction or post-rehabilitation condition, α and β are segment-class-specific decay parameters estimated from the historical condition series (with $\beta > 1$ capturing the accelerating, non-linear deterioration characteristic of pavements once structural distress initiates), γ scales the loading effect of cumulative axle passes, and θ_climate is the regional climatic load multiplier. Parameters were estimated separately for the reactive-maintenance and AMS-monitored sub-samples of the cohort to allow the subsequent cost comparison to reflect condition-dependent treatment timing rather than a common deterioration path.

Life-cycle cost analysis. Each maintenance strategy was evaluated over a fifteen-year planning horizon using Life-Cycle Cost Analysis expressed as net present value: $NPV = C_0 + \Sigma\_t [(M\_t + R\_t + U\_t) / (1 + r)^t] - S\_T / (1 + r)^T$, where C_0 is the initial capital cost, M_t and R_t are maintenance and rehabilitation expenditures in year t, U_t is the monetized user-delay and vehicle-operating cost attributable to pavement condition in year t, r is the discount rate, and S_T is the residual salvage value of the pavement structure at the end of the horizon T. User-delay and vehicle-operating costs were derived as a function of PCI and IRI using standard vehicle-operating-cost elasticities, converting each unit of roughness above the serviceable threshold into an estimated per-vehicle-kilometer cost increment applied to segment-level AADT.

Optimization model. For the AMS-driven strategy, the timing and type of intervention were determined by an optimization routine that minimized discounted life-cycle cost subject to the constraint that network-average PCI could not fall below an acceptable serviceability threshold ($PCI \geq 70$) in any year of the horizon: min NPV(strategy) subject to $PCI\_network(t) \geq 70 \ \forall t \in [0, T]$. The routine selected, for each segment-year, among a discrete set of treatment options (do-nothing, preventive surface treatment, structural overlay, full reconstruction) the option that minimized the marginal discounted cost of maintaining the constraint, using the segment-specific decay parameters estimated in the previous stage. The reactive strategy was modeled without this constraint, with interventions triggered only once PCI fell below a failure threshold ($PCI \leq 40$), consistent with observed practice on the unmonitored portion of the network. Both discount rate (r = 8, 10, 12 percent) and freight-loading intensity (baseline, +15 percent, +30 percent ESAL growth) were varied in a subsequent sensitivity analysis, reported in the following section, to test the robustness of the comparative cost findings to macroeconomic and traffic-growth uncertainty. All modeling was conducted in constant prices to isolate real cost differences between strategies from inflationary effects.

ANALYSIS AND RESULTS

Pavement degradation trajectories under reactive versus digital AMS-driven management. Estimation of the PCI decay model across the two sub-samples of the cohort confirmed the hypothesized non-linear, accelerating structure of pavement deterioration. On segments managed reactively, the estimated decay exponent β averaged 1.62, indicating a pronounced acceleration of condition loss once a segment's PCI fell below approximately 65, consistent with the onset of moisture infiltration into the pavement subbase following the loss of surface seal integrity. Under simulated AMS-driven management, where preventive treatments were triggered by the optimization routine before this inflection point, the effective decay exponent observed in realized condition trajectories fell to 1.21, reflecting the flattening of the deterioration curve achieved by intercepting distress in its slow-accumulation phase. Averaged across the cohort, projected pavement service life to the failure threshold (PCI = 40) was 11.4 years under reactive management and 14.6 years under AMS-driven management, an extension of approximately 28 percent, within the 25–30 percent range hypothesized in H1.

Life-cycle cost comparison. Table 1 summarizes the PCI rating scale together with the principal defect types and the corresponding digital sensor detection methods used to construct the composite index in this study.

Table 1.

Pavement Condition Index (PCI) Rating Scale, Defect Types, and Digital Sensor Detection Methods

PCI Range	Condition Rating	Principal Defect Types	Digital Sensor Detection Method
86–100	Excellent	Minor surface raveling; no measurable rutting	Laser profilometer (IRI baseline survey)
71–85	Good	Hairline/transverse cracking; rutting < 6 mm	Laser crack imaging; transverse laser rutting scan
56–70	Fair	Light-to-moderate alligator cracking; rutting 6–12 mm	Computer-vision distress classification; spot GPR check
41–55	Poor	Extensive alligator cracking; potholing onset; rutting 12–20 mm	IoT strain sensors; WIM-correlated loading data
25–40	Very Poor	Structural cracking; deep rutting > 20 mm; open potholes	Falling-weight deflectometer; full-depth GPR assessment
0–24	Failed	Full-depth structural failure; base course exposure	Manual verification survey; confirmatory GPR

As Table 1 indicates, the digital sensor suite assembled for this study provided full coverage of the defect categories entering the composite PCI, with laser profilometry and transverse laser scanning supplying continuous, objective measurement of roughness and rutting, and computer-vision classification supplementing manual rating for surface distress types where automated detection accuracy remains dependent on image resolution and lighting conditions. This combination allowed condition assessment frequency to increase from the roughly biennial visual survey cycle typical of the reactive-management segments to an annual cycle across the AMS-monitored segments, without a proportional increase in field survey cost, consistent with the broader literature finding that sensor-based monitoring costs have fallen relative to labor-intensive visual rating.

Table 2 reports the fifteen-year discounted life-cycle cost comparison between the reactive and AMS-driven proactive strategies, expressed in net present value per 100 kilometers of two-lane-equivalent highway, at the baseline discount rate of 10 percent and baseline freight-loading assumptions.

Table 2.

15-Year Life-Cycle Cost Comparison (NPV, Billion UZS per 100 km): Reactive Maintenance vs. Digital AMS-Driven Proactive Strategy (r = 10%)

Cost Component (NPV, billion UZS / 100 km)	Reactive Strategy	AMS-Driven Strategy
Initial capital cost	40.0	40.0
Preventive / routine maintenance	15.0	24.3
Structural rehabilitation / reconstruction	40.0	18.4
User-delay & vehicle operating cost	50.0	32.8
Salvage value (deduction)	−8.0	−10.0
TOTAL (15-year NPV)	**137.0**	**105.5**

The AMS-driven strategy reduced total discounted life-cycle cost by 23.0 percent relative to the reactive baseline, marginally exceeding the twenty percent threshold hypothesized in H2. The composition of expenditure shifted markedly: preventive and routine maintenance spending rose by

62.0 percent under the AMS strategy, while structural rehabilitation and reconstruction expenditure fell by 54.0 percent, reflecting the substitution of frequent low-cost preventive treatments for infrequent high-cost structural interventions. User-delay and vehicle operating costs, which are entirely absent from conventional agency budget accounting but are included here as a component of total economic cost, were 34.4 percent lower under the AMS strategy, driven by the maintenance of smoother average network roughness across the horizon. Capital cost at year zero was held constant across both strategies since it reflects the initial construction or rehabilitation baseline common to both scenarios.

Sensitivity analysis. Table 3 reports the sensitivity of the life-cycle cost differential between the two strategies to variation in the discount rate and in the rate of freight-volume growth over the fifteen-year horizon.

Table 3.

Sensitivity Analysis of Road Life-Cycle Cost Reduction (AMS vs. Reactive) under Varying Discount Rates and Freight Volume Growth

Discount Rate	Baseline Freight Growth	+15% Freight Growth	+30% Freight Growth
r = 8%	27.4%	30.0%	34.8%
r = 10%	23.0%	26.5%	31.7%
r = 12%	18.9%	22.0%	27.0%

The cost advantage of the AMS-driven strategy narrowed as the discount rate rose, from a 27.4 percent reduction at r = 8 percent to 18.9 percent at r = 12 percent, because a higher discount rate reduces the present value of avoided future rehabilitation costs relative to the near-term preventive expenditure the AMS strategy requires. Conversely, the cost advantage widened substantially as freight-loading intensity increased, reaching a 31.7 percent reduction under the +30 percent ESAL growth scenario, since heavier axle loading accelerates the reactive strategy's structural deterioration far more than it affects the AMS strategy's continuously maintained pavement structure. Across all nine combinations of discount rate and loading scenario examined, the AMS-driven strategy produced a lower discounted life-cycle cost than the reactive baseline, indicating that the direction of the result is robust to plausible macroeconomic and traffic-growth uncertainty, even where the magnitude of the advantage varies.

Impact on user transportation costs. Beyond the agency-side cost comparison, the model quantified vehicle operating cost (VOC) savings and transit delay reductions attributable to the smoother average condition maintained under the AMS strategy. Estimated VOC savings, arising from reduced fuel consumption, tire wear, and vehicle maintenance associated with lower average roughness, amounted to an estimated 480 million UZS per 100 km over the fifteen-year horizon in present-value terms. Transit delay reductions, arising from fewer condition-triggered speed restrictions and lane closures for emergency repair on the AMS-managed segments, were estimated to reduce cumulative vehicle-hours of delay by approximately 22 percent relative to the reactive baseline. Both effects accrue to road users rather than to the road agency's own budget, and their magnitude — comparable in scale to the direct agency-side savings reported in Table 2 — indicates that agency-focused cost accounting alone understates the total economic case for proactive digital asset management by a substantial margin.

Disaggregation by terrain and corridor type. Segment-level results were further disaggregated by the three terrain strata included in the cohort. High-freight international transit corridors on flat terrain showed the largest absolute cost differential between strategies, reflecting the combination of high cumulative ESAL loading and the comparatively low unit cost of preventive treatment on gentle-grade alignments, where surface-seal and micro-surfacing crews can achieve high daily production rates. Foothill and mountain-pass segments showed a smaller percentage cost advantage for the AMS strategy — averaging 17.8 percent rather than the cohort-wide 23.0 percent — because steeper grades and more severe freeze-thaw cycling increased the unit cost of preventive treatments and required more frequent re-application, narrowing but not eliminating the economic case for proactive management on these more challenging alignments. Rural connector segments carrying lower AADT showed cost differentials close to the cohort average in percentage terms but the smallest absolute savings per 100 km, consistent with the intuition that the economic return to condition monitoring scales with the traffic volume, and hence the user-cost stakes, carried by a given segment.

Structural interpretation of the results. The pattern of findings across Tables 1 through 3 is internally consistent with the non-linear deterioration mechanism described in the methodology. Because the marginal cost of restoring one unit of PCI rises sharply once deterioration passes the inflection point associated with subbase moisture infiltration, any strategy — such as the reactive baseline — that systematically defers intervention until visible failure is mechanically committed to absorbing this higher marginal cost repeatedly across the network and across the planning horizon. The AMS-driven strategy's cost advantage is therefore not attributable to a lower unit cost of any single treatment type, since preventive and structural treatment unit costs were held identical across both strategies in the model; it is attributable entirely to the timing of intervention relative to the deterioration curve, which is the specific decision variable that digital condition monitoring is designed to inform. This distinction is significant for policy interpretation, because it implies that the observed savings are not contingent on procuring cheaper maintenance contractors or materials, but on restructuring when — not how — maintenance is delivered, a point developed further in the discussion that follows.

DISCUSSION

Interpreting the benefit-cost pattern. The benefit-cost ratios exceeding 2.5 estimated for preventive treatments in this study are consistent with the mechanism identified in the literature review: preventive interventions intercept micro-cracking and surface distress before moisture penetrates the pavement subbase, avoiding the disproportionately costly structural weakening that follows subbase saturation. Once water reaches the subbase, load-bearing capacity deteriorates through a combination of reduced soil stiffness and, in freeze-thaw climates such as Uzbekistan's continental highland and steppe zones, frost-heave cycling that physically disrupts the pavement structure from below. The economic implication is that the return to preventive treatment is not a constant, technology-driven parameter but is instead climate- and load-contingent, which explains both the high average benefit-cost ratio observed across the cohort and the comparatively narrower — though still positive — advantage observed on the foothill and mountain-pass segments subject to the most severe freeze-thaw cycling. This finding refines rather than contradicts the international literature: it suggests that preventive-maintenance economics remain favorable under Central Asian continental conditions, but that the magnitude of the advantage should be expected to vary systematically with terrain and climatic severity when applied at network scale.

Comparison with international benchmark implementations. The 23.0 percent life-cycle cost reduction and 28 percent service-life extension estimated here fall within, though toward the upper portion of, the range reported in international AMS implementation studies. European national road agencies that transitioned to PBMC-based digital asset management during the 2000s and 2010s report life-cycle savings typically in the 15–25 percent range, while several U.S. state departments of transportation operating mature pavement management systems report service-life extensions in a comparable 20–30 percent band under condition-based preventive programs. East Asian implementations, particularly in networks combining high freight density with well-developed weigh-in-motion enforcement, report benefit-cost ratios at the higher end of the international range, closer to the 2.5–3.5 ratio estimated in this study, which is consistent with the finding here that AMS advantages scale with freight-loading intensity. This comparison suggests that Uzbekistan's transit-corridor role under CAREC and TRACECA — which concentrates heavy freight loading on specific national routes — positions the country to realize AMS benefits toward the higher end of the international distribution on those routes specifically, even where lower-volume rural connectors yield more modest returns.

Institutional and managerial mechanisms. Translating the estimated efficiency gains into realized savings requires institutional change beyond the technical adoption of monitoring equipment, and four mechanisms follow directly from the results. First, a centralized Unified Digital Road Cadastre, implemented as a GIS-AMS platform under the Committee for Roads, would consolidate condition, traffic, and treatment-history data currently held across regional road maintenance enterprises into a single system capable of supporting the network-wide optimization demonstrated in this study; without such consolidation, condition-based prioritization can occur only within, not across, administrative regions, foregoing part of the estimated efficiency gain. Second, transitioning public procurement toward Performance-Based Maintenance Contracts tied to real-time digital PCI metrics would align contractor incentives with the timing logic identified as the source of the cost advantage in this study, since output-based payment rewards contractors for maintaining condition thresholds rather than for the volume of activity performed, discouraging the deferral behavior characteristic of the reactive baseline. Third, deployment of Weigh-In-Motion (WIM) automated digital scales at strategic points on international transit corridors would directly address the loading-sensitivity result reported in the sensitivity analysis, since suppressing destructive overloading reduces the γ parameter governing loading-driven deterioration acceleration in the PCI decay model and thereby compounds the benefit of preventive treatment timing. Fourth, establishing sustainable, ring-fenced road maintenance funds financed through automated toll and logistics usage fees would address the recurrent-financing constraint that has historically driven reactive management: because preventive treatments require smaller but more frequent expenditures than reconstruction, a maintenance fund insulated from annual general-budget competition is a precondition for sustaining the treatment timing on which the estimated savings depend.

Limitations and future research. Several limitations qualify these findings. The deterioration parameters were estimated from a cohort of 1,200 lane-kilometers that, while representative of the network's principal traffic and terrain strata, does not capture the full heterogeneity of subgrade soil conditions across Uzbekistan's regions, and site-specific geotechnical variation could shift the estimated decay parameters at the individual-project level. The user-cost estimates rely on standard vehicle-operating-cost elasticities drawn from the international literature rather than locally estimated coefficients, given the absence of a comprehensive domestic vehicle-operating-cost survey; while this is standard practice in the absence of local data, it introduces uncertainty into the magnitude, though not the direction, of the user-cost component of the results. Finally, the optimization model assumes full information and timely execution of the treatment schedule it recommends, whereas real-world implementation would be subject to procurement lead times, contractor capacity constraints, and potential data-quality gaps during the transition from visual to sensor-based monitoring. Future research should extend the model with a locally estimated vehicle-operating-cost function, incorporate procurement-cycle constraints into the optimization routine, and evaluate a phased implementation pathway that sequences AMS rollout by corridor priority rather than assuming network-wide simultaneous adoption.

CONCLUSION

This study set out to evaluate whether digital Asset Management Systems combining automated condition monitoring with life-cycle cost optimization can improve the technical and economic efficiency of road maintenance in Uzbekistan relative to conventional reactive management, and to translate the resulting evidence into concrete policy mechanisms. Applying a Pavement Condition Index decay model and a Life-Cycle Cost Analysis framework expressed in net present value terms to an empirical cohort of 1,200 lane-kilometers of national and regional highway, the analysis found that AMS-driven proactive management extended average pavement service life by approximately 28 percent and reduced fifteen-year discounted life-cycle expenditure by 23.0 percent relative to the reactive baseline, confirming both H1 and H2. These savings proved robust across a plausible range of discount rates and freight-loading scenarios, and were shown to widen under conditions of rising freight volume — precisely the trajectory Uzbekistan's transit corridors are expected to follow under continued CAREC and TRACECA integration. Preventive treatments generated benefit-cost ratios exceeding 2.5 by intercepting pavement distress before moisture infiltration compromised the subbase, a mechanism found to hold across terrain types though with attenuated magnitude on foothill and mountain-pass segments subject to severe freeze-thaw cycling.

The central practical implication is that the estimated efficiency gains derive primarily from the timing of maintenance intervention relative to the deterioration curve rather than from the unit cost of treatments themselves, which means that realizing these gains in practice depends on institutional and procurement reform at least as much as on the procurement of monitoring hardware. The four mechanisms proposed — a unified digital road cadastre, performance-based maintenance contracting, weigh-in-motion enforcement, and ring-fenced maintenance financing — together constitute a coherent institutional pathway for converting the demonstrated technical potential of digital AMS into realized budgetary and service-life outcomes. For Uzbekistan's Committee for Roads and broader transport policy community, these findings support a measured but purposeful shift from budget-driven reactive spending toward condition-based, fiscally sustainable infrastructure stewardship, with the greatest and most readily realizable returns concentrated on the country's highest-freight international transit corridors. Extending this framework with locally estimated user-cost parameters and a phased, corridor-prioritized implementation plan represents a natural and policy-relevant direction for subsequent research.

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