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A GIS framework for road asset monitoring in mountainous regions: a Tajikistan case

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Abstract: This article examines an approach to digital monitoring of road conditions and transport accessibility in the mountainous regions of Tajikistan based on modern geoinformation technologies. The first section substantiates the need to transition from occasional field surveys to systematic monitoring using satellite imagery, unmanned aerial vehicle data, and a unified GIS portal for the road network. It describes a methodology for integrating disparate remote sensing and ground-based data, as well as procedures for their preprocessing, georeferencing, and validation. Particular attention is paid to the development of a unified GIS portal structure that enables the storage, updating, and visualization of information on road surface conditions and road infrastructure elements in mountainous areas. The potential of geoinformation analysis for identifying areas of accelerated road degradation, assessing the impact of terrain and climatic factors, and calculating transport accessibility indicators for populated areas and socially significant facilities is demonstrated. The proposed approach allows supporting decision-making on road repair and maintenance, increasing the efficiency of limited financial resources, and forming the basis for the implementation of a road asset management system in the Republic of Tajikistan.

Keywords: geoinformation monitoring, satellite data, GIS portal, roadway degradation, mountain roads, transport accessibility, RAMS

1. Introduction

Roads in mountainous regions are characterized by accelerated degradation due to a combination of difficult terrain, intense climatic influences, and limited accessibility for regular field surveys. These factors are particularly acute in the Republic of Tajikistan, as a significant portion of the road network passes through mountainous and high-altitude areas, where traditional diagnostic methods require significant resources and do not provide sufficiently frequent data updates.

In recent years, approaches to monitoring road asset conditions based on satellite data, unmanned aerial vehicles (UAVs), computer vision, and geographic information systems (GIS) have been rapidly developing globally. Most research focuses on the automatic detection of road surface defects, assessing the accuracy of machine learning algorithms, and comparing the performance of various sensors. However, significantly less work has been devoted to integrating remote sensing results into national road asset management systems (RAMS) using formalized linear referencing, segmentation, and analytical layers oriented toward management decision-making.

In particular, existing literature has insufficiently addressed the issues of aligning highly detailed UAV and satellite monitoring data with official RAMS data structures, such as network segmentation, operational condition indicators (IRI, visual indices), and planning tools (including HDM-IV-type models). This limits the practical application of remote monitoring for repair prioritization and strategic road network management.

The purpose of this article is to develop and test an integrated geoinformation approach to monitoring road assets in the mountainous conditions of Tajikistan. This approach is based on the fusion of satellite and drone data, a linear reference system (ALRS), and GIS analytical methods compatible with RAMS requirements. The paper proposes the structure of a unified GIS portal that enables the transformation of heterogeneous observation data into standardized condition and risk layers suitable for use in road asset planning and management.

The scientific contributions of this paper include the following:

1. A practical framework for integrating remote sensing data into RAMS based on linear referencing and segmentation is proposed;
2. A set of GIS-based analytical layers is developed that enable the interpretation of pavement degradation, taking into account mountain and climatic factors;
3. The applicability of the proposed approach to supporting decision-making in resource-constrained road agencies is demonstrated.

Literature Review

A key contribution of remote sensing is the ability to repeatedly and consistently monitor road condition deterioration over time. Longitudinal UAV monitoring has been used to detect multi-year changes in pavement damage and relate them to environmental factors (e.g., permafrost and slope processes), demonstrating how image-based damage rates and roughness metrics can support temporal comparisons in mountainous and climate-sensitive corridors [1].

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At network scale, satellite imagery combined with pavement management tags has been used to train deep learning models for condition assessment, with one study reporting overall classification accuracy above 90% [2]. This validates the role of satellites as a scalable layer for periodic, wide-coverage monitoring - especially where ground-based diagnostics are sparse or inconsistent.

2.2. From images to measurements: georeferencing, ortho-correction, and quantification.

Decision-making requires comparable measurements across time and space, increasing the importance of pre-processing (geo-referencing, distortion correction, orthomosaic creation). A low-cost, real-time machine vision system demonstrates how photogrammetric homography and planar mapping can transform pixel information into real-world distances without expensive hardware, enabling image-based metric estimates suitable for rapid condition assessment [3].

For UAV surveys, robust stitching and correction remain critical. UAV pavement stitching workflows that consider overlaps and flight control, combined with semantic crack segmentation, have been used to create orthomosaics and quantify crack morphology; reported errors in extracted features (area, length, width) are approximately 16% in complex scenarios [4].

2.3. AI models for near-real-time damage detection and results inference.

Recent studies report high performance in applying computer vision to defect detection on UAVs. A UAV-based defect detection pipeline using the YOLO family detector shows a mAP@0.5 of approximately 89,5% [5], demonstrating the feasibility of real-time screening of common defects in aerial imagery.

Beyond performance, numerous literature highlights deployment-oriented considerations: improving robustness through preprocessing/extension, handling class imbalance and segmentation loss engineering, and generating output data that can be integrated into GIS layers. A literature review summarizes a wide range of approaches to automatic detection and measurement of defects, while noting practical limitations regarding generalization and standardization across sensors and environments [7].

Furthermore, drone-to-web concepts point to future operational models in which autonomous UAV surveys and airborne detection publish geo-referenced emergency data to a web platform for maintenance prioritization [8].

2.4. GIS/RAMS integration: from monitoring to management decisions.

The literature clearly demonstrates that the full value of remote sensing and AI is only realized when the results are integrated into asset management processes. A review of the current state of transportation asset management practices highlights implemented agency workflows combining GIS platforms with photogrammetry, mobile mapping, and LiDAR for inventory and condition management [6, 18].

For mountain road networks, intelligent GIS for mountain roads demonstrates the integration of field studies, laboratory material properties, open remote sensing and meteorological data into a forecasting and management-oriented IGIS framework, emphasizing the need to link observed damage patterns with climatic and terrain factors [9].

In the context of RAMS in Tajikistan, the informal literature provides explicit requirements defining the operationalization of monitoring results. The technical and functional requirements of RAMS emphasize an integrated approach to spatially supported databases (RAMS unified logical database, RDBMS spatial environment) based on a road location reference system (RLRS) to ensure consistent linkage of assets, conditions, and activities [10]. The initial report envisions RAMS as a multi-stakeholder decision support system that should include high-level reporting tools and dashboards, as well as an inventory database linked to GIS technologies and electronic documentation [11].

In the reviewed literature, the most compelling evidence points to (i) the use of UAVs and satellite monitoring as complementary methods, (ii) visual data-based detection/segmentation of incidents, and (iii) integration with GIS for management purposes. However, the provided corpus contains limited empirical data on radar-optical fusion for road condition monitoring, comprehensive comparative sensor matching experiments, and fully described implementations of spatial database schemes. Therefore, these topics should be considered as challenges for future research or as requiring additional specialized sources beyond the scope of the current review.

Study area and input data. The proposed framework is designed for Tajikistan's mountain corridors, where frequent field surveys are difficult and deterioration factors vary dramatically over short distances. The basic input data for assessing operational conditions are (i) IRI-based roughness over 100-meter sections and (ii) visual condition recorded by the ODCC over 10-meter sections. Maintaining data relevance for long-term decision-making requires consistent spatial referencing, verification, and data update management.

Remote sensing complements these studies by providing multiple spatial data for (a) identifying priority network sections and (b) creating high-precision defect inventories along selected corridors.

2.5. Quantitative assessment of the effect of geoinformation filtering.

To assess the practical value of the proposed geoinformation approach, aggregated data on operational condition was processed for 100-meter segments using the IRI indicator and visual damage assessment (ODCC). In the first stage, the entire set of segments of the surveyed national roads was analyzed without preliminary spatial filtering. In the second stage, GIS filtering was applied, based on combining condition data with factors such as topography, drainage, and climate vulnerability.

The results showed that the use of geoinformation filtering reduced the number of segments prioritized for detailed survey and repair planning by an average of 25-30% compared to an analysis based solely on IRI thresholds. Furthermore, the resulting priority sample included areas with the highest degradation rates and increased sensitivity to natural factors, confirming the feasibility of using GIS analytics as a preliminary selection tool.

The obtained result indicates that the integration of remote monitoring and spatial analysis not only allows for more informative condition assessments, but also significantly reduces the burden on resource-intensive field surveys, which is especially important for mountainous regions with limited budgets.

2. Methodology

Using satellite and drone data to assess road conditions

Remote sensing has become a practical complement to traditional pavement surveys because it enables the acquisition of repeatable, georeferenced data across large networks while simultaneously enabling highly detailed inspections of priority corridors. For a road asset management system (RAMS), the value lies not in the images themselves, but in the ability to convert imagery into standardized condition attributes (e.g., cracks, potholes, ruts, roughness indices) that can be linked to the official road location system and stored consistently over time. In ongoing RAMS implementation work in Tajikistan, available condition data already includes 100-m-resolution IRI and 10-m-resolution ODCC visual assessment; however, to improve planning, more accurate damage inventories, rutting, full-weight bearing capacity (FWD), girth thickness (GPR), and skid resistance are necessary or desirable. Figure 1 schematically illustrates the multi-source monitoring approaches.

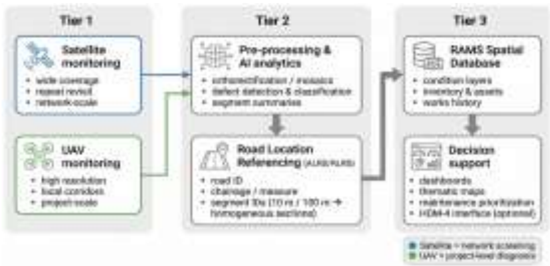

Fig. 1. Conceptual diagram of the multi-source monitoring approach

Satellite observations support network-level screening and change detection, while UAV missions provide project-level defect inventory. Both streams are linked to ALRS location keys and stored as segment-level events/indices for aggregation into homogeneous partitions.

3.1. Road condition monitoring using satellite/UAV data for RAMS.

To support decision-making, remote sensing results must be consistent with the condition information expected in the RAMS database (e.g., surface/structure condition elements such as cracks, deterioration, potholes, edge debris, and ruts; as well as indices such as PCI and roughness/IRI). In practice, this requires: (i) clear definition of target defects and indices; (ii) consistent georeferencing to road station dates/sections; and (iii) recurring update cycles to support trend analysis, budgeting, and performance monitoring.

Fig. 2. Defect taxonomy and annotation scheme for model training, corresponding to RAMS

In Figure 2, the taxonomy defines which defects can be detected (crack classes, potholes, edge failure, divergence, and rut simulation) and specifies annotation geometry (polyline/polygon/rectangle) and severity attributes for consistent dataset creation and loading into RAMS.

A key constraint of RAMS integration is segmentation. Although surveys and images are collected at varying levels of granularity (points, fixed segments, variable segments), planning tools such as HDM-IV require transformation into homogeneous areas. Therefore, remote sensing results must be provided with clear location rules and metadata to support aggregation and transformation.

For practical implementation of the taxonomy (see Figure 2) and loading results into RAMS/SUDA, it is advisable to use the standardized metrics per 100-meter segment and severity level assignment rules (L/M/H) presented in Tables 1 and 2.

Table 1

Defect taxonomy, annotation type, and metrics for a 100-meter segment (for integration into RAMS)

Defect/indicator	Annotation type (ML)	Metric per 100 m	Field in RAMS (example)
Longitudinal/transverse cracks	Polyline	∑ crack length, m/100 m	Cracking: type + severity + qty
Network/fatigue cracking	Mask/Polygon	area, m²/100 m or %	Fatigue cracking area
Block fracturing	Mask/Polygon	area, m²/100 m or %	Block cracking area
Potholes	BBox and/or Mask	quantity, pcs/100 m; area, m²/100 m	Potholes: count / area
Edge destruction	Polyline and/or Mask	length, m/100 m	Edge defects length
Coloring	Mask/Polygon	area, m²/100 m or %	Surface ravelling area

Table 2

Condition indicators and rules for assigning weight (L/M/H) for the 100m segment (including IRI according to ODM 218.6.007-2012)

Indicator	Designation	Unit measurements	Calculation per 100 m	Severity (L/M/H)
Length of cracks	Crack_Len_100	m /100 m	Sum of the lengths	L: ≤A1; M: A1–A2;

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			of crack polylines on a segment	H: ≥A2
Area of mesh/ block cracks	Crack_Area_100	m²/100 m or %	Area of lesion masks (or area fraction)	L: ≤B1; M: B1–B2; H: ≥B2
Potholes	Pothole_Count_100 / Pothole_Area_100	pcs, m²	Number and total area of potholes on a segment	L: ≤C1; M: C1–C2; H: ≥C2
Edge destruction	EdgeBreak_Len_100	m/100 m	Sum of edge fracture length on a segment	L: ≤D1; M: D1–D2; H: ≥D2
Coloring	Ravel_Area_100	m²/100 m or %	Area/proportion of chipping on a segment	L: ≤E1; M: E1–E2; H: ≥E2
Evenness (IRI)	IRI_100	m/km	IRI calculated along a profile on a 100 m segment	L: ≤R1; M: R1–R2; H: ≥R2

Note: Thresholds A1–E2 and R1–R2 are set according to current requirements for operational conditions and/or departmental regulations; for IRI, it is recommended to use the threshold scale adopted in ODM 218.6.007-2012. [19]

Figure 3 shows a schematic of an example of location and segmentation logic.

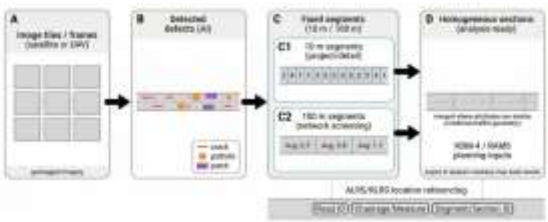

Fig. 3. Example of location and segmentation logic

3.2. Satellite monitoring for network-level inspection and change detection

Satellite imagery is best suited for large-scale surveys, corridor monitoring, and change detection (e.g., flood/landslide effects, earthworks, underlying surface failure patterns) because it provides wide coverage and frequent repeat surveys. Recent research shows that deep learning applied to satellite data can support automatic detection of pavement anomalies and general condition, especially when combined with GIS context and historical observations [1, 3]. Satellite-based approaches are particularly useful for identifying priority locations for high-precision inspections, rather than attempting to completely replace project-level diagnostics.

However, satellite imagery has limitations in detecting fine damage (fine cracks, early-stage failure), which is often below the spatial resolution required for reliable classification. Therefore, satellite data should be presented as risk/priority layers (e.g., "likely damaged areas" or "rapid failure zones") that trigger targeted surveys using UAVs or ground-based assets, rather than as definitive engineering measurements.

3.3. UAV-based monitoring for high-precision damage inventory and engineering evidence.

Unmanned aerial vehicles (UAVs) provide high-resolution imagery suitable for damage inventory and localized diagnostics, including detection and classification of cracks, potholes, edge defects, and repair quality. In the literature, convolutional neural network (CNN)-based models and instance segmentation methods (e.g., Mask R-CNN) have demonstrated high performance in recognizing and delineating pavement defects in images and video streams, enabling automated condition mapping [2, 5, 7]. UAV workflows typically include flight planning, orthomosaic generation, defect detection/segmentation, and conversion of detected defects into GIS layers and summary metrics for each segment.

UAV data collection is operationally limited by weather conditions, lighting, regulatory requirements, and flight duration, and generates large data sets that require computational resources and robust quality control. These limitations necessitate a multi-layered approach: UAV deployment should be prioritized for high-traffic areas, potential maintenance projects, and segments identified using satellite imagery or roughness trend analysis.

3.4. Data processing pipeline and quality assurance for RAMS-ready output.

A RAMS-compliant remote sensing data processing pipeline should be an iterative sequence from data collection to database loading. A practical structure is as follows (see Figure 4):

1. Data Collection (satellite imagery/UAV missions);
2. Pre-processing (radiometric correction, orthorectification, mosaicking);
3. Feature Extraction (AI-assisted feature detection/segmentation + rule-based metrics);
4. Validation (point checks; comparison with ground/vehicle surveys where possible);
5. Conversion to RAMS Schema (events/defects by segment, indices, timestamps, metadata);
6. Publishing (GIS layers, dashboards, and exportable reports).

This meets RAMS expectations for data management, where collected information must be validated, converted into required formats (by links, fixed 100m sections or variable segments) and securely stored for analysis and audit.

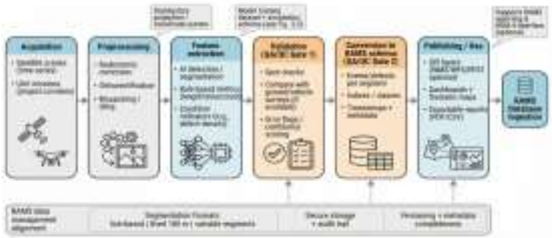

Fig. 4. Integrated remote sensing data processing pipeline to produce RAMS-compliant results

3.5. Recommended outputs for integration: from images to decision layers.

Rather than viewing remote sensing as a stand-alone "monitoring tool," this section should emphasize specific deliverables that support maintenance planning:

- Georeferenced defect layers (by defect type and severity) corresponding to RAMS condition categories;
- Segment summaries (10m/100m, then aggregated into homogeneous areas for planning);
- Derived indices (PCI/condition classes) and change metrics (deterioration rate);
- Supporting documentation packages (images/thumbnails associated with each segment) to enable audit trails and information sharing.

This formulation is consistent with the identified data needs: Tajikistan's RAMS system already has IRI and ODCC data in certain areas, but also explicitly notes the need to expand towards detailed damage inventory, rutting, bearing capacity, and thickness data – areas where UAV imagery combined with AI (and some ground-based instruments) can significantly strengthen the evidence base for planning.

Creation of a unified GIS portal for the road network of Tajikistan

A unified GIS portal is increasingly viewed as a key digital tool for national road agencies, as it integrates disparate road data into a unified spatial environment, reduces duplication, and enables analytics and reporting for planning and maintenance. International experience offers practical precedents: the US Highway Performance Monitoring System (HPMS) provides centralized collection and reporting of road data (usually updated annually), and the EU INSPIRE Transport platform supports interoperable transport layers using OGC standards. Similar approaches have been implemented in Central Asia, for example, within the Kazakhstani RAMS-KZ system, which integrates diagnostics (IRI/PCI) and forecasting into a ministerial portal. Initial developments are currently underway in Tajikistan through Geoportal-TJ, but this does not yet include systematic information on repairs and operations, limiting its value for maintenance planning and accountability.

In the context of the reform of the road risk and condition assessment system in Tajikistan, a unified GIS portal should be viewed not as a stand-alone map viewer, but as a GIS "interface" and spatial framework linking the main subsystems of the road risk and condition assessment system with verified, location-referenced data on road infrastructure and road conditions. The specifications of the road risk and condition assessment system explicitly provide for mapping capabilities through an integrated geographic information system (IGIS), defined as a user-friendly interface linking the subsystems of the road risk and condition assessment system with an external GIS package for use by specialists. This positioning makes the portal a practical tool for: (i) consistent storage and updating of spatial objects and their attributes, (ii) thematic presentation and visualization for decision support, and (iii) standardized export of maps and reports.

Fig. 5. The role of the Unified GIS Portal in the national RAMS ecosystem

Figure 5 shows the data collection process that serves as an intermediate/validation layer before inclusion in RAMS schemes: the portal provides access to validated layers through maps, dashboards and standard export files to support planning and ensure accountability.

4.1. Objectives and scope of the GIS portal.

The Unified GIS Portal of the Road Network of the Republic of Tajikistan (hereinafter referred to as "GIS-RTN") is proposed as a key element of the national digital transport strategy and an operational component of the broader digital platform (DPUS-RTN). Its practical goal is to provide a unified platform for storing, analyzing, and visualizing road network data, while ensuring interoperability across agencies and systems. Specifically, the portal should support: consolidation of interdepartmental datasets, a national road topological model linked to contextual layers (e.g., climate and cadastral), interactive analysis tools (search/filtering/reporting), and mechanisms for systematically updating data from diagnostic and mobile systems (e.g., RTRRMS, FWD, LiDAR, where possible).

4.2. Architecture compliant with RAMS requirements.

A robust portal architecture must have a multi-tiered structure that complies with generally accepted national GIS portal templates and supports gradual scalability. At the same time, RAMS technical requirements emphasize that the spatial framework must integrate storage, processing, and web display: data must be stored in a GIS-enabled database, editable using advanced GIS tools (e.g., QGIS), quickly displayed in a web browser, formatted by attributes, and exportable (including PDF files for printing).

An important principle of RAMS design is the separation of concerns: RAMS is expected to be segmented vertically (web and mobile stacks) and horizontally (security, GIS, user interface, logic, and database layers). The database should store subsystem data in schemas, support system-wide data in a central schema, and include a staging area for data collection results before they impact operational analysis - to support data validation and isolate inconsistencies. A unified GIS portal should utilize the same logic: a controlled path from data upload to verified publication.

4.3. Georeferencing and segmentation as the "foundation of integration".

For Tajikistan, the GIS portal should be tightly linked to the national object location system (ALRS), which enables meter-level georeferencing along road centerlines using specific identifiers (road class/number, carriageway, section, and distance-based measurements) supported by nodal points and location anchor points (see Figure 6). This is necessary to integrate condition survey data, inventory, work history, traffic, and structure data into a single, consistent location logic, as well as to enable the aggregation of results into homogeneous sections required for RAMS analysis (including HDM-IV studies).

The RAMS specifications explicitly state that an interface to HDM-IV is required, capable of dynamic segmentation based on regularly updated condition data, export of representative/homogeneous sections, and exchange of results back to RAMS for reporting and decision support. Thus, the GIS portal must publish (and consume) segmentation-ready layers (e.g. 10m/100m survey segments and then aggregated homogeneous parcels) and maintain a trackable version structure of parcel definitions across update cycles.

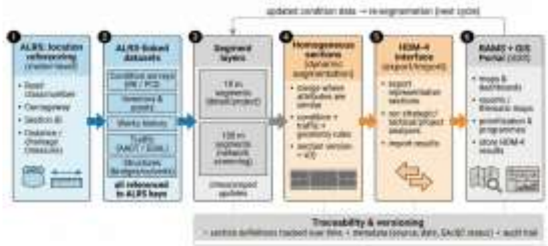

Fig. 6. Data linking and dynamic segmentation workflow based on ALRS

To illustrate the minimum set of HDM-IV input parameters (for strategic/tactical planning), an abbreviated fragment of the initial list of national road sections (data example) is provided below. An abbreviated example of HDM-IV input data and pavement condition attributes is provided below in Table 3.

Table 3

Data on the condition of some national highways

Road Index	Road sections	L, km	Cat.	AADT auto/day	IRI, m/km	Cracks, %	Potholes, pcs/km	Edge, m²/km	Track, mm
RR 004	Pugus – Safedorak	18.3	IY	260	8	50	10	100	20
RR 022	Vahdat-Romit	37.0	III	2665	7	50	4	100	10
RR 032	Vose – Khovaling	86.0	III	783	14	30	5	100	0
RR 033	Kulob – Muminobod	41.8	III	1809	9	100	0	100	0
RR 041	Khorog – Tukuzbulok	154.5	IY	812	16	100	10	50	0
RR 043	Rudaki-Yavan-Uyali	107.0	III	1651	5	50	5	100	0
RR 045	Rudaki – Shurtugay	80.9	III	1402	6	50	2	0	0
RR 048	Dushanbe – Gissar	17.6	IY	13106	5	25	0	0	0
RR 049	Collective farm "Russia" – Guliston	9.1	IY	7908	6	30	5	0	20
RR 054	Bokhtar – Dangara	71.6	III	2680	5	10	1	100	0
RR 059	Uzun – Beshai Palangon (tiger beam)	32.5	III	1352	5	20	2	10	0
RR 070	Gafurov-Pungan	137.2	III	1362	9	50	3	0	0

Summary (based on Table 5, n=13): total length 820.5 km; IRI (weighted average) 9.12 m/km; AADT (average) 3091 vehicles/day; max. gauge 20 mm.

Figures 7-9 show graphical data generated from the RR sections. They are used to visualize coverage quality, traffic relationships, and prioritization in RAMS.

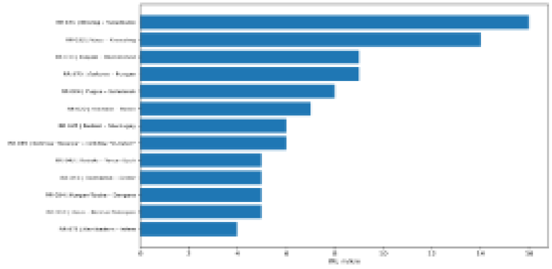

Fig. 7. IRI by sections (sorted by deterioration)

Fig. 8. Conditional linear map of sections (color by IRI class, length - L, km)

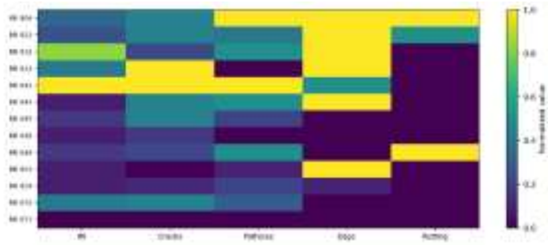

Fig. 9. State profile by sections (standardized 0-1 for each indicator)

4.4. Portal core data model and thematic layers.

The portal database should cover road geometry and classification, pavement characteristics (material, thickness, repair time), diagnostics (IRI, PCI, defects, rutting), structures (bridges, culverts, tunnels, safety features), climatic conditions, traffic loads (ESAL, AADT, vehicle categories), and economic indicators for planning (cost, NPV/PI, or similar). These categories reflect both the agency's practical data sources and the minimum information required for reporting and performance monitoring in a RAMS environment, where reporting should include inventory and condition for each road section, derived condition indices, roughness, predicted wear profiles, and strategic/multi-year plans, supported by thematic maps.

4.5. Dashboards, reporting, and controlled access.

To ensure ease of use by management, not just GIS specialists, the portal should provide visual analytics: interactive maps and dashboards that summarize asset status, inventory, traffic, programs, and value, complemented by charts, filters, and exportable results. In RAMS, dashboards should be user-configurable, comprised of interactive widgets, and accessible through a cloud infrastructure with continuous availability. Furthermore, the system should support role-based access management using profiles (with different permissions for different subsystems, including GIS and dashboards), granting MoT/GUSAD staff, stakeholders, and (if necessary) the public access to selected reports and maps (see Figure 10).

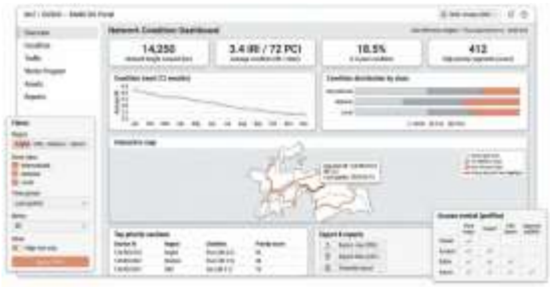

Fig. 10. Proposed dashboard structure for RAMS + GIS portal integration

4.6. Implementation phases and deployment considerations.

A phased implementation mitigates risks and enables early benefits:

1) preparation and audit of existing data (e.g., Geoportal-TJ, OSM) to generate a layer relevance and data quality report;

2) development of a portal prototype, including metadata and API;

3) integration of key diagnostic datasets (e.g., RTRRMS/IRI and other tools, where possible) into a single status database;

4) regional testing;

5) training and methodological materials; and

6) operational deployment on the Ministry of Transport infrastructure.

The deployment should also reflect the RAMS infrastructure requirements, which include a cloud server + a commissioned backup server at the Ministry of Transport/Digitalization Center, as well as minimum connectivity and IT readiness assessments.

Geoinformation analysis of road pavement degradation in mountainous conditions.

Road pavements in mountainous areas deteriorate faster due to the interaction of geomorphological and climatic factors - steep slopes, water erosion, landslides, and freeze-thaw temperature cycles - while many high-risk areas remain difficult to access for frequent field surveys. In these conditions, GIS-based analysis becomes essential, as it allows for the interpretation of wear patterns as a function of spatially varying "factors," rather than just isolated observations during inspections.

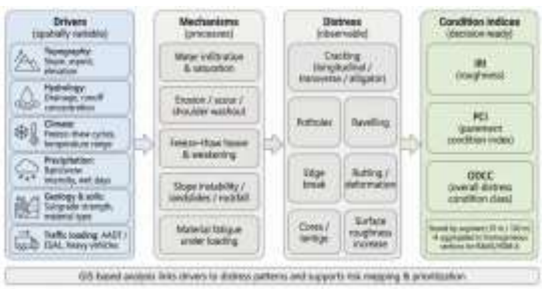

Fig. 11. Conceptual model of mountain road wear: Factors → Mechanisms → Damage → Condition indices

Figure 11 shows the spatial factors (topography, hydrology, climate, geology, transport) influencing the mechanisms (erosion, freeze-thaw weakening, slope instability) that manifest themselves as damage types and ultimately as RAMS condition indices (IRI/PCI/ODCC) stored by segment.

5.1. Spatial degradation drivers and required datasets.

A practical geographic information approach expresses natural and anthropogenic degradation drivers as spatial layers ("spatial degradation drivers") and analyzes their relationship to observed condition outcomes. Key factors typically include slope and aspect (runoff rate), geology/soil type (bearing capacity), precipitation/drainage (water saturation), temperature variations and freeze-thaw cycles, and vegetation/erosion resistance. For mountainous areas of Tajikistan (e.g. Zerafshan, Rasht, Pamir), these layers could be compiled from widely used sources and complemented with national diagnostic datasets: digital elevation models such as SRTM/ALOS for slope/aspect, global climate surfaces (e.g. WorldClim/NASA POWER) for precipitation and temperature, geological and soil maps, and condition diagnostics (IRI/PCI/rutting) from survey systems such as RTRRMS and LiDAR, where available, using satellite imagery to obtain surface deformation signals.

5.2. Analytical methods: from spatial correlation to predictive modeling.

GIS enables the use of several complementary analysis modes depending on the decision-making task. For screening and interpretation, spatial autocorrelation and hotspot statistics (e.g., Moran's I, Gettys-Ord index Gi*) help identify clusters of severe deterioration and relate them to topography, geology, and drainage conditions.

For forecasting, machine learning models (e.g., random forest, XGBoost) can estimate condition metrics (often IRI or condition class) from factor layers; published studies report high predictive performance with appropriate calibration and data quality control. In mountainous areas, hybrid approaches are increasingly used, combining susceptibility layers (e.g., landslide susceptibility) with pavement damage mapping to better reflect geomorphic hazards [20].

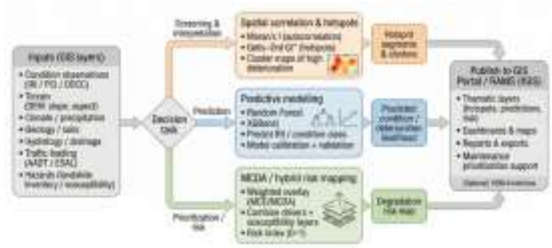

Fig. 12. Selecting a GIS method for assessing the deterioration of mountain roads: deterioration hotspots, forecasting, and risk mapping

Deterioration hotspot statistics are used for screening, machine learning-based regression/classification for forecasting, and multi-criteria decision analysis for interpretable risk indexing; all results are published as portal layers and exported to RAMS reporting (see Figure 12). Deterioration hotspots should be used to determine inspection locations, machine learning to predict expected results, and multi-criteria decision analysis to prioritize tasks.

5.3. Multi-criteria assessment of the degradation risk map.

To support maintenance planning, it is useful to transform multi-layered factors into an interpretable degradation risk surface. Multi-criteria assessment (FEM/MCDA) combines normalized factor layers with weights reflecting the relative contribution of each factor to deterioration (e.g., slope, precipitation, soil/geology, drainage vulnerability, pavement type).

A clear and publishable formula is as follows:

Degradation Risk Index (DRI)

$$DRI(x) = \Sigma_i (w_i \cdot X_i(x)), \text{ where } \Sigma_i w_i = 1 \quad (1)$$

where w_i is the weight of factor i, and $X_i(x)$ is the normalized value (0-1) of layer i at point x.

This replaces the current placeholder formula "Formula (1)" and makes the method verifiable and reproducible.

Weighting factors can be established (and justified) based on expert judgment (e.g., structured assessment/AHP method) or estimated empirically using importance metrics from regression/machine learning models, and then tested for robustness using sensitivity analysis. On mountain roads, the risk surface can be tailored by explicitly incorporating observed condition indicators (IRI/PCI) and damage classes obtained during the survey to ensure that the risk index is related to actual deterioration results.

5.4. Recommended implementation algorithm for Tajikistan.

The following algorithm can be used for practical implementation in Tajikistan:

1) Collect DEM, geological, and precipitation data for priority mountain regions (e.g., Pamir and Sughd);

2) Integrate existing diagnostic datasets (IRI/PCI) from priority corridors (e.g., Dushanbe-Khorog and Dushanbe-Istaravshan);

3) Perform spatial overlay and vulnerability mapping;

4) Build a regression or machine learning model, e.g., IRI = f(slope, precipitation, soil);

5) Validate using multi-year observations (e.g., 2023-2025); and

6) Publish the results in the national GIS portal (DPUS-RT).

This workflow also meets RAMS operational expectations: collected data must be validated, error-checked, converted into the required segmentation formats, securely stored, and audited - so degradation analysis must explicitly rely on verified state layers and ensure traceability from source data to published results.

5.5. Results for decision making and integration into RAMS reporting.

The key results of Section 4 should be presented as decision-ready outputs: (i) maps of accelerated deterioration hotspots, (ii) a degradation risk index surface and ranked high-risk segments, (iii) explanatory models linking factors to observed condition, and (iv) monitoring-ready layers suitable for periodic updating as new IRI/PCI data or remote sensing observations become available.

These outputs directly support RAMS reporting expectations, which include derived condition indices, predicted deterioration profiles, graphical displays, and predefined thematic maps for management and query as needed. To make this connection explicit in the paper, the degradation risk layers should be described as thematic products published on the portal, which can be accessed by dashboards and exported into reporting workflows.

5.6. Limitations and requirements for reliable use.

GIS-based degradation analysis is a powerful tool, but it is limited by (i) the resolution and accuracy of digital elevation models and climate layers, (ii) the computational load when modeling large areas, and (iii) the need for periodic updates of diagnostic and remote sensing data to maintain the reliability of forecasts. These limitations should be clearly stated to avoid exaggerations and to clarify the minimum data update cycle and quality control capabilities required for rapid implementation.

3. Conclusion

This article demonstrates that geoinformation monitoring based on a combination of satellite data, UAV imagery, and GIS analytical capabilities provides an effective basis for managing road assets in mountainous areas. The proposed approach enables the transformation of heterogeneous observation data into standardized condition and risk indicators compatible with RAMS systems and road works planning tools.

The key result of the study is the substantiation of the role of a unified GIS portal as a spatial interface between monitoring processes and management decisions. The use of a linear reference system (ALRS) ensures the consistency of data from various sources, supports dynamic segmentation, and creates the conditions for integrating analytical layers into planning procedures, including the use of HDM-IV-type models.

GIS analysis of road pavement degradation in mountainous areas allows for the identification of areas of accelerated deterioration and the creation of interpretable risk maps that take into account terrain, climate, and operational loads. It has been shown that the use of spatial filtering reduces the volume of priority segments for detailed survey by 25-30%, improving the efficiency of road agencies' limited resources.

The practical significance of the obtained results lies in their scalability and adaptability to other mountainous regions with similar operating conditions. The proposed monitoring and analysis framework can be used as a module for digitalizing the road industry in countries with developing road asset management systems, facilitating the transition from reactive repairs to evidence-based preventative management.

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