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Digital Technologies for Sustainable Highway Maintenance Governance: Evidence from a Scientific Maintenance Pilot in China

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Abstract

Sustainable highway maintenance is increasingly important as road agencies face ageing assets, fiscal constraints and growing requirements for service reliability and resilience. Although digital technologies are widely used in inspection, prediction and construction control, less is known about how they support governance across the full maintenance process. This study examines a Chinese scientific highway maintenance pilot through a document-based qualitative case study. Drawing on project documents and public reports, it develops a framework linking three mechanisms: datafied demand assessment, model-based decision-making and adaptive scheduling. The findings show how digital inspection, remote sensing, multi-source data models and smart construction-control platforms turn dispersed deterioration information into traceable condition evidence, translate this evidence into life-cycle maintenance priorities and connect planning with implementation feedback. Project-reported indicators also suggest gains in inspection efficiency and monitoring timeliness, although the evidence does not permit a comprehensive assessment of sustainability outcomes. Together, the mechanisms strengthen the capacity to move from reactive repair towards evidence-based life-cycle maintenance, resource-conscious prioritisation and adaptive service delivery. The study contributes to sustainable transport infrastructure research by explaining the governance processes through which digital technologies can support highway maintenance and the conditions shaping their transferability.

Keywords: highway maintenance; digital transformation; sustainable infrastructure; life-cycle asset management; maintenance prioritisation; resilience



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1. Introduction

Highway maintenance is central to the sustainability of transport infrastructure. Policy and investment have often favoured network expansion and new construction, but the performance of transport systems also depends on the condition of existing roads, bridges and tunnels. Ageing assets, fiscal constraints, growing traffic demand and exposure to extreme weather make maintenance a matter of long-term service provision rather than routine repair. Decisions about when and where to intervene affect safety, accessibility, life-cycle costs, service continuity and resilience.

Maintenance expenditure affects not only asset condition but also the productivity, growth and distributional consequences of public infrastructure investment [1–4]. Yet visible new construction may be politically and institutionally favoured over routine upkeep, allowing maintenance backlogs to grow [5]. Sustainable highway maintenance therefore

requires transparent decisions about how limited resources are allocated [6]. These decisions must consider life-cycle asset performance, traffic disruption and environmental effects [7,8], the continuity and recovery of transport services under disruption [9,10], and the distributional implications of maintenance priorities for socially vulnerable communities [11]. Maintenance is consequently better understood as a sustainability-oriented governance function than as a residual technical task.

Digital technologies can strengthen this governance function by changing how evidence is produced and used. Sensor networks create more continuous records of infrastructure condition [12], while big-data analysis supports condition-based maintenance decisions [13]. Digital twins further connect monitoring information with asset representation and maintenance planning [14,15]. These technical capabilities alone, however, do not ensure sustainable outcomes. Digital government research shows that technological change is closely intertwined with organisational and institutional arrangements [16], and broader studies of public-sector digital transformation likewise emphasise changes in routines, responsibilities and service-delivery processes [17,18]. In highway maintenance, digital tools become consequential when their outputs are incorporated into data validation, priority setting, resource allocation, quality control and future planning.

Taken together, the economic, engineering and public-sector perspectives outlined above illuminate different parts of the maintenance problem, but they do not explain how those parts are connected in practice. Existing research provides limited insight into how condition evidence moves through the full maintenance process, from demand assessment and priority setting to field implementation and feedback. This gap matters because the sustainability contribution of digital maintenance depends on these connections rather than on the technical performance of individual tools alone.

This paper addresses this gap by asking: How do digital technologies support sustainable highway maintenance governance, and through what mechanisms do they reshape demand identification, life-cycle maintenance prioritisation and implementation coordination? To answer this question, the paper develops a mechanism-based analytical framework. It argues that digital transformation in highway maintenance operates through three interdependent mechanisms. First, datafied demand assessment converts dispersed asset conditions, operational risks and safety-related problems into traceable condition evidence. Second, model-based decision-making translates this evidence into prioritised maintenance strategies by linking engineering indicators with cost, safety, service reliability, life-cycle performance and resilience considerations. Third, adaptive scheduling connects maintenance plans with real-time implementation by coordinating work windows, materials, quality control, construction processes and feedback through smart platforms.

The empirical setting is a Chinese scientific highway maintenance pilot, anonymised as the GX Highway scientific maintenance project. The case combines national policy support with the application of digital technologies across a route of more than 60 km containing seven tunnels and 105 bridges. Mobile inspection, remote sensing, multi-source modelling and smart construction control were used at different stages of the maintenance process. This combination makes the case suitable for examining how condition evidence, maintenance decisions, implementation control and feedback are connected in practice.

The paper makes three contributions to sustainability-oriented transport infrastructure research. First, it shifts attention from digital technologies as isolated inspection or engineering tools to digital maintenance as a governance process for sustainable infrastructure management. Second, it develops a mechanism-based explanation of how digital technologies support sustainable highway maintenance: datafied demand assessment improves condition visibility, model-based decision-making supports life-cycle and resource-efficient prioritisation, and adaptive scheduling strengthens implementation co-

ordination and service reliability. Third, it identifies governance challenges associated with digital maintenance systems, including data quality, algorithmic opacity, platform dependence, accountability gaps and uneven institutional embedding. These challenges suggest that digital maintenance should be governed through data standards, transparent decision rules, organisational integration and scalable feedback mechanisms.

The remainder of the paper is organised as follows. Section 2 reviews the literature on sustainable transport infrastructure maintenance, digital transformation and highway maintenance governance, and develops the analytical framework. Section 3 explains the document-based qualitative case study design, case selection, data sources and coding procedure. Section 4 analyses the GX Highway case through the three mechanisms of datafied demand assessment, model-based decision-making and adaptive scheduling. Section 5 discusses the implications for sustainable highway asset management, life-cycle maintenance prioritisation, implementation coordination and digital governance. Section 6 concludes by summarising the main findings and identifying directions for future research.

2. Literature Review and Analytical Framework

2.1. Highway Maintenance as a Sustainable Infrastructure and Asset Management Problem

Highway maintenance is not solely a technical response to physical deterioration. It is also shaped by public budgeting, institutional capacity, and political priorities. Fiscal stress can constrain state highway infrastructure finance, while economic conditions, political pressures, human resources and information systems affect local governments' capacity to maintain public assets [19,20]. Political incentives may delay routine highway maintenance spending and influence the timing and spatial allocation of maintenance activities [21,22]. A policy preference for new infrastructure can further divert attention and resources from the maintenance of existing assets [5]. Maintenance backlogs should therefore be understood not simply as accumulated physical deterioration, but as the outcome of fiscal choices, administrative capacity and public-sector priority setting.

Highway asset management addresses these constraints by organising condition data, asset inventories, performance measures and network-level priorities into a structured basis for intervention. Evidence from Complete Streets asset management in US state departments of transportation shows that such arrangements can still be hindered by inadequate funding, organisational structures, gaps in performance measurement and problems in data accessibility, collection and management [23]. Research on intelligent road infrastructure has likewise developed indicators to support long-term intelligent transportation system strategies for road appurtenances and operational management [24]. Recent studies have broadened the evidence used in maintenance prioritisation by incorporating life-cycle environmental and traffic effects, geospatial differences among road segments and distributional equity based on social vulnerability [8,11,25].

These developments move maintenance prioritisation beyond visible defect severity and direct engineering cost. Decision-support frameworks can broaden maintenance investment decisions beyond physical condition by incorporating strategic importance, socioeconomic contribution and infrastructure utilisation under limited funding [6]. Life-cycle performance measurement can also identify processes that should be improved to strengthen the adaptability and resilience of transport assets over time [7]. Transport resilience research further argues that resilience cannot be reduced to risk management or robustness alone [9]. At the network level, it can be assessed through the robustness, adaptability and recoverability of transport functions under disruption [10]. Sustainable maintenance decisions therefore concern not only the preservation of physical assets, but also the continuity and recovery of mobility services.

Existing research thus provides established principles for asset management, maintenance prioritisation and transport resilience. However, less attention has been paid to how digital systems alter the sequence through which condition evidence is generated, interventions are prioritised, and maintenance work is coordinated. These activities are often studied separately, although their contribution to sustainable maintenance depends on how they are connected in practice. The present study addresses this gap by examining how digital technologies reshape the evidence used to identify maintenance needs, the criteria applied to set priorities and the coordination of work during implementation.

2.2. Digital Transformation and Sustainable Highway Maintenance Governance

Research on digital maintenance has developed along two complementary lines. Engineering studies examine how sensor networks, structural health monitoring, big-data analysis and digital twins create more continuous and machine-readable accounts of infrastructure condition [12–15]. Public-sector digital transformation research focuses on the organisational processes and institutional arrangements through which such technologies become embedded in administrative practice [16–18]. Read together, these two strands suggest that the significance of digital maintenance lies in the connection between technical information and the routines through which condition data are validated, translated into priorities and incorporated into implementation. This socio-technical connection provides the basis for examining digital technologies as part of sustainable maintenance governance.

The sustainable governance of digital maintenance also requires attention to data quality and accountability. Smart city and digital governance studies have warned that data systems may reproduce blind spots if data collection, interpretation, participation and institutional accountability are not addressed [26–29]. Similar risks exist in highway maintenance. Machine-recognised defects may be affected by uneven sensing coverage, false positives, false negatives or inconsistent technical standards. Model-based prioritisation may obscure value judgements if indicators, weights and thresholds are not transparent. Platform-based coordination may create dependence on specific vendors or information systems if organisational responsibilities are not clearly defined.

Existing research addresses important components of digital maintenance through studies of condition monitoring, asset planning and institutional change. However, it rarely explains how sensing, modelling and platform-based coordination are connected across the full maintenance chain. This unresolved integration problem motivates the analytical framework developed below.

2.3. Analytical Framework: Three Mechanisms of Sustainable Digital Maintenance Governance

Based on the above literature, this paper proposes a three-mechanism framework for analysing sustainable digital maintenance governance. The framework treats digital highway maintenance as a process that links information generation, decision structuring and implementation coordination. These three functions correspond to the main stages of maintenance governance: identifying maintenance needs, prioritising interventions and coordinating implementation. They are analytically distinct, but their sustainability effects depend on their integration across the maintenance process.

The first mechanism is datafied demand assessment. In traditional highway maintenance, demand information is often generated through periodic inspection, manual reporting, field experience and user complaints. These practices remain necessary, but they may produce fragmented or delayed information. Digital technologies transform demand assessment by creating more continuous, spatially referenced and traceable records of asset conditions. Intelligent inspection vehicles, computer vision, UAV inspection, satellite monitoring, pavement detection equipment and other sensing technologies can convert

physical deterioration into data-based condition evidence. The sustainability value of this mechanism lies in earlier and more risk-sensitive identification of maintenance needs. By improving condition visibility, datafied demand assessment can reduce dependence on reactive repair and support more preventive, life-cycle-oriented maintenance.

The second mechanism is model-based decision-making. Maintenance decisions are constrained by budgets, work windows, safety requirements, user costs and service objectives. Digital models can integrate asset condition data, traffic volume, deterioration patterns, maintenance history, cost estimates and service reliability indicators. Recent research also shows that geospatial decision-support systems can help transport authorities allocate maintenance resources across road segments more systematically [25]. In this mechanism, maintenance decision-making is not reduced to the ranking of visible defects. It becomes a multi-objective process in which risk, life-cycle cost, service reliability, resource constraints and resilience are compared. The sustainability value of model-based decision-making lies in its potential to make maintenance prioritisation more transparent, resource-efficient and life-cycle oriented.

The third mechanism is adaptive scheduling. In this study, the term refers to a feedback-based process in which planned maintenance activities, work sequences, work windows and resource allocations are revised during implementation in response to updated information on traffic conditions, weather, site conditions, material supply, construction progress and quality. It differs from general managerial flexibility because it entails a recurring cycle of monitoring, identifying deviations or constraints, reassessing the schedule and resource allocation, implementing an adjustment and recording the resulting feedback. Research on construction scheduling likewise emphasises continuous monitoring and early warning as a basis for timely intervention under uncertain site conditions [30]. Smart construction-control platforms can operationalise this cycle by linking field data to scheduling decisions. In highway maintenance, this process can reduce implementation inefficiencies, strengthen quality control, support service reliability and generate feedback for subsequent maintenance planning.

Taken together, these three mechanisms constitute a process of sustainable maintenance capacity building. Datafied demand assessment strengthens condition visibility by making asset deterioration more traceable and comparable. Model-based decision-making strengthens life-cycle prioritisation by translating heterogeneous data into maintenance strategies under resource constraints. Adaptive scheduling strengthens implementation coordination by linking maintenance plans with real-time field information, quality control and feedback. The framework therefore connects digital technologies with sustainability-oriented maintenance outcomes through the intermediate process of sustainable maintenance governance.

This framework also highlights that digital technologies do not automatically generate sustainable outcomes. Their effects depend on whether the three mechanisms are connected. If sensing systems are not linked to decision models, asset data may accumulate without shaping maintenance priorities. If decision models are not connected to implementation platforms, prioritised strategies may fail to respond to field uncertainty. If implementation feedback is not incorporated into future assessment and planning, digital platforms may become tools of supervision rather than instruments of learning. Sustainable digital maintenance governance therefore requires an integrated chain in which data, models and platforms support each other across the maintenance process. Figure 1 summarises this integrated and feedback-oriented process. Table 1 summarises the literature reviewed in Section 2 under eight thematic strands and shows how each strand informs the analytical framework.

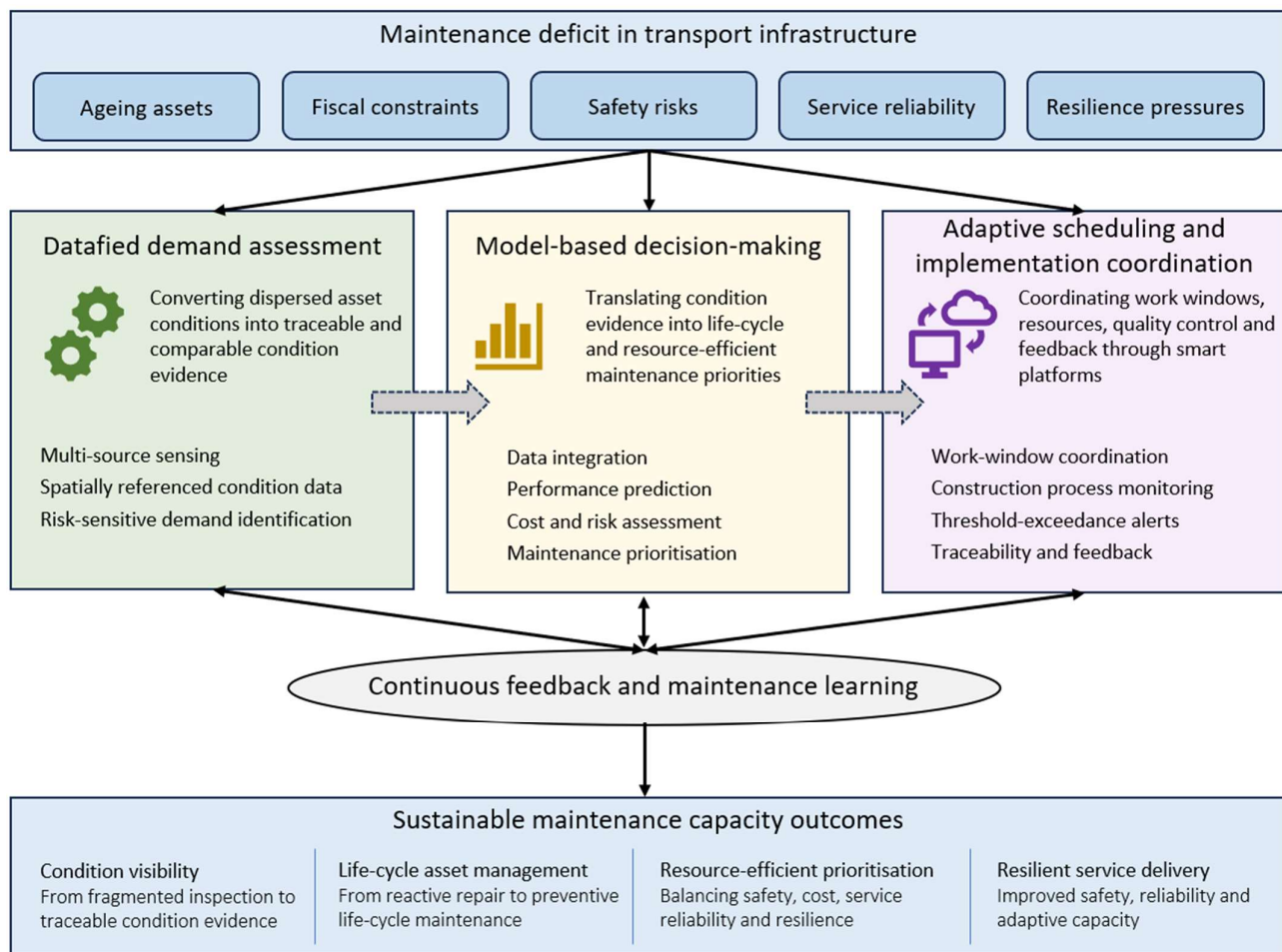


Figure 1. Analytical framework of sustainable digital maintenance governance. Note: The framework shows a feedback-oriented process through which digital technologies support sustainable highway maintenance governance by linking condition visibility, life-cycle asset management, resource-efficient prioritisation and resilient service delivery.

Table 1. Thematic synthesis of the literature reviewed in Section 2.

Literature Theme	Principal Focus	Sources Reviewed	Contribution to This Study
Infrastructure maintenance and public-capital allocation	Examines the allocation of public expenditure between new infrastructure and the maintenance of existing assets, together with its implications for infrastructure productivity, economic growth and welfare.	Rioja (2003) [1]; Kalaitzidakis and Kalyvitis (2004) [2]; Agénor (2009) [3]; Gibson and Rioja (2017) [4]; Gibson and Rioja (2024) [5]	Establishes the economic rationale for treating maintenance as long-term stewardship of public assets rather than as a residual expenditure.
Fiscal, institutional and political constraints	Considers how fiscal stress, administrative capacity, deferred-maintenance practices and electoral incentives affect public infrastructure maintenance.	Chen (2016) [19]; Kim and Ebdon (2021) [20]; Kim (2022) [21]; Bock and Blemings (2024) [22]	Shows that highway maintenance priorities are shaped by budgeting arrangements, organisational capacity and political incentives as well as by asset condition.
Sustainability-oriented asset management	Extends maintenance assessment to include life-cycle environmental impacts, traffic disruption, social vulnerability, distributional equity and the integration of different transport assets.	Liu et al. (2023) [8]; Gadsby et al. (2024) [23]; Amin and Machemehl (2025) [11]	Broadens the criteria used to evaluate maintenance beyond immediate engineering costs and visible physical defects.
Transport resilience and system performance	Examines life-cycle performance, adaptation to climate and operational disruption, and the maintenance or recovery of transport-network functions.	Liu et al. (2019) [7]; Markolf et al. (2019) [9]; Wang et al. (2023) [10]	Connects infrastructure maintenance with service continuity, adaptive capacity and resilience-oriented transport governance.

Table 1. *Cont.*

Literature Theme	Principal Focus	Sources Reviewed	Contribution to This Study
Condition monitoring and intelligent infrastructure	Reviews the use of wireless sensors, condition indicators, big-data analysis, structural health monitoring and digital twins to improve infrastructure-condition assessment.	Lynch and Loh (2006) [12]; Jamshidi et al. (2018) [13]; Lee and Yoon (2021) [24]; Mahmoodian et al. (2022) [14]; Armijo and Zamora-Sánchez (2024) [15]	Provides the technological and analytical basis for datafied demand assessment by making asset deterioration more continuous, traceable and comparable.
Public-sector digital transformation	Treats digital transformation as a process involving changes in technology, organisational routines, institutional arrangements and public-service delivery.	Luna-Reyes and Gil-Garcia (2014) [16]; Mergel et al. (2019) [17]; Haug et al. (2024) [18]	Supports the treatment of digital highway maintenance as a socio-technical and institutional process rather than solely as the adoption of new technologies.
Data governance and smart governance	Examines the governance of data-intensive systems, including data quality, institutional coordination, accountability and the orchestration of organisational resources.	Kitchin (2014) [26]; Gil-Garcia et al. (2015) [27]; Meijer and Bolívar (2016) [28]; Zhang et al. (2022) [29]	Identifies the governance conditions required to translate digital information into accountable and sustainability-oriented maintenance practices.
Model-based prioritisation and adaptive scheduling	Examines decision-support models, geospatial information and project-control data used to prioritise infrastructure interventions and anticipate schedule deviations.	Arif et al. (2016) [6]; de Medeiros Pereira et al. (2024) [25]; Lagos et al. (2024) [30]	Supports the model-based decision-making and adaptive-scheduling mechanisms developed in the analytical framework.

Note: The sources are grouped according to their principal contribution to the literature review. Some studies also inform other themes or analytical mechanisms discussed in Section 2.

3. Research Design and Methodology

3.1. Research Strategy

This study examines how digital technologies are brought together across the highway maintenance process and how their use contributes to sustainable maintenance capacity. The unit of analysis is the GX Highway scientific maintenance project. The empirical analysis is limited to the 2024–2025 implementation period covered by the available project records. The research question concerns how the maintenance process was organised, specifically how sensing, modelling and construction-control systems were connected to maintenance assessment, prioritisation and implementation. Recent methodological work emphasises that the value of a qualitative case study depends on a clear match between the research question, the case design and the scope of the claims being made [31]. The GX project provides a defined setting in which technical systems can be examined in relation to pilot policy, asset-management routines, organisational responsibilities and implementation procedures.

The project was developed and implemented through formal policy, technical and administrative arrangements, each of which generated documentary evidence. Policy documents set out the institutional aims of the pilot, while programme materials record its selection and position within the wider policy initiative. Implementation plans and project reports describe how the project was organised and which technologies were introduced. Technical materials provide further detail on the systems used, and publicly available sources allow factual claims to be cross-checked. Document analysis is particularly useful for tracing policy content and processes when the procedures used to prepare the material, extract evidence, conduct the analysis and interpret the findings are made explicit [32]. In this study, the materials were read as a connected record of the project rather than as a collection of isolated descriptions.

Other approaches commonly used in highway maintenance research address related but different questions. Performance models and optimisation techniques can estimate asset deterioration, compare treatment options and support decisions about the allocation

of maintenance resources [6]. Survey- and interview-based studies can examine how public organisations and infrastructure agencies understand digital transformation and asset-management practice [17,23]. These methods are appropriate when the aim is to evaluate technical performance, compare a wider population or examine the experiences of participating actors. The present study follows the formal sequence from policy objectives and pilot selection to technical configuration and recorded implementation. A document-based case study fits this purpose because it retains the institutional setting and chronology of the project while allowing individual claims to be traced to records produced during its implementation.

Documentary evidence may be incomplete, unrepresentative or shaped by the purposes for which it was produced [33]. The analysis is therefore confined to processes supported by the available record. The procedures used to assess trustworthiness and the resulting limitations are discussed in detail in Section 3.5.

3.2. Case Selection

The empirical case is the GX Highway scientific maintenance project in Province A, China. Under the access conditions agreed with the project owner, the project name, route numbers and participating organisations have been anonymised throughout the paper. Identifying information is therefore withheld from the published manuscript. The case was selected for three main reasons.

First, the case has strong policy and sustainability relevance. The project was included in the national pilot programme for modern highway maintenance engineering, which was designed to explore new concepts, technologies and organisational models for highway maintenance. This makes the case useful for analysing how digital transformation is promoted through transport infrastructure policy and pilot-based implementation. It is also relevant to sustainability-oriented highway maintenance because it addresses life-cycle asset management, resource-efficient maintenance, service reliability and resilience-oriented infrastructure governance.

Second, the case has technological relevance. The project integrates a range of digital technologies, including intelligent road inspection, BeiDou/GPS positioning, millimetre-wave radar, unmanned aerial vehicle inspection, satellite-based monitoring, three-dimensional pavement detection and a smart construction-control platform. These technologies cover different stages of the maintenance process, from condition sensing to decision support and construction control. The case therefore provides an opportunity to examine how multiple digital tools are combined across the maintenance chain rather than applied as isolated technical systems.

Third, the case has analytical relevance. The project includes the main links of highway maintenance governance: identifying maintenance needs, generating maintenance plans, organising construction work, monitoring implementation and feeding information back into management processes. It therefore provides a suitable empirical setting for examining how highway maintenance can shift from reactive, experience-based and fragmented repair towards data-supported, coordinated, adaptive and sustainable maintenance governance.

The case is treated as an instrumental case rather than a statistically representative sample. Its analytical value lies in its ability to illuminate a broader sustainability issue in transport infrastructure management: how road agencies and infrastructure operators can develop digital capacity for life-cycle maintenance, resource-efficient prioritisation and resilient service delivery.

3.3. Data Sources

The documentary corpus was deliberately focused rather than extensive. It was designed to cover the main stages of the case, including policy framing, pilot selection, project implementation, technical configuration and public verification. The study does not use the documents for quantitative content analysis. Instead, the materials are used to reconstruct the implementation process qualitatively and to identify how digital technologies were organised into the mechanisms of demand assessment, decision-making and adaptive scheduling.

Documents were selected purposively. Inclusion required direct relevance to the policy basis, pilot selection, implementation process, technical arrangements or maintenance activities of the case; an identifiable provenance, issuing body and date; substantive information on project practices or processes rather than a general description of digital highway maintenance; and a contribution to at least one stage of the analysis. Project-related and technical documents were used in the qualitative coding, whereas publicly available materials were used primarily to verify the project's selection status and other contextual facts. Materials whose provenance or substantive relevance could not be established were not used as analytical evidence. Table 2 summarises the documentary materials retained for analysis and the analytical role assigned to each source category.

Table 2. Documentary materials and analytical uses.

Type of Material	Examples of Materials	Coverage/Period	Analytical Use
Policy documents	National and provincial documents on highway maintenance, modern maintenance engineering and life-cycle asset management	National and provincial policy context, 2019–2025	To identify the policy background and sustainability-oriented objectives of digital transformation in highway maintenance
Pilot programme materials	National pilot lists, pilot selection materials and implementation notices	National modern highway maintenance pilot programme, 2024	To justify case selection and the relevance of the pilot to sustainable highway maintenance
Project-related materials	Project description, implementation plan, project summary and technical report	GX Highway scientific maintenance project, 2024–2025	To reconstruct the project implementation process and its relevance to sustainable maintenance governance
Technical materials	Materials on intelligent inspection, UAV inspection, satellite monitoring, pavement detection, decision models and smart construction-control platforms	Main digital maintenance systems in the project	To identify digital practices and their functions in condition assessment, prioritisation and implementation coordination
Publicly available information	Publicly available industry reports, transport authority information and company announcements	Publicly available sources related to the national pilot programme and project implementation, 2024–2025	To cross-check the project's selection and implementation and supplement its institutional and technical context

Note: This table was created by the authors to summarise the categories, coverage and analytical use of the documentary materials included in the study. It does not reproduce any table, figure, or substantial text from the underlying materials. The case name, expressway names, participating organisations and identifying details of case-specific documents have been anonymised. Access to the underlying administrative and project materials was granted for research purposes, but the project owner did not authorise their reproduction or public release.

Some of the administrative and project records used in the analysis are internal working materials and are not publicly accessible. The institutional origin and implementation sequence of the case were cross-checked against publicly reported information on the

national pilot programme and subsequent project activities. Direct links and identifying document titles are not included because they would reveal the case and the organisations involved. Public reports were used for factual verification and contextual supplementation rather than as substitutes for the underlying administrative and project records.

Together, these sources allowed the study to trace the project from policy framing and pilot selection to technical implementation and feedback while cross-checking key factual claims.

3.4. Data Analysis and Coding Procedure

The documentary materials were analysed through an iterative qualitative coding process. The purpose of coding was not to count the frequency of terms in the documents, but to identify how digital technologies were organised and connected to different stages of sustainable highway maintenance governance. The analysis moved between the empirical materials and the analytical framework, with particular attention to the ways in which digital technologies changed demand identification, maintenance decision-making and implementation coordination. Figure 2 presents the six-step coding workflow used to move from documentary materials to the three aggregate mechanisms.

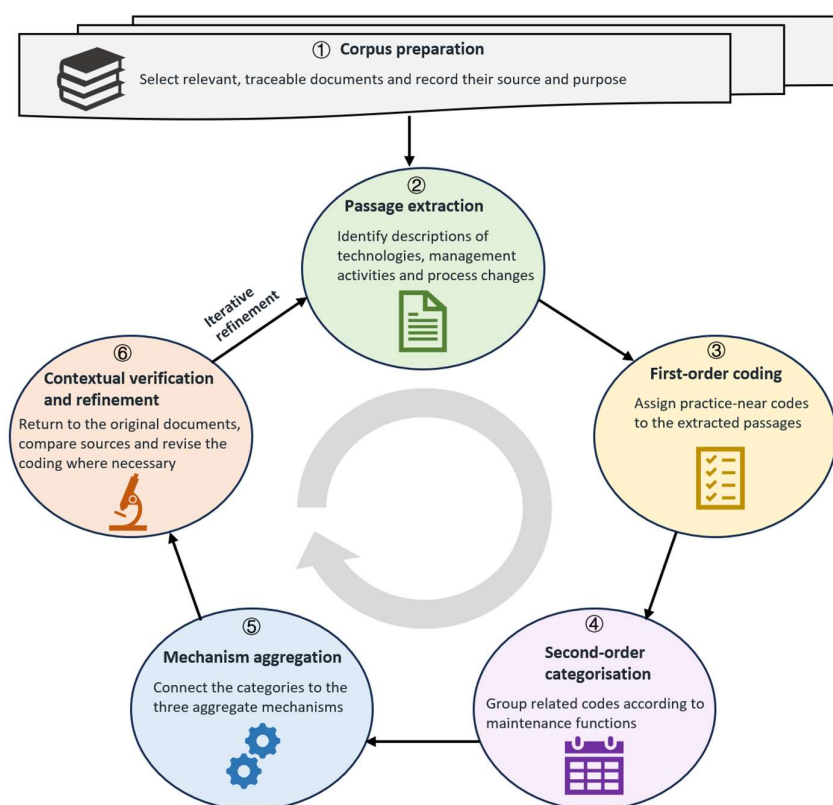


Figure 2. Procedural workflow for qualitative coding and mechanism development. Note: The coding process was iterative. Contextual verification could lead to the revision of extracted passages, first-order codes or second-order categories.

For example, during corpus preparation, one technical project document was retained because its provenance and technical purpose could be established. The document described an intelligent inspection vehicle that used AI-based image recognition to identify pavement distress and BeiDou/GPS positioning to record its location. This passage was extracted because it documented both a technological function and a change in condition-inspection practice. It was assigned the first-order codes “AI-based distress recognition” and “spatial positioning”. These codes were then grouped under the second-order category

“Sensing and condition identification” and linked to the aggregate mechanism “Datafied demand assessment”. Finally, this interpretation was checked against the relevant technical report, implementation plan and project summary. Where the documents differed in wording or level of detail, the code definition was refined to maintain analytical consistency without treating the sources as identical accounts.

At the first-order coding stage, the retained documentary passages were read repeatedly to identify concrete digital practices in the GX Highway scientific maintenance project. Initial codes were assigned to specific technologies, management activities and process changes. These first-order codes included intelligent inspection, AI-based distress recognition, BeiDou/GPS positioning, UAV inspection, satellite-based slope monitoring, three-dimensional pavement detection, data integration, pavement performance assessment, performance prediction, cost estimation, maintenance prioritisation, construction process monitoring, material tracking, quality alarms, work progress visualisation, traceable construction records and feedback reporting.

At the second-order categorisation stage, these first-order codes were grouped into broader analytical categories according to their functions in the maintenance process. Practices related to sensing, monitoring and condition identification were grouped under sensing and condition identification. Practices related to data integration, performance evaluation, prediction, comparison and prioritisation were grouped under decision support and prioritisation. Practices related to construction monitoring, material tracking, quality warning, work progress visualisation and feedback were grouped under process control and coordination.

At the mechanism-aggregation stage, the second-order categories were connected to the three mechanisms of sustainable digital maintenance governance developed in the analytical framework. Sensing and condition identification were linked to datafied demand assessment, because these practices changed how maintenance needs were detected, located and recorded. Decision support and prioritisation were linked to model-based decision-making, because these practices changed how maintenance strategies were generated and compared under resource constraints. Process control and coordination were linked to adaptive scheduling, because these practices changed how maintenance implementation was monitored, adjusted and fed back into the management process. Table 3 summarises the coding structure and the development of the three mechanisms.

Table 3. Coding structure and mechanism development.

First-Order Codes	Second-Order Categories	Aggregate Mechanisms
Intelligent inspection; AI-based distress recognition; BeiDou/GPS positioning; UAV inspection; satellite-based slope monitoring; three-dimensional pavement detection	Sensing and condition identification	Datafied demand assessment
Data integration; pavement performance assessment; performance prediction; scenario comparison; cost estimation; maintenance prioritisation	Decision support and prioritisation	Model-based decision-making
Construction process monitoring; material tracking; quality alarms; work progress visualisation; traceable construction records; feedback reporting	Process control and coordination	Adaptive scheduling

Note: The coding structure was developed through iterative reading of policy documents, project-related materials, technical documents and publicly available information.

To strengthen analytical consistency and traceability, a working coding matrix was used to link key first-order codes and analytical categories to the relevant documentary

passages and document types. During successive readings, coded passages were checked against their original context, and coding decisions were revised where necessary. Factual statements were cross-checked across internal project materials and publicly available sources wherever possible. Interpretations that could not be supported by the available evidence were not retained. Because the study employed interpretive document analysis rather than independently coded quantitative content analysis, no formal inter-coder reliability coefficient was calculated.

The coding structure provided the link between the documentary evidence and the three mechanisms examined in the case analysis below.

3.5. Trustworthiness, Validation and Limitations

Trustworthiness was addressed through source triangulation and process-consistency checks. Source triangulation compares evidence from materials produced for different purposes and by different institutional actors, reducing reliance on any single documentary account [34]. Policy documents and pilot programme materials were used to establish the institutional basis of the case. Project plans, implementation records, technical reports and summary materials were compared to reconstruct the sequence of implementation. Publicly available reports were used to verify project selection, implementation milestones and technical activities. Key empirical claims were checked against more than one category of documentary evidence and against the chronological record of the project. This procedure follows the emphasis placed on systematic preparation, extraction, analysis and synthesis in rigorous document analysis [32,33].

Institutional and technical perspectives documented in the corpus were considered through source provenance. The materials were produced or reviewed by provincial transport authorities, the infrastructure operator, project-management units, engineering teams, technical service providers and experts involved in technical exchange or project acceptance. Coordination records and acceptance materials were used to examine whether the functions described in technical documents were reflected in project organisation and implementation. The documentary corpus therefore brought regulatory, operational, engineering and technical perspectives into the analysis while preserving the anonymity of the individuals and organisations involved.

The study did not include separate interviews or formal member checking with project participants. No direct stakeholder validation was conducted; the credibility of the findings was assessed through documentary triangulation and process-consistency checks. This design cannot fully capture the subjective experiences of frontline maintenance workers, managers, technology providers or transport authority officials. Nor can it directly observe informal coordination, organisational conflicts or day-to-day implementation difficulties. The findings should therefore be understood as a document-based reconstruction of the project rather than a participant-validated account or a comprehensive evaluation of all actors' perceptions.

Although the study reports selected operational indicators from the project summary, it does not provide a comprehensive quantitative sustainability performance assessment of life-cycle costs, emissions, material use, user disruption or resilience outcomes. These indicators are used to document the operational effects reported in the case, including changes in inspection time, monitoring timeliness and resource requirements, rather than to constitute a full environmental or economic impact evaluation. The principal contribution of the study remains an explanation of the governance process through which digital technologies are connected to sustainable highway maintenance. Future research could combine interviews, field observation and longitudinal operational performance data to

assess changes in safety outcomes, life-cycle costs, resource efficiency, service reliability, user disruption and network resilience more comprehensively.

4. Detailed Results for GX Project Case Analysis

4.1. Datafied Demand Assessment Through Multi-Layer Sensing

The first change produced by the GX project was the reorganisation of maintenance demand identification. Conventional highway maintenance relies heavily on periodic inspection, manual patrols and field-based professional judgement. These practices remain necessary, but they tend to generate maintenance information at fixed intervals and often depend on the experience of inspectors. As a result, maintenance needs may be recorded only after defects become visible, complaints are received or scheduled inspections are completed. The GX project attempted to address this limitation by constructing a multi-layer sensing system covering road surfaces, bridges, slopes and traffic-safety facilities.

For pavement inspection, daily patrol vehicles were upgraded into mobile intelligent inspection units. Cameras, BeiDou/GPS positioning devices, millimetre-wave radar, a vehicle-mounted three-dimensional gyroscope and edge-computing equipment were integrated into patrol vehicles. AI-based computer vision was used to analyse road-surface videos and identify maintenance-relevant conditions. This changed the role of patrol vehicles: they were no longer only tools for human observation, but became mobile sensing nodes that continuously collected, located and processed road-condition data.

To further specify the scope of machine-recognised maintenance conditions, Table 4 summarises the main categories identified by the intelligent inspection system. The system not only detects pavement distress but also identifies defects in traffic-safety facilities and road obstacles. This expands routine inspection from pavement-focused defect detection to a broader road-asset and safety-oriented monitoring process.

Table 4. Recognised categories of maintenance-relevant road conditions.

Category	Recognised Types
Road surface distresses	Transverse cracks; longitudinal cracks; block cracks; strip patching; block patching; potholes; alligator cracking; raveling; settlement; rutting; shoving; bleeding
Traffic facility defects	Guardrail settlement; protective facility damage; obscured traffic signs; damaged or opened isolation fences; damaged traffic signs; poor vegetation maintenance; damaged road markings
Road obstacles	Bags; tyres; bottles; ropes; stones; fruit peels; trees or branches; metal/plastic objects; boxes or packaging; plastic waste; leaves; clothing; paper waste; animals

Note: This table was compiled by the authors from factual information contained in anonymised project materials. Publication of the summarised information has been authorised by the project owner.

For bridges and slopes, the project combined UAV automatic inspection with satellite-based remote sensing. UAV inspection routes were generated through three-dimensional scene models, allowing key parts of bridge substructures, superstructures and slopes to be inspected more systematically. Multi-temporal satellite radar interferometry and optical remote sensing were used to screen slope conditions along the route. For traffic-safety facilities, an intelligent guardrail settlement detection system was developed using linear laser scanning and AI deep learning. The system could identify different wave-beam guardrail types and record height information.

Project-level indicators provide further evidence of the operational effects of datafied demand assessment. According to the anonymised project summary, conventional manual road inspection required approximately 3–4 h, whereas the intelligent inspection system

completed a full bidirectional inspection of the case route in approximately 1.6 h at an operating speed of 80 km/h. The project summary also reported results for a lightweight monitoring system. Its reported alert latency was less than one minute, and its accuracy exceeded 90%. It used approximately half as many sensors as conventional monitoring, while equipment costs were reduced by more than 30%. Taken together, these indicators suggest improvements in inspection speed, monitoring timeliness and the resource efficiency of condition assessment.

The project also used three-dimensional pavement detection and ground-penetrating radar to collect information on both surface and internal pavement conditions. This enabled the simultaneous detection of roughness, rutting, surface damage, internal defect layers, defect types and spatial locations. These data were transformed into three-dimensional pavement models and layered maps of internal pavement defects.

By converting periodic observations and field descriptions into spatially located, machine-readable and cumulative records, the GX system changed the evidence available for identifying maintenance needs. Managers could compare conditions across asset categories and locate potential problems before they developed into visible failures. This improved visibility can support earlier intervention and reduce reliance on reactive repair, which is often associated with higher costs, greater traffic disruption and safety risks. Multi-layer sensing therefore contributes to sustainable maintenance when the resulting evidence supports preventive intervention and long-term asset preservation, rather than merely increasing the volume of condition data.

At the same time, datafied demand assessment also raises governance issues. Machine-recognised defects may involve false positives, false negatives, uneven coverage or inconsistent data standards. The expansion of sensing capacity therefore does not eliminate the need for professional judgement. Rather, it changes the relationship between human judgement and machine-generated evidence. Effective sustainable maintenance governance requires rules for data validation, interpretation and use, so that sensing outputs can become reliable condition evidence rather than unexamined technical results.

4.2. Model-Based Decision-Making and Life-Cycle Maintenance Prioritisation

The second change concerns maintenance decision-making. Highway maintenance decisions must translate heterogeneous asset information into feasible intervention strategies under limited budgets, traffic constraints and safety requirements. In conventional maintenance systems, decisions are often based on technical indicators, historical experience and short-term repair needs. Such approaches may be effective for dealing with visible defects, but they are less able to compare multiple maintenance options across different time horizons, asset categories and service objectives.

In the GX project, multi-source data models were used to connect sensing outputs with maintenance planning. The data foundation integrated AI inspection data, traffic data, maintenance history, environmental data and other operational information into a more unified decision-support environment. This integration mattered because maintenance demand data are not automatically decision-ready. Data from patrol vehicles, UAVs, satellite systems, pavement detection equipment and historical maintenance records are produced at different spatial scales, temporal intervals and technical formats. The project's data foundation reorganised these materials into a consistent set of decision variables that could be compared and linked across data sources.

The project defined maintenance objectives using pavement technical condition, traffic volume, funding constraints and service demand rather than a single technical index. It distinguished among three target levels—optimal service, moderate development and minimum service—across short-, medium- and long-term planning horizons. This structure

introduced a sustainability-oriented logic into maintenance decision-making. The question was not simply how to repair defects, but what level of service, reliability and risk control should be sustained under resource constraints.

Four model functions were particularly important: a maintenance treatment model, a performance prediction model, a maintenance cost model and a priority-ranking model. Together, these models supported strategy generation, effect simulation, cost analysis and funding allocation. They helped transform maintenance decision-making from experience-based judgement towards structured analysis. However, this did not mean that decision-makers were replaced by algorithms. The models provided organised evidence and simulated options, while human decision-makers still had to weigh safety, efficiency, cost, service reliability and public value.

The project documents also show how these models were embedded in the maintenance decision process. Annual maintenance objectives were established by combining road-condition indicators, traffic volume, maintenance history, funding constraints and service requirements. Untreated deterioration trends and anticipated post-intervention improvements were examined through performance-prediction models. Alternative treatments were compared using cost models, while road sections were ranked for annual funding allocation through weighted criteria. The practical contribution of the modelling system therefore lay not only in producing predictions, but also in converting heterogeneous evidence into a structured and reviewable prioritisation process.

The sustainability contribution of model-based decision-making lies in its capacity to connect asset condition evidence with longer-term maintenance consequences. A road section with severe visible deterioration may require immediate intervention, but another section with moderate deterioration and high traffic exposure may also deserve priority because of its service reliability and safety implications. Similarly, a lower-cost intervention may appear efficient in the short term but become less sustainable if it accelerates future maintenance demand or increases user disruption. By integrating condition data, cost estimation, performance prediction and service objectives, model-based decision-making supports more resource-efficient and life-cycle-oriented maintenance prioritisation.

These trade-offs make model design a governance issue rather than a purely technical task. Models can organise complex information and compare alternatives, but final decisions must remain subject to institutional responsibility, professional judgement and public accountability. This is especially important in highway maintenance, where prioritisation affects traffic safety, user disruption, budget allocation, service continuity and resilience as well as technical repair outcomes.

4.3. Adaptive Scheduling for Implementation Coordination and Resilient Service Delivery

The third change concerns implementation. A common weakness in maintenance governance is the implementation gap between planned interventions and field execution. Even when maintenance needs are identified and priorities are established, construction-window constraints, weather conditions, traffic management, material delivery, contractor coordination and quality control can all affect whether a maintenance plan produces the intended results. Maintenance governance therefore does not end when a plan is produced. It depends on whether maintenance tasks can be coordinated, monitored and adjusted during implementation.

In the GX case, adaptive scheduling operated through a monitoring–warning–adjustment loop. The platform combined construction progress records, material data, environmental constraints and quality alerts, enabling managers to identify deviations, reassess work sequences and material requirements, and revise implementation arrangements. Its function therefore extended beyond general managerial flexibility: adjustments

were based on traceable process data and were subsequently incorporated into quality control and future planning.

Comparable applications have been reported in other construction settings. Drawing on 1464 observations from 164 projects, Lagos et al. [30] developed an early-warning model for construction schedule outcomes. The selected model achieved a mean absolute error of 1.24% and an R^2 of 0.96, supporting the monitoring and prediction stages of an adaptive scheduling cycle. In a large water-reservoir tunnel project, Chong et al. [35] integrated BIM, real-time site data and supplier information to support dynamic schedule and resource adjustments. The study reported that the progress deviation rate decreased from 18.3% under the traditional method to 10.6% under the BIM–AI framework, representing a relative reduction of 42%. Real-time synchronisation with supplier systems also shortened schedule-adjustment time by 50%. These studies do not establish a universal performance effect across infrastructure settings, but they demonstrate how a monitoring–warning–adjustment process has been implemented beyond the present case. The GX platform followed the same broad logic through material tracking, progress monitoring, quality alerts and adjustments to material scheduling. Because the documents available for the present study do not provide a counterfactual comparison or standardised before-and-after performance measures, adaptive scheduling is treated here as an observed governance mechanism rather than as evidence of a quantified causal effect on project performance.

The platform also monitored operational variables and generated graded alerts when construction conditions or material parameters exceeded specified thresholds. Environmental factors were incorporated into construction restrictions. Vehicle routes, material delivery, on-site construction progress and site video information were displayed through digital maps and cloud-based visualisation. Managers could use these records to identify deviations in work sequences, trace problems to specific locations and adjust material-delivery schedules in response.

Operational records provide more concrete evidence of how the construction-control platform was used during implementation. Transport vehicles were tracked through BeiDou positioning, while pavers and rollers supplied data on location, operating speed, material temperature and rolling passes. These data were displayed through digital maps and progress views, enabling managers to follow construction progress, identify deviations and trace quality-related issues to specific locations along the route. The platform therefore connected field monitoring with construction scheduling and quality control rather than functioning solely as an information-display system.

A further governance effect concerned responsibility tracing. Location-specific data, abnormality alerts and documentation covering the full construction process allowed construction deviations and operational problems to be located more precisely. This changed field coordination from a system relying heavily on experience, oral communication and post-hoc explanation to one supported by digital records and clearer responsibility boundaries. In this sense, the smart platform did not merely improve construction visibility; it also changed how responsibility, quality control and feedback were organised.

Adaptive scheduling should therefore be understood as more than flexible construction management. It is a mechanism through which road agencies and infrastructure operators address the implementation gap between maintenance planning and field execution. By linking plans with real-time process data, adaptive scheduling allows maintenance work to respond to operational uncertainty while maintaining quality control and service reliability. It connects maintenance planning with implementation capacity and creates conditions for more resilient service delivery.

Digital construction control contributes to sustainability only when it changes how maintenance work is carried out. In the GX project, real-time information on materials,

progress and quality provided a basis for revising work sequences and delivery arrangements before deviations resulted in further delays, rework or unnecessary material use. Coordinating these adjustments with traffic restrictions and quality requirements also provided a way to limit avoidable disruption to road users. The same feedback process is relevant to resilience. When weather, supply or site conditions changed, implementation arrangements could be revised, while the resulting records remained available for subsequent maintenance planning. Comparable links between dynamic scheduling, resource coordination and traffic management have been identified in other construction settings [35,36]. This interpretation is also consistent with transport-resilience research, which treats adaptation and the maintenance or recovery of system function as central to resilience [9,10,37].

This mechanism also raises governance requirements. Real-time platform data can improve coordination, but they require clear rules on data ownership, platform access, responsibility allocation and the use of digital records in quality assessment. Without such rules, platform-based coordination may create new ambiguities over who is responsible for delays, quality problems or data errors. The value of adaptive scheduling therefore depends not only on platform functions, but also on institutional arrangements that define how platform information is interpreted and used.

4.4. Coupling Mechanisms into Sustainable Maintenance Capacity

The three mechanisms do not operate independently. In the GX case, multi-layer sensing, model-based decision-making and platform-based implementation formed a connected maintenance chain. Sensing technologies generated traceable condition evidence; multi-source models translated this evidence into strategies and priorities; the smart construction-control platform embedded decisions into field implementation and generated feedback. The result was a shift from a segmented maintenance process to a more integrated sustainable maintenance loop.

This loop can be interpreted as a form of sustainable maintenance capacity. Condition visibility was strengthened because asset deterioration became more visible, spatially located and traceable. Life-cycle prioritisation was strengthened because heterogeneous data could be integrated into models for prediction, costing and prioritisation. Implementation coordination was strengthened because scheduling, construction quality and responsibility tracing were supported by real-time platform feedback. The value of digital maintenance therefore lies not in any single technology, but in the coupling of information generation, decision structuring and implementation coordination.

Table 5 makes an explicit distinction between operational improvements, governance capacities and sustainability-oriented contributions. Faster inspection, greater data availability, model-generated comparisons and real-time visualisation are operational improvements, but they are not sustainability outcomes in themselves. Their sustainability relevance arises when sensing strengthens condition visibility for preventive asset preservation, modelling supports life-cycle and resource-efficient prioritisation, and platform-based implementation improves coordination, traceability, service continuity and resilience. Fragmented digital tools may improve local efficiency without producing this broader transformation. Sustainable value therefore depends on connecting information generation, decision structuring and implementation feedback across the maintenance chain.

This finding has implications beyond the single highway. Many transport authorities now possess increasing amounts of asset data, but still struggle to convert data into maintenance priorities and coordinated implementation. The GX case suggests that digital transformation should be evaluated not only by the number of technologies deployed, but

also by whether those technologies strengthen the capacity to preserve transport assets, allocate maintenance resources efficiently and maintain reliable services over time.

Table 5. Digital mechanisms and sustainable maintenance capacity.

Digital Mechanism	Sustainability Problem Addressed	Sustainable Maintenance Capacity Supported	Sustainability-Oriented Contribution
Datafied demand assessment	Fragmented, delayed and experience-dependent maintenance information	Condition visibility	Earlier, traceable and risk-sensitive identification of maintenance needs for preventive maintenance
Model-based decision-making	Resource constraints and competing maintenance priorities	Life-cycle prioritisation capacity	Resource-efficient prioritisation across safety, cost, service reliability and resilience
Adaptive scheduling	Implementation uncertainty and field-level coordination problems	Coordination and feedback capacity	Coordinated, traceable and resilience-oriented maintenance execution

5. Discussion

5.1. Digital Maintenance as Sustainable Maintenance Capacity

Research on condition-based maintenance, structural health monitoring, digital twins and predictive analytics has shown how digital technologies can improve condition visibility and support infrastructure decisions [12–15]. Public-sector digital transformation research similarly demonstrates that digitalisation changes organisational routines and institutional relationships rather than merely introducing new technologies [16–18]. The present case supports both perspectives but also reveals their respective boundaries. Greater sensing capacity does not determine how maintenance priorities are established, while general accounts of organisational transformation do not explain how condition evidence moves through maintenance planning and field implementation. Unlike studies centred on the performance of individual devices or models, this study traces how digital evidence is connected to prioritisation, implementation coordination and feedback. It therefore interprets digital maintenance as a process of building sustainable maintenance capacity rather than as a collection of technical upgrades.

This capacity-based interpretation contributes to the literature on highway asset management and intelligent road infrastructure. Recent transport infrastructure research has emphasised the need to connect asset management with safety, service quality, sustainability and intelligent transport systems [23,24]. The present study adds a mechanism-based explanation of how such a connection can be organised in maintenance practice. It suggests that digital maintenance can support sustainability-oriented outcomes when technical systems are embedded in asset-management routines, budgeting processes, quality-control procedures and accountability arrangements. Sustainable maintenance capacity therefore refers not to the possession of advanced technologies alone, but to the ability to use digital systems to make deterioration visible, compare maintenance needs across assets and time horizons, prioritise interventions under resource constraints and feed implementation information back into future planning.

The distinction between operational benefits and sustainability contributions is central to this interpretation. The project-reported indicators suggest faster inspection, more timely monitoring and lower equipment requirements, indicating the operational relevance of the digital systems. Broader contributions to life-cycle asset preservation, resource efficiency, service reliability and infrastructure resilience are interpreted as capacities supported by the three mechanisms rather than as quantified impact estimates. This distinction

avoids assuming that digitalisation is inherently sustainable and directs attention to the governance processes through which operational improvements may generate longer-term sustainability value.

5.2. Life-Cycle Maintenance Prioritisation in Sustainable Highway Asset Management

The case also reframes maintenance prioritisation as a life-cycle and resource-allocation process. In conventional highway maintenance, prioritisation is often treated as a technical exercise based on asset condition, deterioration level or engineering urgency. These criteria remain necessary, but they are not sufficient for sustainable highway asset management. Maintenance decisions also involve trade-offs among safety, user costs, service reliability, fiscal constraints, life-cycle performance and network resilience. Life-cycle performance measurement is particularly important because it links maintenance decisions with long-term resilience, service continuity and asset sustainability [7].

The GX case shows how digital models can make these trade-offs more explicit by connecting asset condition data with traffic exposure, maintenance history, cost estimation and service objectives. This finding is consistent with research that calls for moving beyond short-term repair cost and incorporating life-cycle performance, environmental impacts, social vulnerability and user disruption into maintenance decision-making [6,8,11]. It also resonates with studies showing that geospatial and data-driven decision-support systems can help transport authorities allocate maintenance resources across road segments more systematically [25].

Highway work-zone optimisation research provides a related but distinct perspective on these trade-offs. Shahin et al. [38] integrate safety, mobility and project cost within a total-cost optimisation model, while Shahin et al. [39] treat these considerations as separate objectives and examine the resulting trade-offs. These studies provide a formal basis for comparing work-zone alternatives and identifying optimal or Pareto-efficient solutions. The present case complements this research by examining how condition data, performance prediction, cost estimation and priority criteria are incorporated into an organisational process of maintenance planning and implementation. It does not test the mathematical optimality of alternative strategies or quantify Pareto trade-offs. Its contribution instead lies in showing how model-based decision support is embedded within a governance chain that also includes demand identification, professional judgement and implementation feedback.

The comparison highlights an organisational rather than algorithmic contribution. The GX case does not demonstrate that a particular model is optimal; instead, it shows how condition data, performance predictions, cost estimates and service objectives can be incorporated into a reviewable prioritisation process that remains subject to engineering judgement and institutional accountability. In practice, agencies should document the indicators, weights and thresholds used in this process and ensure that model outputs can be explained and challenged. Such transparency is necessary if digital decision support is to improve long-term maintenance planning without obscuring the value choices involved.

5.3. Implementation Coordination, Service Reliability and Resilience

Section 4.3 showed that the GX platform linked material tracking, construction progress, quality alerts, environmental restrictions and traceable records to schedule adjustment and implementation feedback. The broader contribution of this mechanism lies in treating implementation as an integral part of sustainable maintenance governance. Field-level uncertainty was managed through continuous monitoring, coordination and correction rather than through fixed schedules and manual coordination alone.

Studies outside highway maintenance help explain why these capabilities matter. Chong et al. [35] reported that a BIM- and AI-based scheduling system integrating real-time

site data and vendor-system information reduced progress deviation and shortened the time required for schedule adjustment in a large tunnel project. In road-intersection construction, Castañeda et al. [36] combined digital simulation with collaborative planning to integrate construction schedules and traffic-management plans. Although the technologies and project settings differ from those of the GX case, these studies point to a common principle: schedule information becomes operationally valuable when it supports the coordination of resources, work sequences and disruption to road users during implementation.

For resilience, the relevant question is whether the maintenance system can adjust when implementation conditions change and still protect road service. Transport resilience research treats adaptation and the maintenance or recovery of system function as central capabilities [9,10,37]. In the GX case, weather, traffic, material supply and site conditions could be incorporated into implementation decisions, and the resulting digital records could inform subsequent maintenance planning. This linked immediate construction control with longer-term organisational learning. The available documents, however, do not quantify changes in material consumption, traffic disruption or recovery time. We therefore interpret the platform as providing the capacity for more resource-efficient, reliable and resilient implementation, not as direct evidence that these outcomes improved by a measurable amount.

5.4. Governing Risks in Digital Maintenance Systems for Sustainability

The case also highlights the risks of digital maintenance systems for sustainability. Digital technologies can increase visibility, traceability and coordination, but they may also generate new forms of dependence and vulnerability. Datafied demand assessment may privilege conditions that are easier to measure while overlooking less visible forms of deterioration or local knowledge from frontline workers. Model-based decision-making may improve consistency, but it can also obscure the assumptions and value judgements embedded in algorithms. Platform-based coordination may strengthen accountability through traceable records, but it may also blur responsibility when multiple agencies, contractors and technology providers share the same digital environment.

These risks are particularly important because maintenance decisions affect safety, service reliability, resource distribution and long-term asset sustainability. Data quality problems may lead to false priorities. Algorithmic opacity may make it difficult for decision-makers to explain why some road sections are maintained earlier than others. Platform dependence may reduce organisational flexibility if maintenance routines become too tightly tied to specific vendors or proprietary systems. Interoperability problems may also prevent digital systems from being scaled across different road networks, asset types or administrative jurisdictions. Digital maintenance can therefore create new sustainability challenges even as it seeks to solve existing maintenance problems.

The documentary design also limits what can be learned about stakeholder engagement. The materials identify the formal roles and recorded decisions of public agencies, the project owner, design and construction organisations and technology providers. They do not show how disagreements were resolved, how informal coordination affected implementation, or how frontline staff and road users experienced the project. We therefore use these documents as evidence of institutional involvement, not as evidence that all relevant stakeholders participated equally or shared the same assessment of the pilot. Interviews and field observation will be needed to test the mechanisms identified here and to examine how they are understood by the actors involved.

Several governance safeguards are needed. First, transport authorities should establish data governance rules for digital maintenance systems, including standards for data collection, validation, interoperability, storage and correction. Second, maintenance priori-

tisation models should be auditable, with documented assumptions, indicators, weights and thresholds. Third, digital platforms should be embedded in organisational procedures rather than procured as isolated technologies. Data from sensing, modelling and construction control should be linked to maintenance budgeting, performance evaluation, quality assurance and future planning. Fourth, pilot projects should be assessed not only by technical performance, but also by their ability to generate transferable and scalable governance arrangements.

These safeguards point to a broader conclusion: digital highway maintenance should be governed as a socio-technical system. Its success depends not only on the accuracy of sensors or models, but also on the institutional capacity to interpret data, deliberate over priorities, coordinate implementation and learn from feedback. Digital transformation in maintenance is therefore not a one-time technological intervention. It is an ongoing process through which road agencies and infrastructure operators reorganise information, decision-making and action in order to support sustainable highway maintenance.

6. Conclusions

This paper has examined how digital technologies support sustainable highway maintenance governance. Building on the literature on sustainable transport infrastructure management, life-cycle asset management, digital transformation and transport resilience, it developed a mechanism-based analytical framework and applied it to a Chinese scientific highway maintenance pilot. The analysis shows that digital transformation in highway maintenance is not a simple process of adding sensors, models or platforms to existing maintenance routines. Rather, it occurs through the coupling of three mechanisms: datafied demand assessment, model-based decision-making and adaptive scheduling.

The case demonstrates that datafied demand assessment transforms dispersed asset deterioration into spatially located and traceable condition evidence. Model-based decision-making translates this evidence into prioritised maintenance strategies by linking technical deterioration with cost, service reliability, resource constraints and resilience considerations. Adaptive scheduling connects maintenance plans with field implementation through smart construction control, real-time monitoring, quality alarms, material tracking and feedback. Together, these mechanisms support a shift from reactive repair to evidence-based life-cycle maintenance, from fragmented operations to resource-efficient prioritisation, and from fixed implementation plans to adaptive and resilience-oriented service delivery.

The central message for sustainability-oriented transport infrastructure research is that maintenance digitalisation should be understood as a process of building sustainable maintenance capacity. Digital tools become valuable when they help road agencies and infrastructure operators make deterioration visible, transform heterogeneous data into life-cycle-oriented priorities, and coordinate maintenance tasks under operational uncertainty. In this sense, digital highway maintenance links condition visibility, analytical prioritisation and implementation coordination into an integrated governance process for sustainable infrastructure management.

These findings have several implications for practice. For transport authorities and infrastructure operators, digitalisation should begin with the maintenance decision process rather than with the acquisition of isolated technologies. Multi-source inspection and monitoring data should be organised so that identified maintenance needs can be traced to specific asset conditions. Priority-setting models should make explicit how asset condition, life-cycle cost, service reliability, resource constraints and resilience considerations inform treatment decisions. During project delivery, construction-control platforms should connect schedules with material supply, traffic restrictions, quality requirements, weather and site

conditions so that deviations can be identified and addressed before they lead to avoidable delay, rework or disruption.

Putting these arrangements into practice requires more than technical capacity. Agencies need consistent data standards, clear responsibilities for data quality and decision approval, interoperable systems, and coordination among transport authorities, infrastructure operators, designers, contractors and technology providers. The GX case does not provide a universal implementation template, but it suggests a sequence that other agencies may adapt: establish traceable condition evidence, use explicit rules to prioritise interventions, and maintain a feedback loop between planning and field implementation. The appropriate technologies and organisational arrangements will depend on network scale, institutional responsibilities, data availability and local implementation capacity.

Because this is a single-case study, the findings are not intended to be statistically generalised to all highway maintenance systems. Their wider relevance lies in analytical transferability: the three mechanisms provide a framework for examining how digital technologies may support maintenance governance in other settings. Such transferability is conditional. Datafied demand assessment requires sufficiently reliable condition data, compatible data standards and the capacity to interpret machine-generated evidence. Model-based decision-making depends on integrated asset records, transparent prioritisation criteria and continued professional oversight. Adaptive scheduling requires real-time process data, platform connectivity and sufficient organisational authority to adjust construction activities during implementation.

The boundaries of this transferability should also be recognised. The case concerns a policy-supported and technologically intensive expressway pilot with access to specialised equipment, technical expertise and relatively strong organisational coordination. The three mechanisms may be more difficult to reproduce in settings characterised by fragmented data, limited digital capacity, constrained budgets, dispersed responsibilities or weak coordination between infrastructure operators and contractors. In addition, the study relies primarily on documentary and project-based evidence and therefore cannot fully capture the subjective experiences of frontline workers, managers, technology providers or transport authority officials. Although selected operational indicators are reported from the project summary, the study does not provide a comprehensive quantitative assessment of sustainability outcomes such as life-cycle cost savings, emissions reduction, material efficiency, user disruption or resilience improvement.

Future research should test and refine the framework through comparative studies across different road types, regions, institutional settings, governance arrangements and levels of digital capacity. It could also combine interviews, field observation and longitudinal operational performance data to examine the conditions under which digital maintenance systems improve safety outcomes, life-cycle costs, resource efficiency, service reliability, user disruption and network resilience. Further research should explore how data standards, model transparency, organisational authority and platform interoperability affect the transferability and scalability of the three mechanisms across wider transport networks.

Digital highway maintenance should be understood as a change in governance as well as technology. It alters how infrastructure conditions are recorded, maintenance priorities are justified, and implementation is coordinated. For transport systems facing ageing assets, fiscal constraints and growing resilience pressures, the priority is to build accountable, interoperable and scalable maintenance capacity around these technologies.

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