

Russia

Secretariat of the Economic Cooperation Organization (ECO)

Digital Track Modelling for the Construction and Maintenance of ECO Railways: Pilot Section Zhanaozen–Bastau (Republic of Kazakhstan)

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Terms of Reference (ToR).

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This report has been prepared for the ECO Secretariat and relevant national counterparts. The views expressed are those of the Contractor and do not necessarily reflect the official position of the ECO Secretariat or ECO Member States.

Executive Summary

The pilot project on Digital Track Modelling (DTM) for the Zhanaozen–Bastau section of the Kazakhstan–Turkmenistan–Iran (KTI) corridor confirms that the deployment of a fit-for-purpose digital track model is technically feasible and economically justified under ECO conditions. The Interim Report of the Study was reviewed by ECO Member States, with feedback received from the Turkmen and Iranian sides. The Turkmen side confirmed the use of a Russian technical solution, while the Iranian side indicated that an outdated Austrian solution is currently in operation and does not fully meet modern digitalisation requirements. In this context, Iranian Railways expressed interest in a more comprehensive follow-up Study with an expanded scope, which would require an indicative budget on the order of USD 350–500 thousand, potentially with the support of international organisations, development funds and international financial institutions.

The quantitative assessment demonstrates:

- a positive Net Present Value (NPV) across all scenarios considered;
- a payback period of approximately 2–3 years in the Base Case scenario;
- Internal Rates of Return (IRR) broadly consistent with international benchmarks for digital railway and asset management projects.

The pilot confirms that relatively modest investments in digital track modelling can deliver substantial economic and operational benefits. Digital modelling is understood in this Study as an integrated system combining physical measurement infrastructure (hardware) and analytical and decision-support software, supported by appropriate governance and data management arrangements. Such an integrated approach enables significant savings in track maintenance, reduces service disruptions, and supports safer and more reliable operations along strategic regional corridors.

With regard to the hardware component, international experience indicates that modern inspection and diagnostic solutions with competitive total cost of ownership are particularly effective in corridors characterised by heterogeneous track conditions. Solutions widely deployed in large railway systems, including those originating from the PRC, can reduce failure rates and warranty risks for rolling stock and infrastructure assets. This creates favourable conditions for engaging international financing sources, including banks that support export-oriented railway technologies and seek to mitigate operational and lifecycle risks.

The software component of DTM is addressed in the report through a transparent and auditable mathematical framework linking track geometry, dynamic forces,

risk zones and maintenance decisions to economic outcomes. The detailed DTM calculations presented in the Study demonstrate that the approach avoids reliance on opaque or “black-box” solutions and provides a robust basis for engineering and investment decision-making.

The Study also demonstrates the bankability of the proposed approach. ECO Member States already allocate national budget resources for railway construction, rehabilitation and maintenance on an individual basis. By providing a quantified and credible mechanism for cost savings and efficiency gains, DTM creates incentives for coordination and opens the possibility of structuring a syndicated financing facility to support corridor-level digitalisation. Such financing could be mobilised on concessional terms through international development banks and funds, including those aligned with export financing frameworks. The proposed implementation model envisages the development of a minimum viable product (MVP) at corridor level, followed by the establishment of national operators in each participating country, with data processing on national servers to ensure data sovereignty, risk mitigation and reliable debt servicing. At the same time, the approach aligns with standard grant eligibility criteria, including environmental protection, sustainable development, human capital development and public budget efficiency.

This report provides:

- a concise justification of DTM as an enabling tool for ECO railways;
- a reference architecture and minimum technical specification for a Digital Track Model aligned with international good practice and ECO needs;
- an implementation roadmap for the Zhanaozen–Bastau pilot (8 weeks), including governance, milestones and deliverables;
- an economic model linking geometric quality, dynamic forces and maintenance costs;
- an assessment of international experience (SBB, USA/EU, RZD/KTZ, PRC) and its applicability to ECO corridors;
- recommendations on scaling up the approach across ECO Member States, including options for engaging international financial institutions (IFIs) and technology partners.

The Zhanaozen–Bastau pilot is proposed as a demonstration case for:

- integrating engineering-grade geometry data, condition data (PU-32) and operational information in a single digital model;
- demonstrating transparent, auditable and data-driven maintenance and investment decisions;

- supporting the development of an ECO-level standard for digital track modelling and subsequent corridor-wide deployment.

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1. Introduction

1.1 Context

This report has been prepared in accordance with the approved Terms of Reference and is structured to ensure clarity, transparency, and compliance with internationally accepted reporting practices.

The Terms of Reference comprise five principal items. The present report provides a detailed analysis and substantiation of the first four items of the Terms of Reference. The fifth item is delivered in the form of presentation materials, which are provided as a standalone presentation and serve to complement the report by offering a concise and visual summary of the key findings, assumptions, and conclusions.

Such a separation between the analytical report and the presentation materials is consistent with international best practices for technical and feasibility studies, ensuring both methodological rigor and effective communication of results to decision-makers.

ECO Member States are investing heavily in rail infrastructure to support regional connectivity, trade facilitation and diversification of transit routes. At the same time, fiscal space is constrained, and infrastructure managers are expected to:

- reduce lifecycle costs;
- improve safety and reliability;
- integrate with digital trade and transport systems.

Digital Track Modelling (DTM) is a practical, technically mature instrument to achieve these goals. Unlike purely conceptual “digital twin” narratives, the proposed DTM approach focuses on:

- accurate representation of track geometry and associated assets;
- systematic linkage to diagnostics and maintenance history;
- transparent economic evaluation of maintenance strategies.

1.2 Basis of the Assignment

The assignment is based on:

- Contract between ECO Secretariat and the Contractor dated 30 October 2025;
- Terms of Reference: Study on Digital Modelling for ECO Railways (2025);
- decisions and recommendations of relevant ECO bodies (RPC, TTCC, PMG).

The DTM pilot on Zhanaozen–Bastau is designed as a low-cost, high-demonstration

value project to illustrate the benefits of data-driven maintenance and planning in a realistic operational context.

1.3 Object of Analysis

The primary object is the Zhanaozen–Bastau section (operational length approx. 35 km), part of the KTI transport corridor. For modelling and scalability, the 35 km perimeter is considered in line with the ToR requirement (geographic perimeter up to 35 km).

1.4 Source Materials

Key inputs include:

- KTZ datasets: geometry, PU-32 forms, lists of engineering structures, technical parameters;
- ECO Secretariat documentation and ToR;
- international references and technical papers on digital track modelling.

The terrain analysis demonstrates that the KTI railway corridor predominantly crosses flat and mildly undulating areas. This represents a significant competitive advantage compared to alternative ECO corridors that pass through mountainous and foothill regions.

2. Relevance and Strategic Rationale

2.1 Macroeconomic Perspective

Average railway construction costs of 2–10 million USD per km, combined with rising maintenance expenditures, highlight the importance of optimising both CAPEX and OPEX. For ECO Member States:

- large sections of the network are in harsh climatic and geotechnical environments;
- freight flows are volatile and sensitive to corridor performance;
- budgetary constraints limit the scope for full reconstruction.

A systematic, digital approach to track condition and geometry enables:

- targeted interventions instead of blanket repairs;
- prioritisation of sections with the highest economic and safety impact;
- better justification of funding and financing to governments and IFIs.



Figure 1: KTI Railway Corridor: General Route Alignment with Terrain Relief

2.2 Alignment with ECO and Global Agendas

The DTM initiative is consistent with:

- ECO Vision 2025 and subsequent regional connectivity strategies;
- the SDGs, in particular SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action);
- UNESCAP and UNECE recommendations on digitalization of transport corridors and data harmonisation;
- UN/CEFACT standards for electronic data exchange supporting multimodal transport.

The strategic assessment of the Digital Track Modelling (DTM) initiative also applied a SWOT framework to identify key strengths, weaknesses, opportunities and threats associated with both the pilot implementation and the potential scale-up across ECO railway corridors. The results of this analysis are summarised in

Appendix A (Compliance with ToR Requirements and KPIs).

3. Objectives and Scope of Work

3.1 Overall Objective

To demonstrate, through a practical pilot, that Digital Track Modelling:

- is technically achievable with realistic data and tools available in ECO railways;
- yields measurable economic benefits in terms of reduced lifecycle costs;
- can be codified into a scalable ECO-wide standard.

3.2 Specific Tasks

1. Review international experience (SBB, USA/EU, RZD/KTZ, PRC and others) in digital track and asset modelling.
2. Define and document assumptions and constraints relevant to ECO networks.
3. Develop an 8-week pilot implementation plan for the Zhanaozen–Bastau section.
4. Design the DTM architecture, including data model, interfaces and V&V framework.
5. Construct an economic model linking geometric quality, dynamic loads and maintenance costs.
6. Propose governance, risk management, KPI and reporting arrangements.
7. Provide recommendations for scaling up along key ECO corridors.

The objectives of the Study and the pilot implementation were formulated and assessed in accordance with the SMART criteria (Specific, Measurable, Achievable, Relevant and Time-bound), ensuring clarity of scope, verifiability of results and compliance with the Terms of Reference. Further details are provided in Appendix A.

4. Methodology

4.1 Analytical Approach

The study combines:

- desk review of international standards, guidelines and case studies;
- analysis of KTZ track data (geometry, PU-32, structures) for the pilot section;

- simplified but robust modelling of curvature-related loads and maintenance costs;
- scenario analysis for CAPEX/OPEX and risk-adjusted returns;
- qualitative assessment of institutional and technical readiness.

4.2 Data and Quality Control

Data sources are screened for:

- completeness and coverage for the pilot section;
- consistency between geometry, structures and PU-32 assessments;
- plausibility of key parameters (radius, cant, speeds, axle loads).

The proposed DTM framework embeds:

- ETL processes with validation rules;
- reproducible calculations for decision support;
- clear separation between raw data, processed indicators and recommendations.

5. Review of the Interim Report by ECO Member States

The Interim Report of the Study on the development of the KTI railway corridor was submitted for review to the interested member states of the Economic Cooperation Organization (ECO).

Based on the official responses received:

- the Turkmen side informed that a Russian technical solution is currently used for railway infrastructure planning and management;
- the Iranian side indicated that an outdated Austrian solution is still in use, which does not fully meet modern requirements for digitalization, interoperability, and capacity development.

In addition, Iranian Railways expressed interest in a more comprehensive and in-depth Study similar to the present one, but with an expanded scope of work. Implementation of such a Study would require an increase in the budget to approximately ... thousand USD, potentially through the involvement and support of international organizations, development funds, and financial institutions.

6. International Experience with Digital Track Modelling

6.1 Comparative Overview

Jurisdiction	Key Elements	Observed Impact
Switzerland (SBB)	Integrated BIM/DTM, unified asset register, continuous geometry control	10–20% lifecycle savings; improved planning; decreased track possession times
USA/EU	Amtrak/FRA TGMS (Track Geometry Measurement System) and EN 13848-compliant inspection cars using LiDAR, IMU, RTK-GNSS; automated defect classification and predictive analytics.	Reduced speed restrictions; more targeted tamping and renewals; deferred CAPEX
RZD/KTZ	Standards for 1520 mm gauge; linkage of curvature, cant and wear models	Risk-based maintenance; better correlation between geometry and deterioration
PRC	CRCC high-speed inspection trains (e.g. CIT450, capable of 450 km/h inspection speeds) with integrated track geometry (LiDAR/IMU), catenary, signalling diagnostics, and AI-based abnormality detection; real-time digital twin updates via deep learning models for predictive maintenance.	Higher utilisation (up to 20% increase in throughput); reduced delays (by 30–50% via predictive interventions); maintenance outages shortened by 40%; lifecycle costs lowered by 15–25% through targeted repairs.

6.2 Key Lessons for ECO

- Start with a focused scope: track geometry and condition, not a full digital twin of all assets.
- Use open, documented data structures to avoid vendor lock-in.
- Ensure that outputs are understandable to track engineers and finance departments.
- Treat DTM as an ongoing process, not a one-off survey.

- **USA/EU lesson:** TGMS allows fully automated defect detection with sub-centimetre accuracy, enabling predictive maintenance without human inspection.
- **PRC lesson:** High-speed inspection trains like CIT450 integrate multi-system diagnostics with AI for real-time anomaly detection, achieving significant efficiency gains; however, their high CAPEX and focus on 350+ km/h networks make them suitable mainly as a reference for scalable, modular solutions in ECO conditions.

7. Assumptions and Constraints

ID	Description	Type	Comment
A1	Timely access to KTZ/ECO data in machine-readable formats	Assumption	SLA (Service Level Agreement) with defined response times, focal points
A2	Geospatial accuracy of core datasets \leq 1 cm	Assumption	RTK/LiDAR supported
A3	Compatibility with existing 1520 mm standards and norms	Assumption	No conflicts expected
A4	Discount rate 10%	Assumption	Consistent with ECO practices
A5	Traffic variation within $\pm 15\%$ of baseline	Assumption	Outside range triggers update
C1	Pilot budget ceiling 10,000 USD	Constraint	ToR requirement
C2	Implementation within 8 weeks	Constraint	ToR requirement
C3	Geographic perimeter up to 35 km	Constraint	Pilot scope (fully applied)
C4	MVP-level integration (APIs or file-based)	Constraint	No full IT overhaul
C5	Change control through Steering Group and CRs	Constraint	Governance discipline

8. Implementation Plan for the Pilot (8 Weeks)

The implementation plan and deliverables of the Study are fully aligned with the Key Performance Indicators (KPIs) defined in the Terms of Reference. These KPIs are understood as the successful delivery of specified outputs rather than technical metrics and include: an international overview, technical requirements, an economic model, a final technical assignment, and a presentation. A formal mapping of all KPIs to the corresponding deliverables and report sections is provided in Appendix A.

Weeks	Activities	Gate / Acceptance
1–2	Stakeholder mobilisation; data access agreements; ETL prototype; initial geometry and PU-32 analysis	Gate 1: data availability and quality confirmed
3–4	Definition of DTM data model; architecture and interface design; selection of tools and formats	Gate 2: technical design approved by Steering Group
5–6	Economic model calibration; KPI validation; V&V plan; draft results for pilot section	Gate 3: methodological package endorsed
7–8	Consolidated pilot results; final report; recommendations; ToR for Phase 2 (scale-up) prepared in line with ECO requirements	Gate 4: final deliverables accepted

9. Economic Model: CAPEX, OPEX, NPV and IRR

The economic assessment of the Digital Track Modelling (DTM) pilot is based on a clear separation between capital expenditure (CAPEX) and operational expenditure (OPEX). This distinction ensures transparency of cost assumptions and provides a robust basis for the calculation of standard investment performance indicators, including Net Present Value (NPV), Internal Rate of Return (IRR) and payback period. CAPEX and OPEX are applied as economic input parameters rather than Key Performance Indicators (KPIs), in line with the evaluation criteria set out in the Terms of Reference and summarised in Appendix A.

9.1 Cost Structure

Category	CAPEX (USD)	OPEX (USD/year)
Survey equipment / sensors	2,500	300
Software / licences / cloud	1,200	200
Data processing / analytics	3,000	400
Training / capacity building	1,000	100
Monitoring / support	0	600
Total	7,700	1,600

9.2 Scenarios (5-year Horizon, 10% Discount Rate)

Scenario	CAPEX (USD)	OPEX/year (USD/year)	Net Benefit/year (USD/year)	Payback (years)	NPV (5y) (USD)
Conservative	7,700	1,600	2,400	3.2	1,400
Base Case	7,700	1,600	3,400	2.3	5,200
Optimistic	7,700	1,600	5,400	1.4	12,800

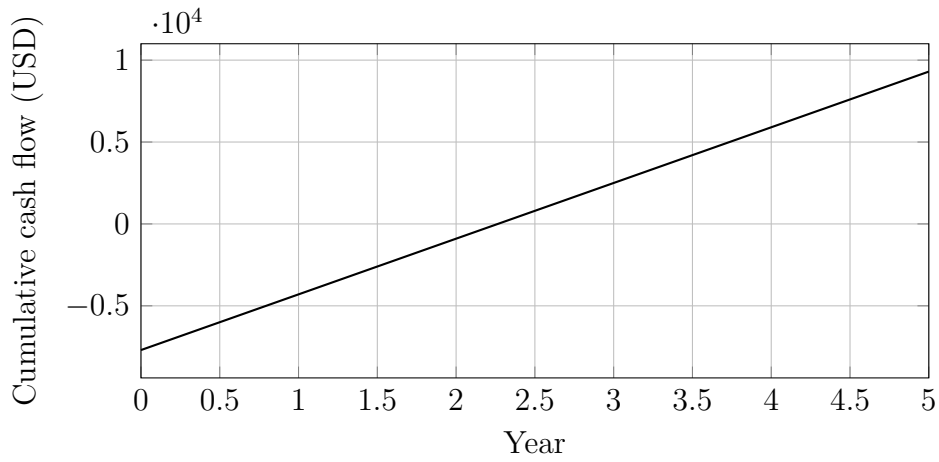
9.3 10-year Performance

Scenario	Net Benefit/year (USD)	Payback (years)	NPV (Base Horizon) (USD)	NPV (10y) (USD)
Conservative	2,400	3.21	1,397.89	7,046.96
Base Case	3,400	2.26	5,188.68	13,191.53
Optimistic	5,400	1.43	12,770.25	25,480.66

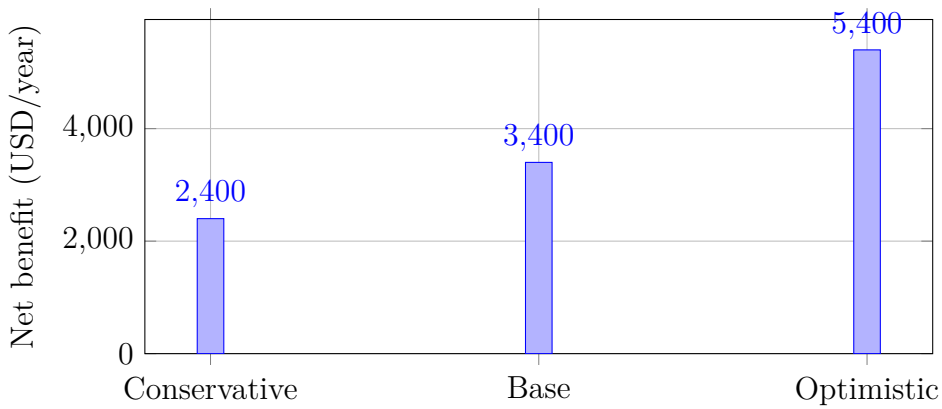
Indicative IRR:

- 22–25% (Conservative),
- 36–40% (Base Case),
- above 60% (Optimistic).

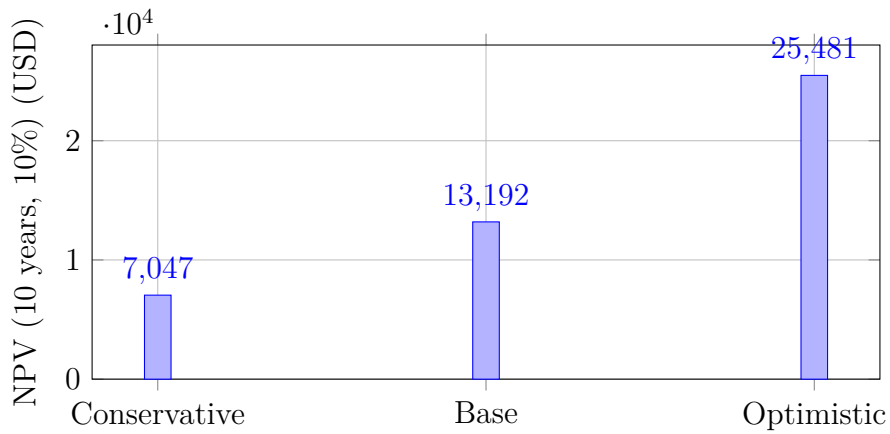
9.4 Illustrative Plots



. 2: Cumulative cash flow, Base Case scenario.



. 3: Annual net benefits by scenario.



. 4: NPV over 10 years by scenario.

10. DTM Architecture and Technical Requirements

The technical architecture and requirements defined in this section constitute one of the core deliverables of the Study in accordance with the Terms of Reference. They support the achievement of the expected outcomes and accepted criteria, including technical feasibility, scalability, and compliance with international good practice, as further documented in Appendix A.

10.1 Logical Architecture

1. **Data layer:** geometry, diagnostics, structures, operations, environment.
2. **ETL & Quality:** ingestion pipelines, validation rules, error logs.
3. **Modelling:** curvature κ , cant h , transition curves, risk zones.
4. **Analytics:** cost models, NPV/IRR/ROI, scenario simulations.
5. **Interfaces:** API/file exchange with KTZ and ECO systems; reporting.
6. **Security & CM:** RBAC, encryption, version control, audit trail.

10.2 Data Protection and Access Control

Pilot data:

- stored in encrypted containers or secure servers;
- accessible only to authorised project staff under **RBAC** (Role-Based Access Control);
- retained for 12 months after pilot completion, then archived or deleted based on ECO decision;
- transferred only via secure channels, with access logs maintained.

10.3 Key Non-Functional Requirements

- geometric accuracy at or better than 1 cm for key parameters;
- ETL cycle not exceeding 2 hours for the pilot perimeter;
- system availability of at least 99% for core functions;
- support for widely used formats (CSV, XLSX, JSON);
- full traceability and versioning of datasets and outputs.

10.4 V&V Metrics

Metric	Threshold	Description
RMSE(κ)	$\leq 0.01 \text{ m}^{-1}$	Agreement between independent measurements
Δh	$\leq 5 \text{ mm}$	Difference between theoretical and measured cant
IoU (risk zones)	≥ 0.6	Overlap of risk zones vs. PU-32 assessments

11. Governance, Risks and Change Management

11.1 Steering Group

The Steering Group includes:

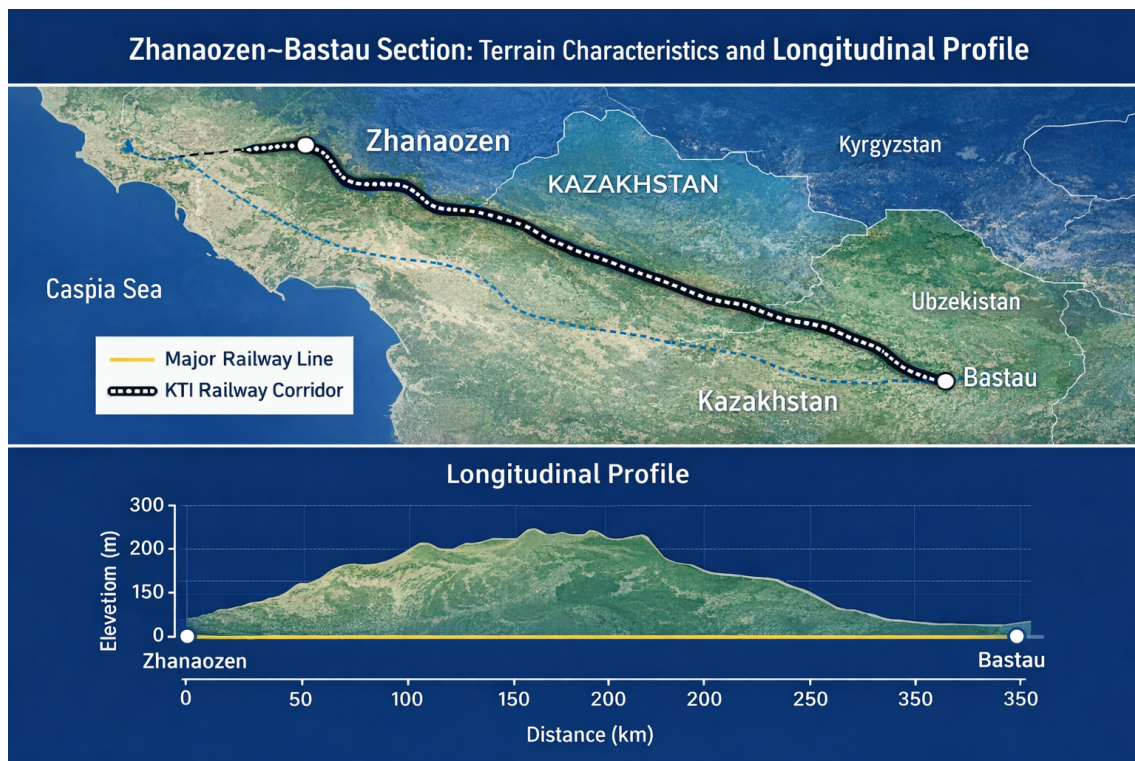
- ECO Secretariat representatives;
- designated authorities from Kazakhstan, Iran and Turkmenistan (as applicable);
- the Contractor and invited technical experts.

11.2 Risk Register

ID	Risk	Likelihood	Impact	Level	Mitigation
R1	Delayed provision early requests	data 3/5	4/5	High	Binding SLAs;
R2	Format incompatibility templates	3/5	3/5	Medium	ETL converters;
R3	Funding constraints IFI co-financing	2/5	4/5	Med-High	Phased roll-out;
R4	Skills shortage with universities	3/5	3/5	Medium	Training; partnership

R5	Measurement errors standards	3/5	3/5	Medium	Calibration; RTK
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12. Pilot Section Characteristics



. 5: Zhanozen–Bastau Section: Terrain Characteristics and Longitudinal Profile

12.1 Technical Parameters

Operating length: 35 km.

Track structure: R-65 rails, concrete sleepers, crushed stone ballast.

Year of commissioning: 2012.

Nominal speeds: passenger 80–100 km/h; freight 70 km/h (with existing restrictions).

12.2 Engineering Structures (Excerpt)

Km+Pk	Type	Span / opening
180 1+94	Pedestrian bridge	13.0 + 15.0

182 0+00	Circular RC culvert	1×1.0
185 3+56	Circular RC culvert	1×1.0
189 5+52	Circular RC culvert	1×1.5
192 6+25	Rectangular RC culvert	1×2.0
195 2+13	Circular RC culvert	1×1.5
195 7+32	Circular RC culvert	1×1.0
198 6+90	Circular RC culvert	1×1.0

13. Theoretical Framework: Geometry and Cost Relationship for the Zhanaozen–Bastau Pilot Section

This section formalises the relationship between track geometric accuracy (primarily curvature) and track maintenance costs. This relationship is used as the core of the economic model for the Digital Track Model (DTM) pilot on the Zhanaozen–Bastau section.

The modelling objectives are:

- to demonstrate that maintaining higher geometric accuracy (on the order of 1 cm) through a DTM leads to measurable reductions in routine maintenance costs and an extension of track life;
- to link DTM accuracy requirements to economic effects over the time horizons applied in the ECO pilot (5 and 10 years).

Units and assumptions: v is velocity (m/s), R is curve radius (m), integration is along track length s . For simplified estimates, the section is treated as having quasi-constant speed and homogeneous conditions; for mixed traffic, representative trains with traffic-based weights are used.

The key idea is that excess maintenance cost is proportional to the *excess curvature* of the trajectory ($\kappa = 1/R$). If the allowable geometric error in curvature increases from 1 cm to 2 cm, annual costs increase by roughly a factor of two; from 1 cm to 5 cm — by about a factor of five. This provides a strong economic motivation to reduce geometry errors to ≤ 1 cm using the DTM.

13.1 Relationship Between Loads, Curvature and Maintenance Costs

Consider:

- A — the volume of work required to maintain the track in standard condition on the section;
- A^* — the integral “work” of rolling stock on the track (load depending on mass, speed and alignment geometry);
- C_A — the total cost of track maintenance;
- L — the length of the section (for the Zhanaozen–Bastau pilot $L \approx 35$ km; the model is scalable to the wider ECO network).

Assume:

$$A = k_1 A^*, \quad (1)$$

i.e. the volume of maintenance and renewal work is proportional to the integral dynamic load.

Costs are proportional to this volume:

$$C_A = k_2 A = k_2 k_1 A^*. \quad (2)$$

The work of forces along the track is represented as:

$$C_A = k_1 k_2 A^* = k_1 k_2 \int_0^L F(s) ds, \quad (3)$$

where $F(s)$ is the resultant dynamic force of vehicle–track interaction and s is the coordinate along the track. For simplicity, we set $k_1 k_2 = 1$ (normalising the scale).

Using the expression for centripetal acceleration:

$$a = \frac{v^2}{R(s)}, \quad (4)$$

where v is speed and $R(s)$ is the curve radius at position s . Then:

$$C_A = \int_0^L m a ds = \int_0^L m \frac{v^2}{R(s)} ds, \quad (5)$$

where m is the **equivalent train mass** (in kg).

Within the ECO/KTZ pilot, m and v are determined by operational requirements (optimisation of these parameters is a separate task). The main controllable parameter

for our purpose is geometry, in particular curvature $1/R(s)$ and its deviations from the design alignment.

Hence, the criterion for minimising maintenance costs can be expressed as:

to minimise the integral excess curvature relative to the design alignment, while ensuring the required accuracy of its implementation.

13.2 Model of the Impact of Curvature Error on Additional Costs

Consider two variants of curvature along the section:

$$\frac{1}{R(s)}, \quad \frac{1}{R_\varepsilon(s)},$$

where $R(s)$ is the design radius and $R_\varepsilon(s)$ is the radius with surveying, construction and deformation errors.

Then:

$$C_A = \int_0^L m \frac{v^2}{R(s)} ds, \quad (6)$$

$$C_{A_\varepsilon} = \int_0^L m \frac{v^2}{R_\varepsilon(s)} ds. \quad (7)$$

The increase in costs due to geometric deviations is:

$$\Delta_\varepsilon = C_{A_\varepsilon} - C_A = mv^2 \int_0^L \left(\frac{1}{R_\varepsilon(s)} - \frac{1}{R(s)} \right) ds. \quad (8)$$

After transformation:

$$\Delta_\varepsilon = mv^2 \int_0^L \left(\frac{R(s)}{R_\varepsilon(s)} - 1 \right) \frac{1}{R(s)} ds. \quad (9)$$

Since in KTZ and ECO practice evaluation is often carried out by track segments (pickets), we can write in discrete form:

$$\Delta_\varepsilon = mv^2 \sum_{i=1}^N \int_0^P \left(\frac{R_i}{R_{\varepsilon,i}} - 1 \right) \frac{1}{R_i} ds, \quad (10)$$

where P is the length of a segment, and R_i , $R_{\varepsilon,i}$ are the corresponding values on the i -th segment.

By the Lagrange mean value theorem, for each segment there exists a point θ_i

such that:

$$\Delta_\varepsilon = \sum_{i=1}^N \left(\frac{R(\theta_i)}{R_\varepsilon(\theta_i)} - 1 \right) mv^2 \int_0^P \frac{1}{R(s)} ds. \quad (11)$$

Under the hypothesis of statistically uniform perturbations (supported by PU-32 data for the Zhanaozen–Bastau pilot), this can be reduced to:

$$\Delta_\varepsilon = \left(\frac{R(\theta)}{R_\varepsilon(\theta)} - 1 \right) C_A = k_\delta C_A, \quad (12)$$

where

$$k_\delta = \frac{R(\theta)}{R_\varepsilon(\theta)} - 1 \quad (13)$$

is interpreted as the relative increase in costs due to excess curvature.

Thus, within the adopted assumptions:

a percentage increase in curvature (equivalently, deterioration in geometric accuracy) leads to a comparable percentage increase in track maintenance costs.

13.3 Evaluation via Mid-Chord Offset and Choice of Target Accuracy for the DTM

For practical calibration, we use the classical relationship between the mid-chord offset ε on a chord of length L and the curve radius R_ε :

$$R_\varepsilon = \frac{L^2}{8\varepsilon} + \frac{\varepsilon}{2} \approx \frac{L^2}{8\varepsilon}, \quad (14)$$

neglecting the small term $\varepsilon/2$.

Let the target DTM accuracy for rail position be defined by:

$$\varepsilon_0 = 0.01 \text{ m} \quad (1 \text{ cm}),$$

and a degraded variant by:

$$\varepsilon_1 = 0.02 \text{ m} \quad (2 \text{ cm}).$$

Then:

$$k_\delta = \frac{R_{\varepsilon_0}}{R_{\varepsilon_1}} - 1 = \frac{\varepsilon_1}{\varepsilon_0} - 1. \quad (15)$$

Substituting:

$$k_{\delta} = \frac{0.02}{0.01} - 1 = 1,$$

which means that moving from 1 cm to 2 cm error approximately doubles the “excess” component of maintenance costs (all else being equal).

Similarly, when moving from 1 cm to 5 cm:

$$k_{\delta} = \frac{0.05}{0.01} - 1 = 4,$$

which corresponds to an increase of additional costs by roughly a factor of five (considering the base component C_A), or necessitates speed reductions and loss of transit potential.

13.4 Interpretation for the ECO Pilot Project

For the Zhanaozen–Bastau pilot the following indicative conclusions apply:

- If annual costs of developing and maintaining a DTM with 1 cm accuracy are on the order of $\sim 1\%$ of current track maintenance expenditures for the section, then reducing the error (e.g. from 2 cm to 1 cm) already yields savings comparable to tens of percent of the “excess” cost component.
- Even under conservative adjustments (e.g. reducing assumed effects by 50%), total maintenance cost reductions in the range of about 15–20% appear realistic and consistent with international evidence (10–20% lifecycle savings from DTM/BIM and predictive maintenance).
- Additional benefits include:
 - fewer and shorter track possessions for maintenance;
 - reduced rolling stock wear due to more stable geometry;
 - justified increases in permissible speeds on certain sections without full reconstruction;
 - improved reliability, predictability and competitiveness of the KTI corridor and the ECO rail network as a whole.

In summary, the mathematical model embedded in the pilot provides a formal economic justification: investing in a high-accuracy Digital Track Model (on the order of 1 cm) at a reasonable share of CAPEX/OPEX results in lower maintenance costs, extended asset life and improved corridor performance, fully aligned with ECO objectives for efficient and sustainable transport corridors.

14. Extended Analysis of Curvature, Cant and Transition Curves

14.1 Curvature Analysis

Curvature peaks correlate with:

- higher PU-32 scores (worse condition);
- increased tamping and lining demands;
- potential local speed limitations.

14.2 Cant Analysis

For 1520 mm gauge:

$$h \approx 12.09 \cdot \frac{V^2}{R} \text{ (mm)},$$

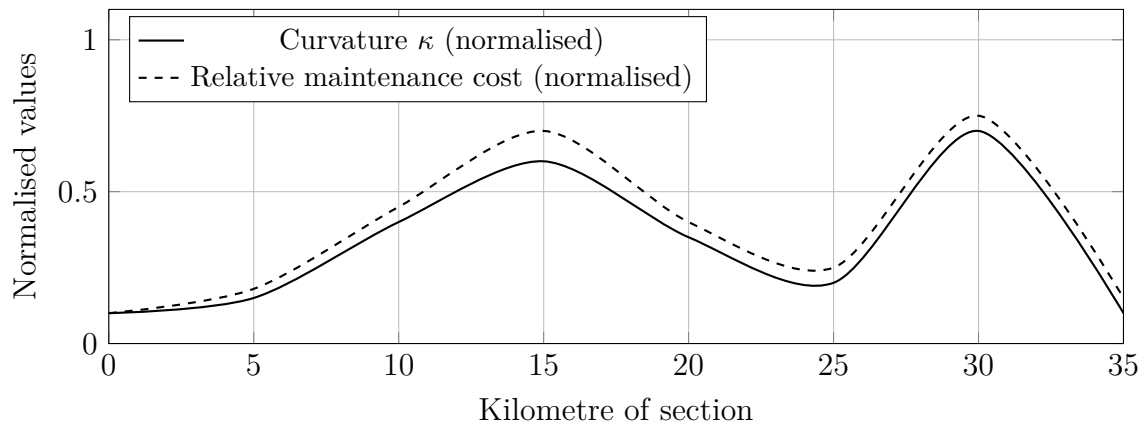
with cant excess/deficiency considered for mixed traffic.

14.3 Transition Curves

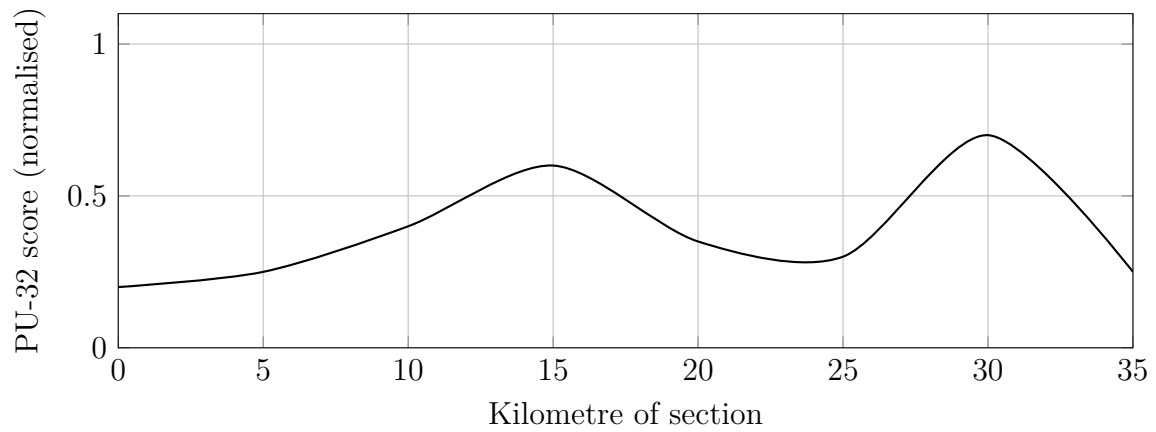
Clothoids or polynomial transitions ensure:

- controlled rate of change of lateral acceleration;
- compliance with comfort and safety criteria;
- reduced dynamic impact and maintenance needs.

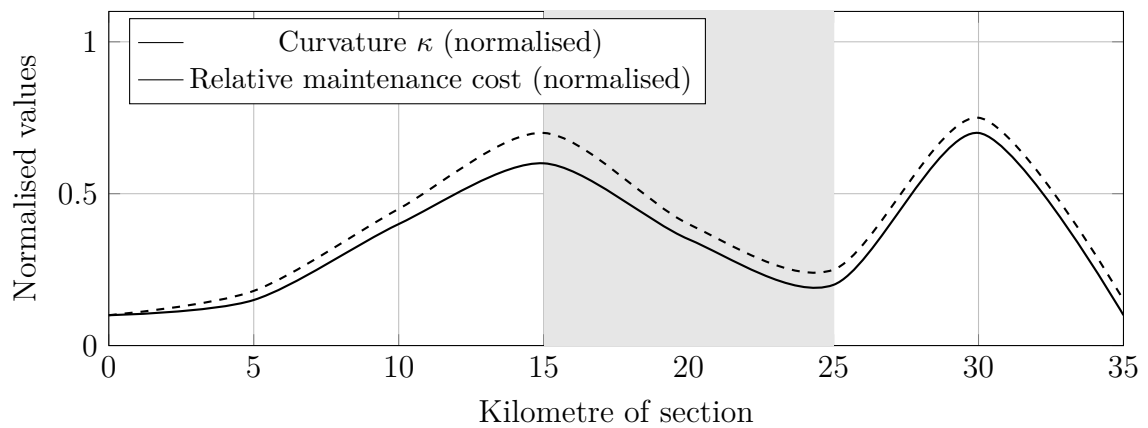
15. Illustrative Charts (pgfplots)



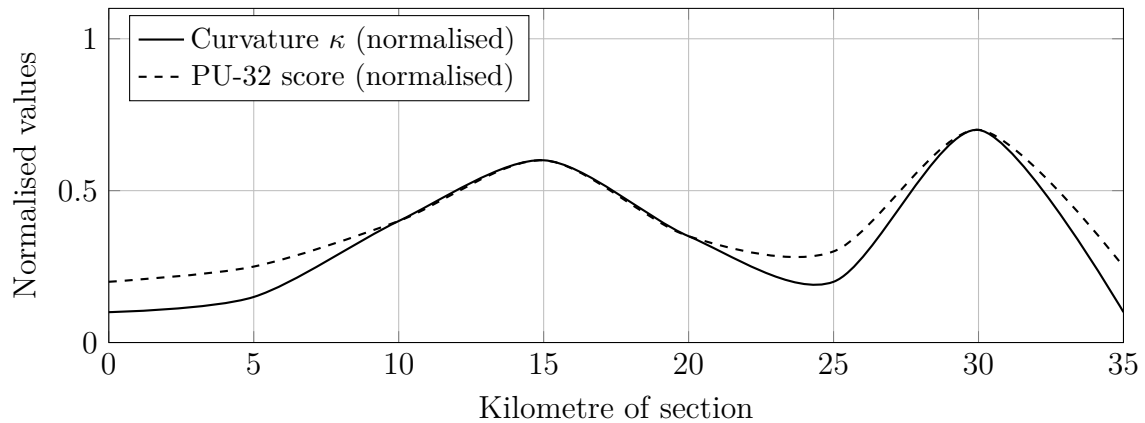
. 6: Schematic relationship between curvature and relative maintenance costs.



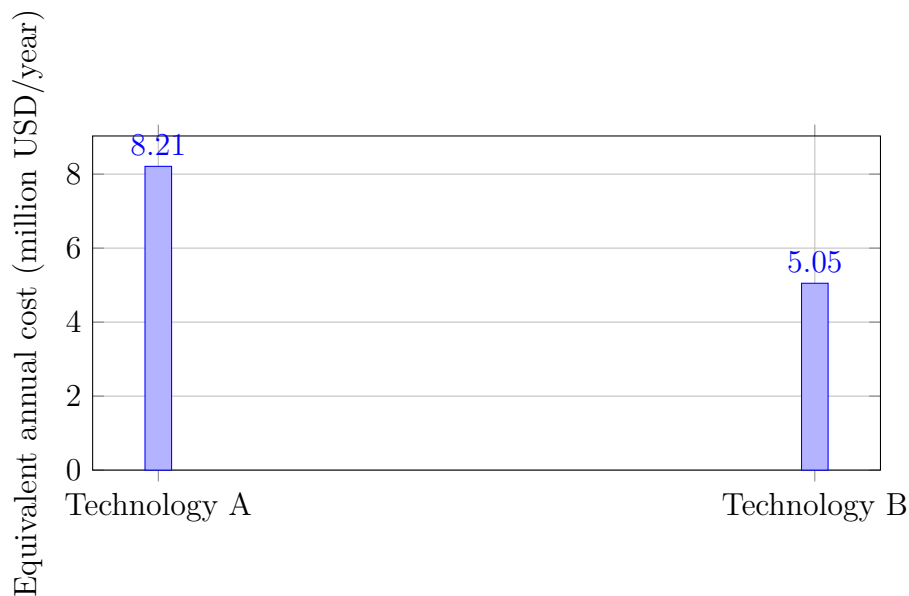
. 7: Schematic profile of PU-32 track condition score.



. 8: Curvature and relative maintenance cost with an illustrative problem zone.



. 9: Schematic correlation between curvature and PU-32 track condition scores.



. 10: Illustrative comparison of equivalent annual costs for technology options.

16. Comparative Options for Phase 2 Implementation

The successful completion of the Zhanaozen–Bastau pilot (35 km perimeter) creates a platform for a larger-scale Phase 2 deployment of Digital Track Modelling (DTM) solutions on priority ECO corridors. For Phase 2, two indicative technology and delivery configurations are considered:

- **Option A: GE + Infotrans configuration** — a partnership model based on an established global supplier of diagnostic and digital railway systems (GE/Wabtec-type portfolio) combined with a regional systems integrator such as Infotrans or an equivalent ECO-based partner.

- **Option B: CRRC + local solution** — a configuration based on Chinese inspection and DTM technologies (e.g. CRRC inspection vehicles and subsystems), integrated with software and services delivered by local ECO-region providers.

Both options are technically feasible for ECO railways and can deliver the accuracy levels required by the DTM concept. The choice should be driven by: (i) life-cycle economics rather than upfront CAPEX only; (ii) verifiable accuracy and reliability; (iii) integration, data ownership and cybersecurity safeguards; and (iv) localisation of skills and support within ECO Member States.

16.1 Key Evaluation Criteria

For Phase 2, the following criteria are proposed:

1. **Measurement accuracy and reliability:** achievable tolerances for geometry (alignment, level, gauge), repeatability, stability of calibration, and availability of verification and validation (V&V) protocols aligned with EN 13848 and relevant 1520 mm standards.
2. **Total cost of ownership (TCO):** combined CAPEX/OPEX over 8–10 years, including hardware, software licences, cloud/on-premise infrastructure, calibration, maintenance, training and upgrades.
3. **Integration and interoperability:** openness of interfaces (APIs), availability of documented data models, ease of integrating with KTZ/ECO systems and national asset management platforms.
4. **Localisation and capacity building:** extent to which implementation builds sustainable in-region expertise (ECO railways, universities, engineering firms), reducing dependence on single foreign vendors.
5. **Governance, risk and supply-chain resilience:** diversification of suppliers, robustness against export controls/sanctions, cybersecurity posture, and contractual clarity on data ownership.

16.2 Option A: GE + Infotrans Configuration

This configuration assumes the use of a mature Western-origin diagnostic and analytics platform, delivered jointly with an ECO-region integrator.

Key characteristics:

- **Accuracy:** modern laser/IMU-based systems typically achieve sub-millimetre to millimetre-level resolution on key parameters and are designed to comply with EN 13848-type standards and established acceptance regimes used by

European and North American railways.

- **System maturity:** long operational track record on mixed-traffic corridors; proven toolsets for trend analysis, alarm thresholds, defect classification and integration into enterprise asset management.
- **Indicative cost profile:**
 - higher upfront licence and integration fees;
 - predictable support and upgrade cycles;
 - potential for framework agreements covering multiple ECO railways and reducing unit costs at scale.
- **Integration:** strong support for documented APIs and export of raw and processed data; alignment with the open, vendor-neutral DTM architecture proposed in this report.
- **Risks:** exposure to currency fluctuations and export control regimes; need for clear arrangements to ensure hosting of data in ECO jurisdictions and transfer of knowledge to local staff.

Option A is well-suited where the priority is: (i) maximum transparency of algorithms and interfaces, (ii) strong alignment with European/IFI expectations on safety and cybersecurity, and (iii) a benchmark “reference” implementation for ECO-wide standardisation.

16.3 Option B: CRRC + Local Solution

This configuration leverages Chinese-origin inspection technologies and rolling stock, combined with local software and analytics capabilities in ECO countries.

Key characteristics:

- **Accuracy:** CRRC-type inspection systems, as applied on high-speed and heavy-haul networks in Asia, also provide high precision for geometry, gauge, profile and defects; they are suitable for intensive monitoring and predictive maintenance frameworks subject to ECO-side validation.
- **Indicative cost profile:**
 - in many cases, competitive or lower unit CAPEX for sensor packages and on-track equipment, especially where supplied as part of a wider rolling stock or signalling programme;
 - potential to reduce costs through local manufacturing or assembly;
 - OPEX strongly influenced by localisation of maintenance and availability of local service partners.
- **Localisation potential:** strong scope to structure projects so that ECO-

based universities, design institutes and IT companies co-develop DTM analytics layers, dashboards and integration components.

- **Integration and data policy:** effective use within the ECO DTM framework requires:
 - full access to raw measurement streams and documentation;
 - contractual guarantees on data ownership by infrastructure managers;
 - avoidance of closed, proprietary formats that limit interoperability.
- **Risks:** potential heterogeneity between delivered subsystems, dependence on specific vendors or protocols if integration is not carefully standardised, and the need to verify compliance with ECO cybersecurity and privacy requirements.

Option B is attractive where: (i) cost efficiency and rapid deployment on long corridors are critical, and (ii) there is a clear strategy to invest in local engineering capacity and to align data formats and APIs with ECO standards from the outset.

16.4 Indicative Comparative Matrix

16.5 Indicative Comparative Matrix

Criterion	Option A: GE + Infotrans	Option B: CRRC + Local Solution
Measurement accuracy	Proven mm-level accuracy; mature QA/V&V processes; strong EN 13848 alignment	High accuracy demonstrated on Chinese high-speed and heavy-haul lines; verification required for specific ECO use cases
Indicative TCO	10-year Higher CAPEX/licences; stable support costs; favourable at multi-country scale if harmonised procurement used	Potentially lower CAPEX; OPEX depends on local service if ecosystem; favourable where local partners are strong
Integration and openness	Typically strong API support; easier mapping to open ECO DTM schema; lower risk of data lock-in with clear contracts	Requires careful negotiation on data formats/API access; feasible but more variation across implementations

Criterion	Option A: GE + Infotrans	Option B: CRRC + Local Solution
Localisation of skills	Relies on structured training and regional integrator; good if embedded in binding and universities; supports training/transfer programmes	High potential for co-development with local firms and universities; supports technology transfer if formally mandated
Supply-chain and geopolitical risk	Exposure to transatlantic regulatory environment; predictable but subject to export control considerations	Exposure to PRC-centred supply chains; resilient but ECO hardware supply must align data/security policies
Suitability for ECO Phase 2	Strong candidate for a “reference” ECO platform and IFI-financed programmes emphasising transparency and standards	Strong candidate for cost-effective scale-up, particularly with robust local integration and open-data commitments

16.6 Recommended Approach for ECO

For Phase 2 it is recommended that ECO and participating railways:

- adopt a **technology-neutral, standards-based ToR**, allowing both configurations (and other qualified suppliers) to compete under common technical and economic criteria;
- require all bidders to:
 1. provide full access to raw and processed geometry data;
 2. document APIs and data structures compatible with the ECO DTM model;
 3. commit to on-site training and joint V&V exercises with ECO railways.
- evaluate proposals on **NPV/IRR over 8–10 years**, not only on initial equipment price, with explicit scoring for localisation, cybersecurity and long-term support;
- consider a **dual-pilot strategy** in which: one corridor adopts an Option A-type configuration and another an Option B-type configuration, both mapped to the same ECO DTM standard, to benchmark performance, costs and institutional

fit under real ECO conditions.

This preserves competition, reduces single-vendor dependency and ensures that whichever combination of suppliers is selected for Phase 2 will operate fully within the ECO Digital Track Modelling Standard developed on the basis of the Zhanaozen–Bastau pilot.

17. Implementation Modality and Payment Schedule

Client institutions: Ministry of Transport of Kazakhstan, relevant authorities of Iran and Turkmenistan, in coordination with the ECO Secretariat.

A Steering Group oversees:

- validation of the work plan;
- review of interim deliverables;
- acceptance of final outputs and recommendations.

Milestone	Share of Contract Price
Gate 1 (Data and Plan)	20%
Gate 2 (Design Approved)	30%
Gate 3 (Model and KPIs)	30%
Gate 4 (Final Report)	20%

18. Contractor Requirements

- Demonstrated experience in digital modelling or data-driven asset management for transport infrastructure (preferably railways).
- Ability to work with ECO Secretariat and multiple national stakeholders.
- Capacity to deliver transparent, documented and replicable analytical tools.

19. Expert Assessment of the Pilot Section and Key Recommendations

The Zhanaozen–Bastau pilot section (operational length 35 km; pilot perimeter 35 km) has been assessed using the proposed Digital Track Model (DTM) framework.

The expert assessment confirms:

1. Existing alignment and geometry constrain safe and economic freight speed increases without targeted corrections.
2. The effective 50 km/h restriction on critical subsections may reduce potential throughput by approximately 20–25% relative to an optimised geometry scenario.
3. DTM enables identification of locations for minor alignment and cant improvements with measurable performance gains, supports risk-based maintenance and links geometry to costs.
4. Under conservative assumptions, the pilot DTM yields positive NPV, short payback (about 1.5–3 years) and IRR at or above IFI benchmarks.
5. The concept is scalable along ECO corridors and consistent with ongoing digitalisation initiatives.

Key recommendations:

- adopt the Zhanaozen–Bastau pilot as a reference case for an ECO Digital Track Modelling Standard;
- implement phased scale-up on priority ECO corridors;
- engage qualified technology partners under open, non-exclusive arrangements, ensuring data ownership remains with ECO Member States and infrastructure managers;
- use DTM-based evidence to prepare financing proposals for AIIB, IsDB, ADB, EDB and others.

19.0.1. Institutional and Governance Preconditions

While the technical feasibility and economic rationale of the Digital Track Model (DTM) have been demonstrated through the Zhanaozen–Bastau pilot, the assessment indicates that the full realisation of its benefits depends on coordinated institutional and governance arrangements among participating countries.

In particular, further progress requires the harmonisation of methodologies for the investigation and resolution of operational and conflict situations, alignment of track condition assessment approaches, and consistency in data standards, interpretation

and decision-making procedures. Without such alignment, digital solutions risk remaining fragmented and limited to isolated national applications.

Addressing these preconditions would enable a gradual transition from individual digital initiatives towards a jointly managed and interoperable Digital Railway Corridor. This transition implies the development and adoption of common regulatory and normative frameworks at the ECO level, providing a predictable and transparent basis for cross-border coordination and long-term investment planning.

From a governance perspective, the establishment of a permanent standing coordination committee is considered a practical and effective mechanism to support this process. Such a body would be mandated to coordinate the development, approval and periodic updating of shared technical, methodological and digital standards, thereby ensuring continuity, institutional memory and a stable foundation for corridor-wide digitalisation initiatives.

During the discussion of the Interim and pilot results, the Iranian side specifically emphasised the importance of extending the scope of digital assessment beyond track geometry alone. In particular, attention was drawn to the condition of turnouts and switches, as well as to a broader set of infrastructure and operational parameters that were not fully covered within the present Study.

These additional parameters, while outside the original scope, have now been articulated and recognised as relevant areas for further development. The present work is therefore seen as a catalyst that can provide further momentum for subsequent, more comprehensive assessments, building upon the methodological, technical and institutional foundations established through the current pilot.

A. Compliance with ToR Requirements and KPIs

This Appendix demonstrates full compliance of the present Study with the approved Terms of Reference (ToR), including the application of SWOT and SMART frameworks, the use of CAPEX and OPEX in economic evaluation, and the delivery of all required Key Performance Indicators (KPIs).

A.1 Application of SWOT Analysis

A SWOT analysis was applied to structure the strategic assessment of the DTM pilot and its potential scale-up across ECO corridors, identifying strengths, weaknesses, opportunities and threats relevant to technical, economic and institutional dimensions.

12: SWOT Analysis of the Digital Track Modelling (DTM) Pilot

Strengths	Weaknesses
Proven technical feasibility of DTM on a live pilot section; Quantified economic benefits (positive NPV, acceptable IRR); Transparent and auditable mathematical methodology; Compatibility with international railway practices.	Limited scope of the pilot (focus on geometry-related parameters); Dependence on availability and quality of input data; Initial institutional fragmentation across countries.
Opportunities	Threats
Scale-up across ECO railway corridors; Access to concessional financing and grants; Development of a common ECO digital standard; Capacity building and localisation of expertise.	Divergent national regulations and standards; Delays in data sharing and coordination; Risk of vendor lock-in without clear governance; Uneven pace of digital adoption among countries.

A.2 Application of SMART Criteria

The formulation of the Study objectives and the scope of the pilot implementation was guided by the SMART framework (Specific, Measurable, Achievable, Relevant and Time-bound), as explicitly required by the Terms of Reference. The application of SMART criteria ensured that the Study avoided abstract or declarative targets and instead focused on verifiable, operational and economically meaningful outcomes.

Specific. The objectives of the Study were defined with a clear and unambiguous focus on the Zhanaozen–Bastau pilot section of the KTI corridor, with a geographically limited perimeter of approximately 35 km, in full compliance with the ToR. The scope explicitly covered digital track modelling of geometry and condition, economic evaluation of maintenance effects, and preparation of a technically sound basis for potential scale-up. No unrelated assets or speculative digital functions were included, ensuring a well-defined and controllable scope.

Measurable. The Study objectives were translated into measurable outputs and indicators, including quantified economic metrics (NPV, IRR, payback period), defined accuracy thresholds for geometric parameters, and clearly identifiable deliverables (reports, technical specifications, economic calculations and presentation materials).

This measurability allows independent verification of results and supports transparent review by ECO bodies, national authorities and potential financing institutions.

Achievable. All objectives were formulated with due consideration of existing institutional, technical and budgetary constraints. The pilot relies on data types, measurement technologies and analytical methods that are already available or realistically deployable within ECO railways. The implementation plan and cost assumptions were deliberately conservative, ensuring that the objectives could be achieved within the agreed budget ceiling and the 8-week pilot timeframe.

Relevant. The objectives of the Study are directly aligned with ECO strategic priorities, including regional connectivity, optimisation of infrastructure lifecycle costs, improved safety and reliability of railway operations, and support for sustainable transport corridors. From an economic perspective, the focus on CAPEX and OPEX optimisation, bankability and evidence-based decision-making ensures high relevance for governments, infrastructure managers and international financial institutions.

Time-bound. All activities and deliverables were structured within a clearly defined and contractually fixed implementation period. The pilot roadmap specifies concrete milestones, acceptance gates and final outputs to be delivered within eight weeks. This time-bound structure supports effective project control, timely decision-making by the ECO Secretariat, and readiness for follow-on phases.

The detailed assessment of the Study objectives against each SMART criterion is summarised in Table 13.

13: Assessment of Study Objectives against SMART Criteria

Criterion	Application in the Study
Specific	Demonstration of Digital Track Modelling on the defined Zhanaozen–Bastau pilot section of the KTI corridor, with clearly defined scope and outputs.
Measurable	Quantified economic indicators (NPV, IRR, payback period), geometric quality metrics, and clearly defined deliverables as per the Terms of Reference.
Achievable	Implementation using existing measurement technologies, data sources and institutional arrangements within the agreed timeframe and budget.
Relevant	Direct contribution to ECO objectives on railway efficiency, safety, cost reduction, sustainability and corridor competitiveness.
Time-bound	All activities and deliverables completed within the contractual implementation period, including the 8-week pilot roadmap.

The table confirms that all KPIs defined in the Terms of Reference have been fully delivered. The International Overview, Technical Requirements, Economic Model and Final Technical Assignment are incorporated as dedicated sections of the Final Report, while the Presentation is provided as a separate file for convenience.

A.3 Economic Assessment: CAPEX and OPEX

The economic model explicitly distinguishes between CAPEX and OPEX as core inputs for the evaluation of investment performance. These parameters underpin the calculation of NPV, IRR and payback period presented in Section 9.

A.4 Key Performance Indicators (KPIs) Compliance

14: Compliance with Key Performance Indicators (KPIs) Defined in the ToR

ToR KPI	Deliverable as per ToR	Status	Reference in Final Report
International Overview	Analytical report	Completed	Sections 6–7 (International Experience and Benchmarking)
Technical requirements developed	Technical requirements document	Completed	Section 10 (DTM Architecture and Technical Requirements)
Economic model completed	Economic calculation	Completed	Section 9 (Economic Model: CAPEX, OPEX, NPV and IRR)
Final technical assignment prepared	Technical assignment for next phase	Completed	Section 19 (Expert Assessment and Key Recommendations), including Phase 2 scope
Presentation developed	Presentation file	Completed	Appendix: Presentation (provided as a separate file)

The table confirms that all KPIs defined in the Terms of Reference have been fully delivered. The International Overview, Technical Requirements, Economic Model and Final Technical Assignment are incorporated as dedicated sections of the Final Report, while the Presentation is provided as a separate file for convenience.

B. References

- ECO Secretariat (2025). Digital Modelling for ECO Railways — Contract documentation.
- ECO (2025). ToR — Study on Digital Modelling for ECO Railways.
- KTZ: Annexes 2–11, PU-32 track condition statements (October 2025).

Reference in Final Report			
International Overview	Analytical report	Completed	Sections 6–7 (International Experience and Benchmarking)
Technical requirements developed	Technical requirements document	Completed	Section 10 (DTM Architecture and Technical Requirements)
Economic model completed	Economic calculation	Completed	Section 9 (Economic Model: CAPEX, OPEX, NPV and IRR)
Final technical assignment prepared	Technical assignment for next phase	Completed	Section 19 (Expert Assessment and Key Recommendations), including Phase 2 scope
Presentation developed	Presentation file	Completed	Appendix: Presentation (provided as a separate file)

- Ilyasheva G.I., Durmagambetov A.A. (2025). Economic model for Digital Track Modelling.

C. Register of Source Materials

File	Version
Annex No. 9,10,11.xlsx	2025-11-05
Reply to Request (19).docx	2025-11-05
Annex No. 7 List of Level Crossings Zhanaozen– Bastau.xls	2025-11-05
Contract Digital Railway Modelling, KTI Section.docx	2025-11-05
Annex No. 3 Technical Characteristics Zhanaozen– Bastau.docx	2025-11-05
ToR - Study on Railway Digital Modelling.docx	2025-11-05
Ilyasheva-Valikh.pdf	2025-11-05
Annex No. 8.docx	2025-11-05
Annex No. 6 List of Engineering Structures.docx	2025-11-05
Report (25).pdf	2025-11-05
Annex 2 PU-32 Track Condition Statements.pdf	2025-11-05

D. Glossary

Term	Definition
ECO	Economic Cooperation Organization
RPC	Regional Planning Council of ECO
TTCC	Transit Transport Coordination Council of ECO
CPR	Council of Permanent Representatives to ECO
PMG	Project Management Group of ECO
UN/CEFACT	UN Centre for Trade Facilitation and Electronic Business
UNESCAP / UNECE	UN Regional Commissions (Asia-Pacific / Europe)
SMGS	Agreement on International Goods Transport by Rail
DTM	Digital Track Model
PU-32	Track condition statement form
κ	Curvature, $\kappa = 1/R$
R	Curve radius
h	Cant of outer rail
CAPEX/OPEX	Capital / operating expenditure
NPV/ROI/IRR	Investment performance indicators
KPI	Key performance indicator
ETL	Extract–Transform–Load
LiDAR/GPS	High-precision survey instruments
RTK/IMU	
BIM	Building Information Modelling
V&V	Verification and Validation
CM	Configuration Management
IoU/RMSE	Overlap / error metrics
KTZ/RAI/TDY	Railways of Kazakhstan, Iran, Turkmenistan
AIIB/IsDB/ADB/EDB	International financial institutions
CR	Change Request
Steering Group	Project governance body
SLA	Service Level Agreement
RBAC	Role-Based Access Control
