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Technical and Economic Feasibility Study of Electrifying Coal Transportation: A Case Study of Tavan Tolgoi–Gashuun Sukhait

Bachelor's Thesis

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2026

Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

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I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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ABSTRACT

The Tavan Tolgoi–Gashuun Sukhait (TT–GS) corridor is one of Mongolia's most critical coal export routes, spanning approximately 250 km from the Tavan Tolgoi coking coal mine in the South Gobi to the Gashuun Sukhait border crossing with China. Currently, this corridor depends almost exclusively on fleets of diesel-powered heavy-duty trucks, resulting in high fuel costs, substantial CO_2, NO_x, and particulate matter (PM) emissions, severe road wear from high axle loads, and logistical inefficiency. Mongolia's commitments under its Nationally Determined Contribution (NDC) to the UNFCCC mandate significant reductions in transport-sector emissions, making electrification of the heavy freight fleet a strategic priority.

This thesis presents a preliminary technical and economic feasibility study evaluating the CR130EVT wide-body dual-trailer heavy-duty vehicle — available in a pure electric variant (783 kWh lithium-ion battery, 600 kW rated / 900 kW peak powertrain) and a diesel-electric hybrid variant (≥170 kWh battery plus 400 kW diesel engine) — for deployment on the TT–GS coal transport corridor.

The study is structured around five analytical dimensions: (1) vehicle technical specifications and platform design; (2) axle loading mechanics and road infrastructure requirements; (3) multi-axle powertrain, electrical system, and control architecture; (4) traction force, power demand, and battery range modelling using sensitivity analysis over a 250 km route; and (5) preliminary economic comparison of the pure electric, hybrid, and conventional diesel options across per-km, per-cycle, per-tonne, and per-tonne-km cost metrics.

Key findings are as follows. The pure electric CR130EVT with 783 kWh battery capacity can complete a one-way 250 km trip within normal consumption bounds of 2.0–2.7 kWh/km with a 90% usable State of Charge (SOC) window (704.7 kWh usable), leaving a positive SOC margin at the destination terminal. Under adverse operating conditions (energy consumption ≥ 3.0 kWh/km, e.g. severe cold, strong headwinds, high sustained gradients), the practical range falls to approximately 234.9 km, necessitating a mid-route battery swap or charging support station at approximately km 110–140. A proposed three-station infrastructure layout (S0: Tavan Tolgoi terminal; S1: km 110–140 optional mid-route; S2: Gashuun Sukhait terminal) is presented. The recommended charging infrastructure configuration is Grid + Solar PV + Battery Energy Storage System (BESS), providing peak demand shaving and operational resilience, with an installed capacity requirement of 3–4 MW per terminal station.

Economic analysis at baseline parameters (electricity tariff: 300 MNT/kWh; diesel price: 4,250 MNT/L; EV energy consumption: 2.5 kWh/km; diesel fuel consumption: 1.3 L/km) yields total direct operating costs of 1,850 MNT/km for the pure electric variant, 5,175 MNT/km for the hybrid, and 7,025 MNT/km for conventional diesel — making the pure electric vehicle 3.8× cheaper to operate per kilometre than diesel. On a per-tonne-km basis, the pure electric achieves 28.5 MNT/t·km versus 79.6 MNT/t·km (hybrid) and 108.1 MNT/t·km (diesel). With one vehicle completing two 500 km round-trip cycles per day for 330 operational days per year, the annual operating cost saving versus diesel is approximately 1.71 billion MNT per vehicle. For a fleet of 10 vehicles, fleet-level annual savings versus diesel reach approximately 17.08 billion MNT. Payback period on additional EV infrastructure investment of 12 billion MNT (10-vehicle fleet) is estimated at approximately 1.09 years — a highly compelling economic case for electrification transition.

The hybrid CR130EVT is identified as a viable transitional solution during the infrastructure build-out phase, when terminal swap stations and mid-route support infrastructure are not yet fully commissioned. The hybrid's diesel engine provides operational flexibility without range anxiety, but its higher per-km cost (5,175 MNT/km vs. 1,850 MNT/km) and retained emissions make it unsuitable as a long-term primary fleet strategy.

Lateral stability analysis using a static roll model demonstrates that the CR130EVT combination maintains an adequate theoretical stability margin (critical roll angle $\theta_{cr} \approx 34.3°$ at B = 3.0 m, h_{cg} = 2.2 m) but requires strict operational protocols: turning speed not exceeding 20–30 km/h on curves with radius ≤ 25 m; maximum working side slope limited to 6–8°; symmetric coal loading of 60 t per trailer body; and level unloading areas.

This thesis concludes that the pure electric CR130EVT, deployed with purpose-designed terminal swap stations and mid-route support, represents the most economically and environmentally advantageous long-term solution for the TT–GS coal transport corridor. Recommendations for next steps include a 1–2 vehicle pilot programme to validate field consumption rates across all four Mongolian seasons, followed by staged fleet electrification.

Keywords: CR130EVT, pure electric vehicle, diesel-electric hybrid, dual-trailer, Tavan Tolgoi–Gashuun Sukhait, battery range, State of Charge, SOC sensitivity analysis, IGBT-FOC, VCU, BMS, DCU, PDU, regenerative braking, battery swap station, Grid+Solar+BESS, coal transport electrification, economic feasibility, Mongolia.

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LIST OF ABBREVIATIONS

Table 1.1: Abbreviations

Abbreviation	Full Term
BMS	Battery Management System
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
DCU	Drive Control Unit
DEM	Digital Elevation Model
ERS	Electric Road System
EV	Electric Vehicle
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
IGBT	Insulated Gate Bipolar Transistor (power semiconductor switch)
MCU	Motor Control Unit
MNT	Mongolian Tugrik (₮)
NDC	Nationally Determined Contribution (UNFCCC)
NMC	Lithium Nickel Manganese Cobalt Oxide battery chemistry
OPEX	Operational Expenditure
PDU	Power Distribution Unit
PM	Particulate Matter
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
SOC	State of Charge [%]
SOH	State of Health [%]
TLC	Total Lifecycle Cost
TT–GS	Tavan Tolgoi–Gashuun Sukhait corridor
UTM	Universal Transverse Mercator coordinate system
VCU	Vehicle Control Unit

Table 1.2: Greek Symbols and Mathematical Notation

Symbol	Description	Unit
η	Efficiency coefficient	—
η_sys	Overall powertrain system efficiency	—
η_g	Mechanical transmission (reducer/drive) efficiency	—
μ	Tyre–road adhesion coefficient	—
ρ	Air density	kg/m³
ω_m	Traction motor angular velocity	rad/s
θ_cr	Critical static roll angle (wheel-lift threshold)	°

Table 1.3: Main Variables and Parameters

Symbol	Description	Unit
a_y	Lateral acceleration during cornering	m/s²
A	Vehicle frontal area	m²
B	Effective track width (wheel-to-wheel)	m
C_D	Aerodynamic drag coefficient	—
E_bat	Total battery pack capacity	kWh
E_usable	Usable battery energy (SOC window)	kWh
e	Energy consumption per km	kWh/km
E_k	Kinetic energy	J / MJ
F_r	Rolling resistance force	N / kN
F_grade	Grade resistance force	N / kN
F_aero	Aerodynamic drag force	N / kN
F_trac	Total traction force required	N / kN
f_r	Rolling resistance coefficient	—
g	Gravitational acceleration (9.81 m/s²)	m/s²
h_cg	Height of center of gravity (laden)	m
i	Road gradient (decimal fraction)	—
L	Route length (one-way)	km
m	Gross vehicle mass	kg / t
N_i	Normal reaction force at axle i	N / kN
P_wheel	Mechanical power at wheel rim	kW

P_bat	Battery discharge / charge power	kW
Q	Payload per cycle	t
R	Turning radius	m
R_practical	Practical driving range	km
r_w	Effective wheel radius	m
SOC(s)	State of Charge at distance s	%
T_cycle	Total cycle duration (round trip)	h
T_m	Motor electromagnetic torque	N·m
v	Vehicle speed	m/s / km/h

1. INTRODUCTION

1.1 Background and Context

Mongolia's resource export economy depends critically on the efficient transport of coal from major deposits to border crossings for export to China. The Tavan Tolgoi–Gashuun Sukhait (TT–GS) corridor, stretching approximately 240–250 km through the South Gobi desert, is the single most important coal export artery in the country. The Tavan Tolgoi deposit — one of the world's largest known coking coal reserves — supplies the international steel and energy markets, with annual throughput on the corridor measured in tens of millions of tonnes [2].

The current transport model relies overwhelmingly on diesel-powered heavy-duty trucks. This model has served the corridor's growth trajectory but now faces several compounding pressures: rising and volatile diesel fuel prices, driven by Mongolia's import dependence; escalating CO_2, NO_x, and PM emission burdens inconsistent with Mongolia's NDC commitments to the UNFCCC; structural road deterioration from repeated high-axle-load passages; and the logistical overhead of fuelling operations across a remote desert corridor.

Globally, the heavy-duty road freight sector is undergoing a fundamental technological transition. Battery-electric trucks, hybrid-electric trucks, and catenary-assisted electric road systems (ERS) are entering commercial deployment in Europe, the United States, and China at scale. Chinese manufacturers have been particularly active in developing heavy-duty electric vehicles for mining and bulk freight applications, leveraging decades of PMSM and IGBT-FOC technology from railway traction programmes [3,4]. The CR130EVT wide-body dual-trailer electric heavy-duty vehicle is a purpose-built product in this lineage — designed specifically for high-frequency, fixed-route bulk freight corridors analogous to TT–GS.

This thesis investigates whether the CR130EVT, in its pure electric and hybrid configurations, is technically and economically suitable for deployment on the TT–GS corridor under current conditions in Mongolia, and what infrastructure would be required to realise that deployment.

1.2 The TT–GS Corridor Environment

The TT–GS corridor presents a specific combination of engineering and operational challenges that distinguish it from typical road freight routes:

Extreme temperature range:

The South Gobi experiences ambient temperatures from −40°C in winter to +40°C in summer — an 80°C annual swing. At −40°C, diesel cold-starting requires pre-heating, and battery thermal management must complete pre-conditioning before operation can begin. At +40°C, thermal management of battery packs and power electronics becomes critical. Both extremes must be within the vehicle's design envelope for year-round operation.

Remote desert corridor with limited infrastructure:

The route traverses 250 km of sparse desert terrain with limited grid electricity access. Any electrification strategy must address energy supply for charging or battery swapping at both terminal locations and, where necessary, at mid-route support points. Cellular connectivity may be intermittent, placing requirements on on-board autonomy of control and diagnostic systems.

Haul road geometry and gradient:

The primary route is a heavy-haul corridor with gradients varying along its length. Unlike purpose-built mine haul roads where gradients are precisely controlled, the TT–GS corridor incorporates natural terrain variation. Sustained gradients above 3–5% have significant implications for electric vehicle energy consumption and battery range. Short-section grades up to 8–12% are possible and must be within the vehicle's traction capability.

Scale and frequency of operations:

With annual throughput targets measured in millions of tonnes, the TT–GS corridor operates a large fleet at high cycle frequency. Even modest per-vehicle energy and cost savings compound to large fleet-level figures, making fleet electrification economically impactful.

1.3 Problem Statement

Mongolian coal transport operators currently lack a quantitative technical and economic framework for evaluating the CR130EVT electric vehicle platform against conventional diesel transport for the TT–GS corridor. Procurement decisions default to catalogue specifications and unit purchase price — criteria that systematically exclude the operational cost, energy efficiency, emission, and infrastructure dimensions most relevant to an electrification transition. Without such a framework, the risk of either premature commitment to an unsuitable technology or unnecessary delay of a beneficial transition is high.

1.4 Research Objectives

This thesis addresses the following research questions:

(1) Is the CR130EVT technically suitable for the TT–GS corridor — with respect to payload capacity, range, gradient capability, lateral stability, and road loading?

(2) How do the pure electric and hybrid variants compare on energy consumption, operating cost, and transport productivity?

(3) What battery swap, charging, and power supply infrastructure is required to support electric vehicle fleet operations on this corridor?

(4) What is the economic case for electrification — in terms of per-km, per-tonne, and per-tonne-km costs, annual savings, and payback period relative to diesel transport?

(5) What are the key risks, uncertainties, and recommended next steps?

1.5 Scope and Limitations

This is a preliminary engineering feasibility study conducted at bachelor thesis level. Technical specifications are drawn from the CR130EVT manufacturer's documentation [1]. Route parameters are based on a user-provided map [2] with estimated corridor length. Detailed Digital Elevation Model (DEM) data for the TT–GS route were not available; a simulated gradient profile is used for power modelling. All cost figures are in MNT and reflect 2024–2025 reference prices. Sensitivity analysis is applied where key input parameters are uncertain. The study does not include full lifecycle cost analysis, regulatory compliance assessment, environmental impact assessment, or detailed civil engineering design.

1.6 Thesis Structure

Chapter 2 reviews the state of the art in electric road freight, the TT–GS corridor context, and relevant battery technology. Chapter 3 describes the research methodology and engineering calculation framework. Chapter 4 presents the technical study of the CR130EVT platform. Chapter 5 analyses the route and road infrastructure requirements. Chapter 6 details the powertrain, electrical system, and control architecture. Chapter 7 presents traction force, power demand, and battery range calculations. Chapter 8 addresses battery swapping and charging

infrastructure. Chapter 9 presents the economic feasibility assessment. Chapter 10 provides discussion, and Chapter 11 states conclusions and recommendations.

2. STATE OF THE ART

2.1 Electric Road Freight: Technology Generations

The electrification of heavy-duty road freight has progressed through distinct technology generations. Three primary pathways are commercially relevant today.

Generation 1 — Diesel-Mechanical:

The diesel engine transmits power through a torque converter, multi-speed gearbox, cardan shaft, and rear axle differential. This architecture — dominant for decades — introduces torque converter slip losses of 8–15% at partial load, offers no braking energy recovery, and provides rear-axle-only drive. All braking energy is permanently dissipated through hydraulic retarders or service brakes [15].

Generation 2 — Series Diesel-Electric:

The diesel engine drives an alternator whose rectified DC output powers IGBT inverters and AC induction traction motors. This eliminates the mechanical transmission and enables electric retarding, but all braking energy is dissipated through dynamic braking resistor grids. The diesel engine follows instantaneous wheel demand, preventing sustained operation at peak thermal efficiency. The BelAZ 75131 is representative of this generation [4].

Generation 3 — Battery-Assisted Electric with Regenerative Braking:

A lithium-ion battery buffer decouples the diesel engine operating point from instantaneous wheel demand, enables braking energy recovery, and (in distributed drive configurations) provides per-wheel torque control. The CR130EVT builds on this lineage: it extends the concept to an all-electric or diesel-electric-hybrid wide-body dual-trailer platform for fixed-route corridor transport [1,5].

2.2 The TT–GS Corridor in Context

The Tavan Tolgoi coking coal deposit and the TT–GS export corridor have been the subject of national-level infrastructure studies for over a decade. The most prominent alternative is railway construction — a project under intermittent development but with a completion timeline that remains uncertain [2]. In the absence of rail connectivity, truck transport will dominate TT–GS coal logistics for the foreseeable future, creating a clear opportunity for truck fleet electrification to deliver near-term emission and cost reductions.

Annual coal throughput on the corridor has ranged from 15 to over 60 million tonnes in different years, reflecting market conditions and operational capacity. At these volumes, even a 10% improvement in per-tonne-km operating cost translates to hundreds of millions of MNT in annual fleet savings. Electric vehicle technology, with its significantly lower fuel equivalent cost per kWh compared to diesel, offers improvements measured in factors rather than percentage points [2].

International precedents for corridor electrification using battery-electric or catenary-assisted trucks include Sweden's eRoad Arlanda project, Germany's Siemens eHighway deployments, and several Chinese heavy-haul mining corridor projects. These demonstrate the technical feasibility of electric heavy freight on dedicated corridors, while also highlighting the importance of purpose-designed infrastructure [3].

2.3 CR130EVT Platform Overview

The CR130EVT is a product of CRRC Corporation's off-highway electric vehicle programme, which transfers PMSM traction motor and IGBT-FOC technology from railway applications to mining and heavy freight vehicles [1,5]. The CR130EVT is distinct from mine haul trucks (which operate on private roads with very short cycles) and standard road trucks (which operate at much lower payload). It occupies a specific niche: ultra-high-capacity coal transport on a dedicated, fixed-route corridor.

The CR130EVT family includes the pure electric variant (CR130EV designation elements, 783 kWh), the pantograph-assisted variant (overhead catenary contact for charging during travel), and the diesel-electric hybrid variant (≥170 kWh battery plus 400 kW diesel engine). This platform flexibility allows operators to select the variant appropriate for their infrastructure status — an important consideration for TT–GS, where full charging infrastructure does not yet exist.

Chinese manufacturers have deployed similar platforms on coal transport corridors in Inner Mongolia and Xinjiang, providing operational data that informs manufacturer specifications. The TT–GS corridor presents more severe environmental conditions (lower temperatures, longer distances) than most Chinese reference deployments, making independent technical evaluation essential.

2.4 Battery Technology for Heavy-Duty Applications

The 783 kWh battery system in the CR130EVT pure electric variant represents a very large battery pack by current industry standards — approximately six times the capacity of a battery-

electric passenger car and approximately three times the capacity of leading battery-electric heavy truck platforms such as the Mercedes-Benz eActros 600. Lithium Nickel Manganese Cobalt Oxide (NMC) chemistry, the most likely candidate at this scale, provides energy density and cycle life suitable for this application but requires robust thermal management across the −40°C to +40°C Gobi temperature range [7].

Battery swap technology — in which a depleted pack is mechanically exchanged for a pre-charged one — offers operational advantages over long charging stops for fleet operations on fixed routes. The concept has been demonstrated commercially at car scale (NIO), and several Chinese manufacturers are developing heavy-duty truck swap systems. The primary engineering challenges at the CR130EVT scale are mechanical (handling a very heavy pack), electrical (safe disconnection and reconnection of high-voltage connectors), and thermal (temperature management of stored packs). These challenges are addressable with purpose-built infrastructure at terminal stations [5].

2.5 Summary

The convergence of mature battery-electric drivetrain technology, demonstrated corridor electrification precedents, and Mongolia's policy and economic motivations for decarbonising the transport sector creates a favourable context for the CR130EVT on the TT–GS corridor. The scale of the vehicle (dual-trailer, 200 t GVW, 783 kWh), the severity of the operating environment, and the remoteness of the corridor make detailed technical and economic analysis a prerequisite for sound investment decisions — which this thesis provides at a preliminary engineering level.

3. MATERIAL AND METHODS

3.1 Research Design

This thesis applies a quantitative engineering methodology structured around four analytical layers: (1) systematic review and verification of technical specifications from primary sources; (2) derivation and application of engineering calculation models for traction force, power demand, SOC depletion, and lateral stability; (3) preliminary economic cost modelling with sensitivity analysis; and (4) infrastructure sizing and configuration assessment. A dedicated Calculations chapter (Chapter 7) presents all derivations transparently.

3.2 Data Sources

Table 3.1: Primary data sources

Source	Type	Confidence
CR130EVT Technical Documentation [1]	Manufacturer engineering specification	High — verified parameters
TT–GS Route Map [2]	User-provided GIS map, UTM Zone 48N, 217.8 km linear	High for geometry; estimated for gradient
Schulte & Ny (2018) [3]	Peer-reviewed ERS feasibility study	High
Tajima et al. (2022) [4]	IEEE journal, 800 V charging systems for trucks	High
CRRC product documentation [5]	Manufacturer brochure CR120EH family	Medium-High
Goodenough & Park (2013) [7]	Peer-reviewed Li-ion battery technology reference	High
Heavy transport engineering standards [6,8,9]	Applied engineering reference methodology	High

3.3 Reference Route and Operating Scenario

A single reference operating scenario is applied consistently throughout all calculations:

— One-way route length: L = 250 km (conservative estimate from 217.8 km linear distance, accounting for route deviation, service zones, and safety buffers)

— Round-trip cycle length: L_cycle = 500 km (loaded outbound + empty return)

— Payload per cycle: Q = 130 t (maximum rated payload)

— Gross vehicle mass (laden): m = 200 t (preliminary mean estimate; 73 t tare + 130 t payload = 203 t; 200 t used as engineering approximation)

— Operating cycles per day: 2 (one vehicle)

— Operating days per year: 330

3.4 Engineering Calculation Equations

The following equations are applied in Chapters 4–7:

$$F_r = f_r \cdot m \cdot g \quad [N] \qquad \text{(Eq. 1)}$$

Rolling resistance

$$F_{grade} = m \cdot g \cdot i \quad [N] \qquad \text{(Eq. 2)}$$

Grade resistance

$$F_{aero} = \tfrac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v^2 \quad [N] \qquad \text{(Eq. 3)}$$

Aerodynamic drag

$$F_{trac} = m \cdot g \cdot (f_r + i) + \tfrac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v^2 \quad [N] \qquad \text{(Eq. 4)}$$

Total traction force

$$P_{wheel} = F_{trac} \cdot v \quad [W] \qquad \text{(Eq. 5)}$$

Wheel power

$$E_k = \tfrac{1}{2} \cdot m \cdot v^2 \quad [J] \qquad \text{(Eq. 6)}$$

Kinetic energy

$$SOC(s) = 100 \times (1 - e \cdot s / E_{bat}) \quad [\%] \qquad \text{(Eq. 7)}$$

SOC at distance s

$$R_{practical} = E_{usable} / e \quad [km] \qquad \text{(Eq. 8)}$$

Practical range

$$a_{y,cr} = g \cdot B / (2 \cdot h_{cg}) \quad [m/s^2] \qquad \text{(Eq. 9)}$$

Wheel-lift critical acceleration

$$\tan(\theta_{cr}) = B / (2 \cdot h_{cg}) \qquad \text{(Eq. 10)}$$

Critical roll angle

$$a_y = v^2 / R \quad [m/s^2] \qquad \text{(Eq. 11)}$$

Cornering acceleration

$$G_{dyn} = k_d \cdot G_{static} \quad [t] \qquad \text{(Eq. 12)}$$

Dynamic axle load

$$T_i = \alpha_i \cdot T_{req}; \quad \Sigma \alpha_i = 1 \qquad \text{(Eq. 13)}$$

Torque distribution

$$P_m = T_m \cdot \omega_m \quad [W] \qquad \text{(Eq. 14)}$$

Motor mechanical power

$$i_{max} \approx P_{rated}/(m \cdot g \cdot v) - f_r \qquad \text{(Eq. 15)}$$

Sustained grade limit

3.5 Economic Assessment Method

Direct operating costs are calculated per km for three scenarios — pure electric (EV), hybrid (H), and conventional diesel (D) — and aggregated to per-cycle, per-tonne, and per-tonne-km metrics. Annual savings and payback period are calculated using:

$$C_{EV,total} = e_{EV} \cdot C_{el} + C_{EV,aux} \quad [MNT/km]$$

$$C_{H,total} = q_d \cdot C_d + e_H \cdot C_{el} + C_{H,maint} \quad [MNT/km]$$

$$C_{D,total} = q_D \cdot C_d + C_{D,maint} \quad [MNT/km]$$

$$\text{Annual saving (per vehicle)} = (C_{ref} - C_{EV}) \times L_{cycle} \times N_{cycles/year}$$

$$\text{Payback period} = \text{Additional CAPEX} / \text{Annual saving} \quad [years]$$

Sensitivity analysis is performed for energy consumption (2.0–3.0 kWh/km) and usable SOC window (85–100%).

4. TECHNICAL STUDY OF THE CR130EVT

4.1 General Structure and Purpose

The CR130EVT is a wide-body, dual-trailer, heavy-duty vehicle designed for bulk material transport — primarily coal and ore — over long and medium-distance fixed-route corridors. The combination consists of a tractor unit, a first trailer, and a second trailer, together spanning approximately 29 m in overall length. This dual-trailer configuration is designed to maximise the payload per trip: each trailer carries a cargo body rated at 60 t, giving a total rated payload of 120 t (maximum 130 t), approximately double that of a conventional single-body articulated truck.

Unlike purpose-built mine haul trucks — which operate at very high cycle frequency over very short distances on private haul roads — the CR130EVT is designed for long-distance corridor transport on semi-public or dedicated heavy-haul roads. This places different demands on the vehicle: sustained cruising efficiency is more important than peak traction; battery range rather than recharging during short stops; and road compatibility (turning radius, axle spacing, lane requirements) rather than tight-radius mine ramp performance.

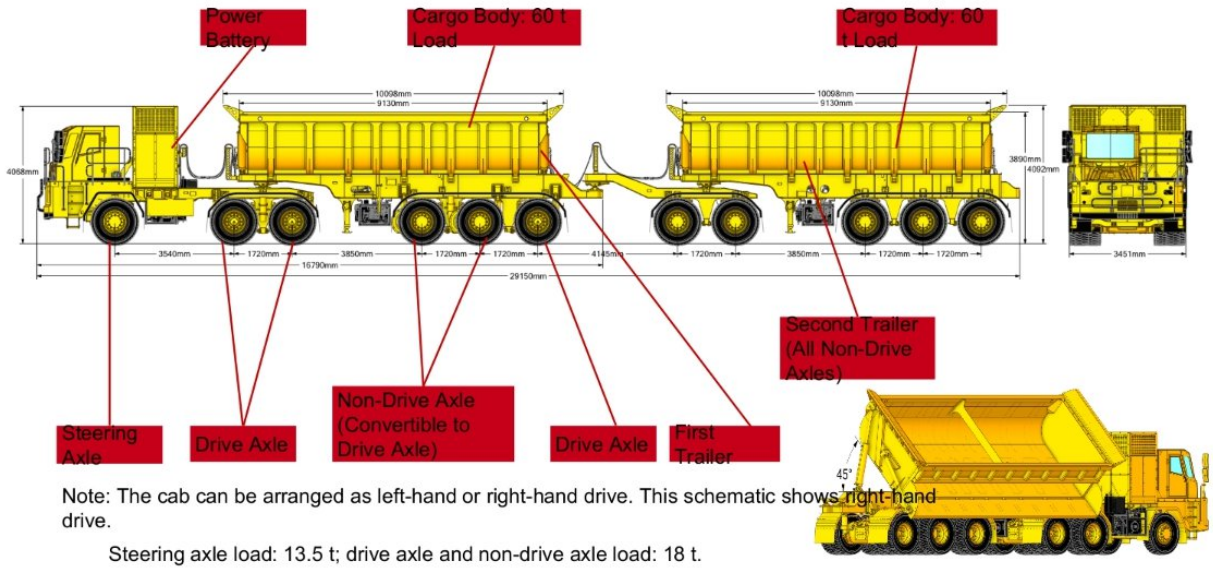


Figure 3.1: Structural layout of the CR130EVT dual-trailer combination [1]

4.2 Key Technical Specifications

Table 4.1: CR130EVT key technical specifications [1]

Parameter	Pure Electric Variant	Hybrid Variant	Notes
Overall dimensions (L×W×H)	29 m × 3.4–3.5 m × 4 m	29 m × 3.4–3.5 m × 4 m	Dual-trailer combination
Rated payload	120 t, max 130 t	120 t, max 130 t	2 × 60 t cargo bodies
Tare weight	73 t	~73 t	Manufacturer data
Battery capacity	783 kWh	≥ 170 kWh	Hybrid uses smaller pack
Diesel engine	None	400 kW rated	Hybrid auxiliary source
Rated / peak power	600 kW / 900 kW	600 kW / 900 kW	Electric powertrain
Maximum speed	65 km/h	65 km/h	Adequate for corridor
Max. gradient capability	13%	13%	Short-section technical limit
Minimum turning radius	11.5 m	11.5 m	Good for long combination
Tire specification	14.00R25	14.00R25	Mining-grade tires
Control architecture	VCU–BMS–DCU–MCU	VCU–BMS–DCU–MCU	Four-level CAN hierarchy

4.3 Axle Loading and Road Infrastructure Impact

A rigorous assessment of the CR130EVT's operational suitability requires analysis beyond total payload and motor power. For a multi-axle heavy-duty combination vehicle, the load on each individual axle directly determines road wear, tire degradation, suspension fatigue, braking thermal load, traction capability, and operational safety. This section derives and quantifies these effects.

Total Laden Mass:

From manufacturer data, tare mass m_empty = 73 t and maximum payload m_payload = 130 t. Thus:

$$m_{total} = m_{empty} + m_{payload} = 73 + 130 = 203\ t \quad (maximum)$$

$$m_{total} = 73 + 120 = 193\ t \quad (rated\ payload)$$

A value of m = 200 t is used throughout this thesis as an engineering approximation between rated and maximum configurations.

Axle Load Distribution:

The manufacturer specifies a steering axle load of approximately 13.5 t and drive / trailing axle loads of approximately 18 t each. The aggregate load balance across N axles must equal the GVM:

$$G_{total} = \Sigma\ G_i \quad (summed\ over\ all\ axles\ i) \qquad (Eq.\ 1\ applied)$$

Because the load is distributed across many axles in the CR130EVT dual-trailer configuration, the per-axle loading is significantly lower than for a rigid dump truck of comparable total payload — a structural advantage for road preservation. However, the cumulative effect of multiple axle passages per vehicle pass increases pavement fatigue loading.

Fourth-Power Law: Pavement Damage

The relative pavement damage contribution of an axle load compared to a reference axle load P_0 is approximately:

$$D \sim (P / P_0)^4 \qquad (Eq.\ derived\ from\ AASHTO\ road\ design\ standard)$$

Comparing the 18 t drive axle load to the 13.5 t steering axle:

$$D_{ratio} = (18 / 13.5)^4 = 1.33^4 \approx 3.1$$

The 18 t axle imposes approximately 3.1× more pavement damage per pass than the 13.5 t axle. This factor must be incorporated into pavement design and maintenance interval planning for the TT–GS corridor.

Normal Reaction Force and Rolling Resistance:

At each 18 t drive axle, the normal reaction force is:

$$N_i = 18{,}000 \times 9.81 = 176{,}580\ N \approx 176.6\ kN \qquad (Eq.\ derived\ from\ Newton's\ second\ law)$$

Total rolling resistance for the fully laden vehicle (m = 200 t, f_r = 0.015 on improved road):

$$F_r = f_r \cdot m \cdot g = 0.015 \times 200{,}000 \times 9.81 = 29{,}430\ N \approx 29.4\ kN \quad (Eq.\ 1)$$

On rougher unpaved surfaces, f_r increases to 0.020–0.025, raising both battery consumption and thermal load on the drive system.

Kinetic Energy and Braking Load:

At typical operating speed v = 40 km/h = 11.11 m/s, the kinetic energy of the fully laden vehicle is:

$$E_k = \tfrac{1}{2} \cdot m \cdot v^2 = \tfrac{1}{2} \times 200{,}000 \times 11.11^2 \approx 12.34\ MJ \quad (Eq.\ 6)$$

This kinetic energy must be absorbed during every braking event. The electric drivetrain enables regenerative braking — recovering part of this energy into the battery — but battery SOC, temperature, and BMS limits constrain regenerative capacity, so mechanical brakes remain essential.

Dynamic Axle Load Factor:

In motion, axle loads are amplified by dynamic effects from road roughness:

$$G_{dyn} = k_d \cdot G_{static} \quad (Eq.\ 12)$$

k_d = 1.1–1.2 on improved road; k_d = 1.3–1.5 on rough gravel. For the 18 t static axle on rough terrain (k_d = 1.3):

$$G_{dyn} = 1.3 \times 18 = 23.4\ t$$

Pavement and foundation design must therefore accommodate dynamic axle loads well above static design values. Table 4.2 summarises road design requirements.

Table 4.2: Road design requirements for CR130EVT corridor operation

Parameter	Recommended Value	Justification
Lane width	5.0–5.5 m	Safe clearance for 3.4–3.5 m vehicle width
Total carriageway width	10–11 m	Two-way traffic flow
Shoulder width	1.0–1.5 m	Emergency stop, breakdown, tire service
Recommended turning radius	≥ 25 m (≥ 50 m preferred)	29 m long combination stability
Maximum sustained gradient	< 6–8%	Energy efficiency and battery

		range
Service stop spacing	30–50 km	HV safety checks, tires, service access
Pavement design axle load	≥ 23 t (dynamic, k_d=1.3)	Fourth-power law damage factor
Pavement base type	Reinforced heavy-haul grade	Standard gravel insufficient

4.4 Pure Electric and Hybrid Variants

4.4.1 Pure Electric Variant — Characteristics

The pure electric CR130EVT uses the 783 kWh battery pack as its sole traction energy source. All motor power, hydraulic auxiliaries, control electronics, IGBT converters, and PDU loads are fed from this pack. This architecture delivers:

— Zero tailpipe emissions during operation (no CO_2, NO_x, or PM from the vehicle)

— Lower mechanical complexity: no diesel engine, gearbox, lubricating oil system, or exhaust aftertreatment

— Regenerative braking capability: kinetic and potential energy recovery on downhill sections

— Suitability for deployment in environmentally sensitive zones and port areas with emission restrictions

The energy balance for a one-way 250 km trip at 2.5 kWh/km consumption:

$$E_{req} = e_{EV} \times L = 2.5 \times 250 = 625 \text{ kWh}$$

Fraction of total battery capacity consumed: 625 / 783 = 79.8% ≈ 80%, leaving approximately 20% SOC reserve.

With 90% usable SOC (E_usable = 704.7 kWh), practical range at 2.5 kWh/km:

$$R_{practical} = 704.7 / 2.5 = 281.9 \text{ km} > 250 \text{ km} \quad ✓$$

Table 4.3: Advantages and disadvantages of the pure electric CR130EVT variant

Attribute	Description
✓ Lower direct fuel cost	No diesel consumed; electricity cost per kWh-equivalent is significantly lower than diesel

✓ Zero operational emissions	No CO_2, NO_x, or PM emitted during operation; supports Mongolia's NDC commitments
✓ Lower maintenance cost	No diesel engine, gearbox, oil, filters, or exhaust aftertreatment to service
✓ Regenerative braking	Energy recovery on downhill sections and during deceleration; reduces net consumption
✓ Long-term cost advantage	Fuel and engine maintenance costs eliminated; advantage grows with diesel price inflation
✓ Quiet operation	Reduced noise at terminal areas and along route
✗ Charging/swap infrastructure required	High-power electricity supply and battery swap equipment required at terminals
✗ High initial infrastructure CAPEX	Charging stations, BESS, spare battery packs add to capital requirements
✗ Temperature sensitivity	Battery thermal management critical at −40°C and +40°C Gobi extremes
✗ Range depends on operating conditions	Wind, gradient, cold temperature, and load variations all reduce effective range
✗ Cold-start pre-conditioning time	Battery must reach minimum operating temperature before departure in severe cold

4.4.2 Hybrid Variant — Characteristics

The hybrid CR130EVT combines a smaller battery pack (≥ 170 kWh) with a 400 kW diesel engine. The diesel engine supplements battery power on demanding sections and can charge the battery during operation. This architecture provides:

— Operational flexibility when charging infrastructure is incomplete or unavailable

— Reduced "range anxiety" — the diesel provides backup energy on any section where the battery approaches depletion

— Compatibility with existing diesel fuel supply logistics on the TT–GS corridor

The total direct operating cost per km for the hybrid variant at baseline parameters:

$$C_{H,total} = q_d \cdot C_d + e_H \cdot C_{el} + C_{H,maint}$$

$$C_{H,total} = (0.9 \times 4{,}250) + (0.5 \times 300) + 1{,}200 = 3{,}825 + 150 + 1{,}200 = 5{,}175 \text{ MNT/km}$$

For comparison, the pure electric variant:

$$C_{EV,total} = e_{EV} \cdot C_{el} + C_{EV,aux} = (2.5 \times 300) + 1{,}100 = 750 + 1{,}100 = 1{,}850 \text{ MNT/km}$$

The per-km cost premium of the hybrid over the pure electric: 5,175 − 1,850 = 3,325 MNT/km.

Table 4.4: Advantages and disadvantages of the hybrid CR130EVT variant

Attribute	Description
✓ Infrastructure flexibility	Operates on diesel fuel when charging/swap infrastructure is not yet available
✓ Reduced range anxiety	Diesel engine extends effective operational range; eliminates stranding risk
✓ Transitional deployment	Allows fleet electrification to begin before full infrastructure is commissioned
✓ Cold-weather reserve	Diesel engine provides heat and power backup in extreme cold conditions
✓ Familiar logistics	Uses existing diesel fuel supply chain at TT–GS corridor fuelling points
✗ Diesel fuel cost retained	Operating cost significantly higher than pure electric (5,175 vs. 1,850 MNT/km)
✗ Emissions not eliminated	CO_2, NO_x, and PM from diesel combustion remain; NDC benefit reduced
✗ Higher maintenance	Diesel engine, oil, filters, cooling, and exhaust system add maintenance burden
✗ More complex system	Battery + diesel + generator integration requires more sophisticated control
✗ Smaller battery	≥170 kWh versus 783 kWh; less regenerative braking benefit

4.4.3 Technical Comparison: Pure Electric vs. Hybrid

Table 4.5: Technical comparison — pure electric vs. hybrid CR130EVT [1]

Criterion	Pure Electric	Hybrid	Conclusion
Energy source	783 kWh battery	Battery + 400 kW diesel	EV: no fuel cost; Hybrid: range reserve
Traction energy	Fully electric	Electric + diesel support	EV cleaner; Hybrid more flexible
Infrastructure need	Charging/swap station	Diesel supply is	Hybrid easier in early

	required	sufficient	deployment
Operational range	SOC and consumption dependent	Diesel extends effective range	Hybrid has range advantage initially
Operational emissions	Zero during operation	Diesel exhaust present	EV environmentally superior
Maintenance complexity	Low (no diesel engine)	High (diesel + electric)	EV lower long-term maintenance
Energy cost	Based on electricity tariff	Dominated by diesel price	EV lower operating cost
Long-term role	Primary fleet variant	Transitional/backup variant	EV is strategic choice for TT–GS

4.4.4 Preliminary Cost Comparison: 500 km Cycle

For a complete 500 km round-trip cycle (250 km loaded outbound + 250 km empty return), the direct operating costs are:

$$C_{EV,cycle} = 1{,}850 \times 500 = 925{,}000 \text{ MNT/cycle}$$

$$C_{H,cycle} = 5{,}175 \times 500 = 2{,}587{,}500 \text{ MNT/cycle}$$

$$C_{D,cycle} = 7{,}025 \times 500 = 3{,}512{,}500 \text{ MNT/cycle}$$

(Diesel vehicle: $C_{D,total} = q_D \cdot C_d + C_{D,maint} = 1.3 \times 4{,}250 + 1{,}500 = 7{,}025$ MNT/km)

Table 4.6: Per-km cost breakdown and 500 km cycle comparison

Cost Component	Pure Electric	Hybrid	Diesel
Electricity cost	750 MNT/km	150 MNT/km	0 MNT/km
Diesel fuel cost	0 MNT/km	3,825 MNT/km	5,525 MNT/km
Maintenance / auxiliary	1,100 MNT/km	1,200 MNT/km	1,500 MNT/km
Total per km	1,850 MNT/km	5,175 MNT/km	7,025 MNT/km
500 km cycle total	925,000 MNT	2,587,500 MNT	3,512,500 MNT
Cost per t·km (130 t, 250 km load leg)	28.5 MNT/t·km	79.6 MNT/t·km	108.1 MNT/t·km

5. ROUTE AND ROAD ANALYSIS: TT–GS CORRIDOR

5.1 Route Map and Basic Data

The route map provided [2] marks the departure point in the vicinity of Tavan Tolgoi mine facilities and the destination at the Gashuun Sukhait border terminal, using UTM Zone 48N coordinates. The straight-line (linear) distance between the two points as measured on the map is 217.8 km. However, the actual coal transport corridor incorporates route deviation around terrain features, safety buffer zones, loading and unloading areas, service stop locations, and future road realignments. A conservative design route length of 250 km is adopted for all calculations in this thesis.

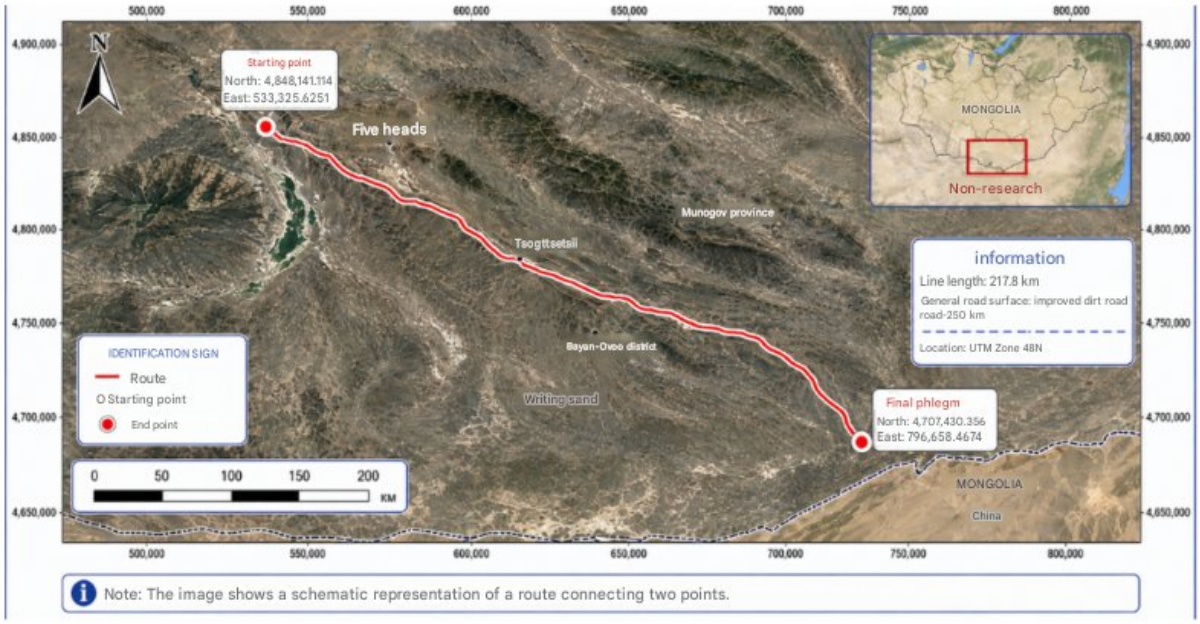


Figure 5.1: Route map of the Tavan Tolgoi–Gashuun Sukhait corridor [2]

Table 5.1: Route basic data and design parameters

Parameter	Value	Notes
Straight-line distance (from map)	217.8 km	Provided user map, UTM Zone 48N
Design route length (this thesis)	250 km	Conservative estimate used in all calculations

Road surface condition	Improved compacted gravel / heavy-haul corridor	Reinforced base required for CR130EVT axle loads
Estimated gradient range	0–8% (typical); up to 13% (short sections)	No detailed DEM available; simulated profile used
Geographic context	South Gobi desert, elevation ~1,000–1,500 m asl	Altitude slightly reduces air density; minor effect on aerodynamics
Coordinate system	UTM Zone 48N	As indicated on route map

5.2 Recommended Road Parameters

The CR130EVT's overall dimensions (29 m length, 3.4–3.5 m width) and high axle loads require road cross-sections significantly beyond those of a standard rural highway. These parameters are derived from the vehicle specifications and standard heavy-haul road design methodology.

Table 5.2: Recommended road parameters for the CR130EVT heavy-duty corridor

Parameter	Recommended Value	Justification
Lane width	5.0–5.5 m	Safe clearance for 3.4–3.5 m vehicle width; passing margin
Total carriageway width	10–11 m	Two-way simultaneous traffic flow
Shoulder width	1.0–1.5 m	Emergency stop, tire change, breakdown access
Minimum turning radius	≥ 25 m	Long combination articulation; 50 m+ preferred at intersections
Sustained gradient limit	< 6–8%	Energy efficiency, battery range, and safety margin
Service stop spacing	30–50 km	HV safety checks, tire inspection, fluid checks
Pavement design class	Heavy-haul (≥ 23 t dynamic axle)	Fourth-power law damage from 18 t static axle at k_d=1.3

5.3 Elevation Profile and Gradient Modelling

Detailed Digital Elevation Model (DEM) data for the TT–GS corridor were not available for this study. A simulated gradient profile is used to approximate terrain variation. This approach follows

standard practice for preliminary feasibility studies when survey data are unavailable. Actual detailed design would require GNSS survey data and DEM-based route analysis.

The gradient at any point along the route is defined as:

$$i = (H_{j+1} - H_j) / \Delta s \times 100\% \quad \text{(Eq. 2 applied)}$$

where H_j and H_{j+1} are elevations at two consecutive points (m) and Δs is the horizontal distance between them (m). A positive i indicates an uphill grade; negative indicates downhill.

For the MATLAB-style simulation in Chapter 7, the gradient profile is approximated as:

$$grade(s) = 0.012 \cdot \sin(2\pi \cdot s / L \cdot 3) - 0.0023 \quad [dimensionless]$$

This sinusoidal function creates alternating uphill and downhill sections with a mean slight downhill bias (representing net elevation decrease from Tavan Tolgoi mine elevation to border crossing elevation). The amplitude of 0.012 corresponds to approximately 1.2% maximum gradient in this simulation — a conservative value for the typical terrain, with short steeper sections represented by the model extremes.

Figure 5.2: Simulated elevation profile along the TT–GS corridor (250 km, sinusoidal approximation)

Figure 5.3: Power demand variation as a function of simulated route gradient

The power demand profile shows that on uphill sections, wheel power P_wheel increases significantly above the rolling-resistance baseline, while downhill sections offer regenerative braking potential. The range of P_wheel in this gradient model is approximately 180–400 kW at 40 km/h — well within the 600 kW rated motor power for most of the route, confirming that the route is generally manageable for the pure electric variant without sustained power limiting.

5.4 Lateral Stability and Wheel-Lift Criterion

The CR130EVT, as a 29 m long dual-trailer combination with 120–130 t payload and 200 t GVW, requires assessment of lateral stability not only in straight-line travel but also during cornering, operation on cross-slopes, and asymmetric loading conditions. A combination vehicle with a high center of gravity and long wheelbase is susceptible to rollover, particularly in long dual-trailer configurations.

Lateral stability refers to the vehicle's ability to traverse curves, cross-slope terrain, and asymmetric load conditions without the inner wheels lifting off the road surface (wheel-lift). Wheel-

lift is the precursor to rollover: once inner wheel contact is lost, the stabilising moment is reduced and rollover can occur.

5.4.1 Static Wheel-Lift Analysis

In a simplified static lateral stability model, the critical lateral acceleration at which inner wheel-lift begins is:

$$a_{y,cr} = g \cdot B / (2 \cdot h_{cg}) \quad \text{(Eq. 9)}$$

The corresponding critical roll angle is:

$$\tan(\theta_{cr}) = B / (2 \cdot h_{cg}) \quad \text{(Eq. 10)}$$

For preliminary calculations with B = 3.0 m (effective track width between tire centerlines) and h_cg = 2.2 m (laden center of gravity height estimate):

$$\tan(\theta_{cr}) = 3.0 / (2 \times 2.2) = 3.0 / 4.4 = 0.682 \rightarrow \theta_{cr} = \arctan(0.682) \approx 34.3°$$

$$a_{y,cr} = (9.81 \times 3.0) / (2 \times 2.2) = 29.43 / 4.4 = 6.69 \text{ m/s}^2 \approx 0.68g$$

These are theoretical static limits for a rigid body. In practice, the operational safety limit is far lower because of: dynamic load transfer during trailer oscillation; asymmetric cargo loading; road surface unevenness amplifying dynamic lateral forces; and driver steering inputs. It is therefore recommended that the maximum working side slope be limited to 6–8°, not the theoretical 34.3°.

5.4.2 Effect of Cornering Speed and Radius

During cornering, the lateral centripetal acceleration is:

$$a_y = v^2 / R \quad \text{(Eq. 11)}$$

This acceleration increases quadratically with speed — a small speed increase causes a disproportionate increase in lateral force. For long dual-trailer vehicles, turning speed management is therefore a critical safety parameter.

Table 5.3: Lateral acceleration and safety assessment by turning radius and speed

Turning Radius R	Speed v	Lateral Acceleration a_y	a_y / g	Safety Assessment
25 m	20 km/h (5.56 m/s)	1.24 m/s²	0.13g	Low risk
25 m	25 km/h (6.94 m/s)	1.93 m/s²	0.20g	Acceptable

25 m	30 km/h (8.33 m/s)	2.78 m/s²	0.28g	Caution — approach limit
25 m	40 km/h (11.11 m/s)	4.94 m/s²	0.50g	High risk — near wheel-lift threshold
50 m	40 km/h (11.11 m/s)	2.47 m/s²	0.25g	Acceptable
100 m	50 km/h (13.89 m/s)	1.93 m/s²	0.20g	Acceptable

At 25 m radius with 40 km/h speed, a_y / g = 0.50g — approaching the static threshold of 0.68g. Given trailer oscillation and load asymmetry in real operation, this condition must be considered dangerous for the fully laden CR130EVT. Speed limits of 20–30 km/h are recommended on curves with radius ≤ 25 m.

5.4.3 Effect of Center-of-Gravity Height and Load Asymmetry

The center of gravity height h_cg is directly influenced by how cargo is loaded. If coal is piled higher on one side, or if one trailer body is loaded more than the other, h_cg increases and the stability margin decreases. The sensitivity is:

$$\theta_{cr} = \arctan[B / (2 \cdot h_{cg})] \quad \text{— decreasing function of } h_{cg}$$

Table 5.4: Effect of center-of-gravity height on theoretical roll stability

CG Height h_cg	tan(θ_cr)	Critical Angle θ_cr	Assessment
2.0 m	0.750	36.9°	Good stability margin
2.2 m (baseline)	0.682	34.3°	Baseline calculation
2.6 m	0.577	30.0°	Stability reduced
3.0 m	0.500	26.6°	Elevated risk; caution required

These results confirm that symmetric, level loading of each trailer body (60 t per body, evenly distributed) is an operational safety requirement — not merely a best-practice recommendation.

5.4.4 Operational Safety Requirements

Combining the static analysis, the cornering speed analysis, and the load distribution sensitivity, the following operational requirements are derived for CR130EVT operation on the TT–GS corridor:

Table 5.5: Stability engineering requirements — summary for TT–GS corridor design and operations

Parameter	Required Value	Justification
Road cross-slope (main route)	2–4%	Drainage and lateral force reduction
Maximum working side slope	6–8° (10–14% gradient)	Dynamic safety margin above static 34.3° threshold
Turning radius at intersections	≥ 25 m (50 m preferred)	Limit a_y below 0.25g at 25 km/h
Speed limit on curves R ≤ 25 m	20–30 km/h	Keep a_y/g < 0.30g
Trailer loading procedure	Even 60 t per trailer body	Prevent CG shift; symmetric distribution
Unloading area requirement	Level, compacted, stable surface	Trailer tipping risk when body elevated
Road surface quality	Minimize potholes and ruts	Reduce dynamic wheel load amplification
Driver operational protocol	No sudden steering or hard braking	Prevent trailer sway oscillation

6. POWERTRAIN, CONTROL, AND ELECTRICAL SYSTEM

6.1 Drivetrain Architecture and Block Diagram

The CR130EVT uses a multi-axle distributed electric traction architecture. Rather than a conventional centralised mechanical drivetrain — with a single engine, gearbox, cardan shaft, and differential — the electrical system integrates the battery pack, high-voltage Power Distribution Unit (PDU), IGBT power converters, and traction motors through a coordinated four-level electronic control hierarchy. This architecture is derived from proven railway traction technology and adapted for heavy-duty road freight application [1,5].

Table 6.1: CR130EVT powertrain control system — blocks and functions

Control Block	Level	Function
Vehicle Control Unit (VCU)	Level 1 — Master	Processes all driver commands; executes energy management strategy; coordinates BMS, DCU, and generator
Battery Management System (BMS)	Level 2 — Battery	Monitors SOC, voltage, current, temperature, insulation; enforces charge/discharge limits; communicates to VCU via CAN2
Drive Control Unit (DCU)	Level 3 — Torque	Receives total torque demand from VCU; distributes torque commands to individual drive axles; applies anti-slip corrections
IGBT Power Converters	Level 4 — Power	Converts DC battery energy to controlled three-phase AC for each traction motor; executes FOC; manages regenerative mode
Traction Motors	Actuators	Convert electrical energy to mechanical rotational torque; operate in generator mode during regenerative braking
PDU / HV DC Bus	Distribution	Routes high-voltage energy from battery to all converters; integrates contactors, fuses, and isolation monitoring

The Vehicle Control Unit (VCU) is the master controller. It receives driver inputs (accelerator pedal, brake, gear mode, direction) and real-time vehicle state data, then computes the total traction torque demand:

$$T_{req} = f(pedal, v, SOC, mode, safety_state) \quad \text{(Eq. 13 applied)}$$

The BMS communicates battery parameters to the VCU via the high-priority CAN2 bus. When battery temperature is high or SOC is low, the BMS reduces the allowable discharge power

P_allow, and the VCU limits traction power accordingly. This protection is critical at both temperature extremes of the Gobi climate.

Figure 6.1: Drivetrain and control system block diagram of the CR130EVT [1]

6.1.1 BMS Functions

The BMS is the safety and performance guardian of the battery system. It monitors the following parameters continuously:

Table 6.2: BMS monitoring parameters and protective functions

Parameter	Description	Protective Action
SOC	State of charge — remaining energy percentage	Limits discharge (lower SOC) and charge (upper SOC) rates
SOH	State of health — capacity degradation over service life	Adjusts SOC estimation; triggers maintenance alerts
Cell voltage	Individual cell and module voltage	Disconnects pack on under/overvoltage; balances cells
Pack current	Charge and discharge current (bidirectional)	Overcurrent cutoff; limits peak rates
Temperature	Cell, module, and pack thermal status	Pre-heating, cooling, and charge/discharge rate derating
Insulation resistance	High-voltage isolation from chassis ground	Ground fault alarm; automatic isolation on fault
Fault flags	Overvoltage, overcurrent, overtemperature, short-circuit	Hardware cutoff; VCU notification; fire suppression trigger

Cold-weather operation note: below −10°C ambient, the BMS must complete battery pre-heating to a minimum operating temperature (typically +5°C to +15°C) before any significant discharge current is permitted. This is a safety-critical operational procedure enforced by the BMS — failure to pre-condition before departure risks lithium plating (metallic lithium deposition on the anode), which can lead to internal short circuits and thermal runaway.

6.1.2 DCU and Torque Distribution

The Drive Control Unit (DCU) receives the total torque demand T_req from the VCU and distributes it across the drive axles:

$$T_req = T_1 + T_2 + T_3 \quad \text{(three drive axle groups)} \quad \text{(Eq. 13)}$$

$$T_i = \alpha_i \cdot T_req, \quad \text{with } \alpha_1 + \alpha_2 + \alpha_3 = 1$$

The distribution coefficients α_i are not fixed; they are computed dynamically as a function of axle load, detected wheel slip, road gradient, turning radius, battery power limits, motor temperature, and IGBT temperature. This dynamic torque allocation is a key safety feature: if any drive wheel slips, the DCU reduces its torque command while maintaining full torque on the remaining axles.

6.1.3 IGBT Power Converter

The battery pack outputs high-voltage DC. Traction motors require controlled three-phase AC. The IGBT power converter performs this conversion using Pulse Width Modulation (PWM) control:

$$\text{DC Battery Energy} \rightarrow \text{IGBT Converter (PWM)} \rightarrow \text{Three-Phase AC} \rightarrow \text{Traction Motor}$$

Motor electromagnetic torque is proportional to motor current (q-axis component in FOC):

$$T_m \sim I_q \quad \text{(Field-Oriented Control relationship)}$$

The IGBT controls switching frequency and duty cycle to precisely regulate I_q and therefore torque, achieving sub-10 ms torque response for anti-slip control.

6.1.4 Regenerative Braking

During deceleration or downhill travel, the traction motors switch from motor mode to generator mode. The energy flow reverses:

$$\text{Wheel} \rightarrow \text{Drive Axle} \rightarrow \text{Traction Motor (generator)} \rightarrow \text{IGBT Converter} \rightarrow \text{DC Bus} \rightarrow \text{Battery}$$

Regenerative braking capability is constrained by: battery SOC (cannot charge if nearly full), battery temperature, BMS maximum charging current, tire-road adhesion conditions, and IGBT/motor temperature. Mechanical service brakes are therefore always required for emergency stops and high-deceleration situations. The regenerative system augments — but does not replace — the mechanical braking system.

6.2 Power Flow and PDU Scheme

The complete energy flow from the battery pack to the drive wheels passes through multiple protection and distribution stages. The normal (motoring) energy flow path is:

Battery → HV Contactor → Fuse → PDU/DC Bus → IGBT Converter → Traction Motor → Drive Axle → Wheels

Each stage in this chain serves a specific function:

— HV Contactor: controlled disconnection and reconnection of the battery from the system; emergency isolation

— Fuse: overcurrent and short-circuit protection for downstream components

— PDU/DC Bus: distributes high-voltage energy to all IGBT converters and auxiliary loads; maintains stable DC bus voltage

— IGBT Converter: DC-to-AC conversion with precise current and torque control

— Traction Motor: electromechanical energy conversion (electrical to mechanical)

Figure 6.2: Power flow and PDU scheme of the CR130EVT electrical system [1]

The system power balance is:

$$P_{total} = P_{trac} + P_{aux} \quad \text{(Eq. derived from energy conservation)}$$

where P_trac is traction power to the motors and P_aux covers all auxiliary loads (steering hydraulics, braking system, thermal management, lighting, HVAC, control systems). Auxiliary loads for a vehicle of this scale are estimated at 30–50 kW. For example, with P_trac = 520 kW and P_aux = 35 kW: P_total = 555 kW drawn from the battery.

The system energy efficiency from battery to wheel:

$$\eta_{sys} = P_{wheel} / P_{battery} \quad \text{(Eq. derived)}$$

Example: P_battery = 600 kW drawn, P_wheel = 510 kW delivered: η_sys = 510/600 = 0.85 = 85%. All losses (battery internal resistance, contactor, PDU, IGBT switching, motor copper and iron losses, reducer) are embedded in this figure.

6.2.1 PDU Functions

The PDU performs five critical functions in the CR130EVT electrical system:

Table 6.3: PDU functions in the CR130EVT electrical system

Function	Description
Energy distribution	Routes high-voltage battery energy to traction IGBT converters and auxiliary loads
Protection integration	Integrates fuses, contactors, interlock circuits, and isolation monitoring into a coordinated protection layer
DC bus stabilisation	Maintains a stable high-voltage DC rail for all converters, buffering transient demand spikes
Continuous monitoring	Measures bus voltage, branch currents, and insulation resistance in real time
Emergency isolation	Executes automatic circuit isolation on fault detection; enables controlled safe shutdown

6.2.2 Regenerative Energy Recovery

During downhill travel or deceleration, the energy flow reverses completely. The traction motor operates as a generator, and IGBT converters route the recovered AC energy back through the DC bus into the battery:

$$\text{Wheels} \rightarrow \text{Drive Axle} \rightarrow \text{Traction Motor (generator)} \rightarrow \text{IGBT (AC}\rightarrow\text{DC)} \rightarrow \text{PDU/DC Bus} \rightarrow \text{Battery}$$

The system efficiency during regeneration:

$$\eta_{regen} = P_{battery,stored} / P_{wheel,input} \approx 0.75\text{–}0.85 \quad \text{[typical for this class]}$$

The maximum recoverable power is limited by battery charge acceptance rate (determined by BMS), IGBT thermal limits, and motor thermal limits. When the battery approaches 90–100% SOC, regenerative power is reduced and supplemented by mechanical brakes.

6.3 Torque Distribution Across Drive Axles

The DCU dynamically allocates the total traction torque T_req across the drive axles. Table 6.3 gives representative distribution coefficients for four operating modes:

Table 6.4: Torque distribution coefficients (α_i) by driving mode [1]

Mode	α_1 (Front drive)	α_2 (Middle drive)	α_3 (Rear drive)	Notes

Level road (steady state)	0.34	0.33	0.33	Near-equal distribution across axles
Uphill grade	0.38	0.32	0.30	Front axle commands more torque for traction control
Slip detected on one axle	0.40	0.38	0.22	Slipping axle torque reduced; others compensate
Regenerative braking	0.30	0.35	0.35	Rear-emphasis for braking stability and CG transfer

6.4 Electric Motor Operating Characteristics

The traction motors of the CR130EVT operate across two fundamental regimes, corresponding to the standard characteristic curve of electric motors under constant voltage supply:

Table 6.5: Traction motor operating zones and significance

Operating Zone	Characteristic	Operational Significance for CR130EVT
Constant torque zone (low speed)	High torque at low RPM; power increases with speed	Starting from standstill; climbing steep grades; traction on loose surfaces
Constant power zone (high speed)	Torque decreases as speed increases; power constant	Steady-state cruising at 40–65 km/h on level to moderate gradient road

The fundamental power-torque-speed relationship:

$$P_m = T_m \cdot \omega_m \qquad \text{(Eq. 14)}$$

At low speed, ω_m is small, so the motor can produce high T_m without exceeding rated power. As speed increases, ω_m rises until P_m reaches the rated power ceiling (600 kW). Beyond this point, T_m must decrease proportionally. This is the physical reason why a fully laden CR130EVT loses speed on sustained steep gradients — the motor's power ceiling requires trading speed for sustained force at equilibrium.

Required grade climbing force on a 3% gradient (i = 0.03, m = 200,000 kg):

$$F_{grade} = m \cdot g \cdot i = 200{,}000 \times 9.81 \times 0.03 = 58{,}860\ N \approx 58.9\ kN \quad \text{(Eq. 2)}$$

This must be added to rolling resistance (≈ 29.4 kN) and aerodynamic drag. At 40 km/h on a 3% grade, total wheel power exceeds 600 kW — see Chapter 7 calculations.

Figure 6.3: CR130EVT characteristic torque-speed curve showing constant torque and constant power zones

Table 6.6: Motor operating behaviour under different route conditions

Route Condition	Motor Mode	Energy / Operational Outcome
Starting from rest (laden)	Constant torque maximum	Strong initial traction; high current draw from battery
Loose gravel / sand	Torque control active (slip detection)	Anti-slip via DCU; torque redistributed to gripping axles
Sustained uphill grade	Power-limited constant power	Speed reduced to equilibrium; battery consumption elevated
Level road cruising	Constant power, moderate torque	Stable, predictable consumption profile
Downhill travel	Generator mode (regenerative)	Energy recovery into battery; mechanical brakes supplement
High speed (65 km/h)	Constant power zone — low torque	Reduced wheel traction force; not limiting on level road

7. CALCULATIONS: TRACTION FORCE, POWER, AND RANGE

7.1 Input Parameters

Table 7.1 consolidates all input parameters used in the traction force, power demand, and battery range calculations in this chapter.

Table 7.1: Input parameters for traction force, power, and range calculations

Parameter	Symbol	Value	Notes
One-way route length	L	250 km	Conservative design estimate
Round-trip cycle length	L_cycle	500 km	Loaded + empty return
Maximum payload	Q	130 t	CR130EVT maximum capacity
Gross vehicle mass (laden)	m	200,000 kg (200 t)	Engineering approximation; 73+130=203 t actual
Battery capacity (EV)	E_bat	783 kWh	Pure electric variant [1]
Usable SOC window	SOC_use	90%	10% reserve at each end
Usable battery energy	E_usable	704.7 kWh	E_bat × SOC_use = 783 × 0.90
Rolling resistance coefficient	f_r	0.015	Improved compacted gravel road
Air density	ρ	1.2 kg/m³	Standard conditions at ~1,250 m altitude
Aerodynamic drag coefficient	C_D	0.9	Blunt frontal profile, dual trailer
Frontal area	A	13.6 m²	Estimated: 3.4 m width × 4.0 m height
Operating speed (typical)	v	40 km/h = 11.11 m/s	Laden outbound; conservative for range
EV consumption range (sensitivity)	e	2.0–3.0 kWh/km	Range for sensitivity analysis

7.2 Range and SOC Sensitivity Analysis

The usable battery energy for a 90% SOC window:

$$E_{usable} = E_{bat} \times SOC_{use} = 783 \times 0.90 = 704.7 \text{ kWh}$$

The practical driving range at energy consumption rate e:

$$R_{practical} = E_{usable} / e \quad (Eq.\ 8)$$

The SOC at distance s along the route:

$$SOC(s) = 100 \times (1 - e \cdot s / E_{bat}) \quad [\%] \quad (Eq.\ 7)$$

Table 7.2 presents range and trip feasibility for five energy consumption scenarios over the 250 km one-way route.

Table 7.2: Range and SOC analysis — pure electric CR130EVT, 250 km route, SOC_use = 90%

Consumption e (kWh/km)	Usable Energy (kWh)	Practical Range (km)	Energy for 250 km trip (kWh)	SOC residual at 250 km (%)	Support station needed?
2.0	704.7	352.4	500.0	36.1%	No — ample reserve
2.3	704.7	306.4	575.0	26.6%	No — adequate
2.5	704.7	281.9	625.0	20.2%	No — sufficient
2.7	704.7	261.0	675.0	13.8%	No — near limit
3.0	704.7	234.9	750.0	4.2%	Yes — mid-route station required

Detailed SOC calculations for the 2.5 kWh/km and 3.0 kWh/km scenarios:

$$\text{At } 2.5 \text{ kWh/km:} \quad E_{250} = 2.5 \times 250 = 625 \text{ kWh}$$

$$SOC_{end} = 100 \times (1 - 625/783) = 100 \times 0.202 = 20.2\% \quad \checkmark \text{ (adequate)}$$

$$\text{At } 3.0 \text{ kWh/km:} \quad E_{250} = 3.0 \times 250 = 750 \text{ kWh}$$

$$SOC_{end} = 100 \times (1 - 750/783) = 100 \times 0.042 = 4.2\% \quad \times \text{ (insufficient — support station required)}$$

Conclusion from SOC analysis: For energy consumption rates up to approximately 2.8 kWh/km with 90% usable SOC, the pure electric CR130EVT can complete the one-way 250 km route with a positive SOC residual. For adverse conditions (severe cold, headwind, prolonged steep grades) where consumption approaches or exceeds 3.0 kWh/km, a mid-route support station at approximately km 110–140 is required. Detailed placement should be determined based on the actual elevation profile and gradient data from a proper DEM survey.

Figure 7.1: SOC depletion profiles for five energy consumption scenarios along the 250 km TT–GS route

Figure 7.2: Cumulative energy consumption along the 250 km route by consumption scenario

7.3 Resistance Force and Power Demand

The total traction force required to maintain motion against rolling resistance, grade resistance, and aerodynamic drag:

$$F_{trac} = m \cdot g \cdot (f_r + i) + \tfrac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot v^2 \qquad (Eq.\ 4)$$

Required wheel power:

$$P_{wheel} = F_{trac} \cdot v \qquad (Eq.\ 5)$$

Calculating the aerodynamic drag component at v = 40 km/h = 11.11 m/s:

$$F_{aero} = \tfrac{1}{2} \times 1.2 \times 0.9 \times 13.6 \times 11.11^2 = 0.6 \times 0.9 \times 13.6 \times 123.4 = 908\ N \approx 0.9\ kN$$

Aerodynamic drag is negligible at these speeds compared to rolling and grade resistance — consistent with the low maximum speed and heavy mass of this vehicle class.

Table 7.3 presents traction force and wheel power for four combinations of gradient and speed.

Table 7.3: Traction force and wheel power — effect of gradient and speed (m = 200 t, f_r = 0.015)

Gradient i	Speed v	F_r (kN)	F_grade (kN)	F_aero (kN)	F_trac (kN)	P_wheel (kW)	Assessment vs. 600 kW rated
0% (level)	40 km/h	29.4	0	0.9	30.3	337	Well within rated — normal cruise
2% grade	40 km/h	29.4	39.2	0.9	69.5	772	Exceeds 600 kW — speed

							must reduce
4% grade	30 km/h	29.4	78.5	0.5	108.4	903	Near peak 900 kW — short section only
8% grade	20 km/h	29.4	157.0	0.2	186.6	1,037	Requires derating — not sustained

The maximum sustained gradient at 40 km/h and 600 kW rated power can be estimated by solving P_wheel = P_rated:

$$F_{trac} \cdot v = P_{rated} \quad \rightarrow \quad F_{trac} = P_{rated} / v = 600{,}000 / 11.11 = 54{,}005\ N$$

$$m \cdot g \cdot (f_r + i_{max,sustained}) = 54{,}005 \quad \rightarrow \quad 200{,}000 \times 9.81 \times (0.015 + i) = 54{,}005$$

$$0.015 + i_{max} = 54{,}005 / (200{,}000 \times 9.81) = 0.02752 \quad \rightarrow \quad i_{max,sustained} \approx 1.25\% \quad (Eq.\ 15)$$

This confirms that on a 2% sustained gradient at 40 km/h, required power (772 kW) exceeds rated power. In practice, the VCU would reduce torque demand and the vehicle would decelerate until equilibrium is reached at a lower speed. The 13% maximum gradient specification in Table 4.1 refers to a short-section capability at significantly reduced speed (estimated ≤ 15–20 km/h) using peak 900 kW power momentarily.

The practical sustained gradient capability at 40 km/h is approximately 1.2%, and at 30 km/h (reducing F_aero and adjusting the balance) approximately 2.0–2.5%. TT–GS corridor gradient design should target ≤ 3–4% sustained grades wherever possible.

7.4 Summary: Pure Electric vs. Hybrid

On a technical level, the pure electric CR130EVT's viability for the TT–GS corridor depends primarily on two factors: maintaining energy consumption below 2.8 kWh/km (achievable under normal to moderate operating conditions with 90% usable SOC) and providing terminal battery swap/charge stations at both ends of the route. The hybrid CR130EVT is viable without any dedicated electric infrastructure but carries a 3,325 MNT/km operating cost premium and retains

diesel emissions. The conclusion is consistent with the cost analysis in Chapter 4: the pure electric variant is the long-term strategic choice, and the hybrid is the transitional solution.

8. BATTERY SWAPPING AND CHARGING INFRASTRUCTURE

8.1 Battery Swap Station Layout

For the pure electric CR130EVT fleet on the TT–GS corridor, battery swap stations offer a key operational advantage: vehicle downtime for energy replenishment is minimised to the time required for mechanical pack exchange (estimated 5–20 minutes for purpose-built equipment), decoupling charging time from vehicle cycle time. This preserves fleet productivity regardless of the time required to charge a spare battery pack.

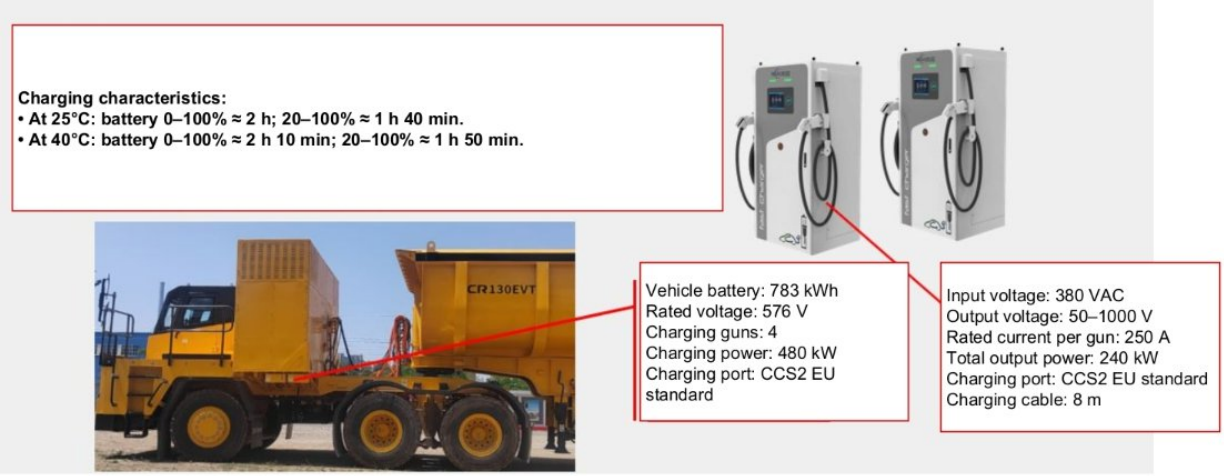


Figure 8.1: Proposed battery swap and charging station layout on the TT–GS corridor

Table 8.1: Proposed battery swap/charging station locations and functions

Station ID	Location	Primary Function	Notes
S0	km 0 — Tavan Tolgoi terminal	Dispatch, full battery swap, fleet servicing	Full swap capability; fleet maintenance base
S1	km 110–140 (optional mid-route)	Emergency top-up or swap for high-consumption trips	Required for ≥ 2.8 kWh/km or adverse conditions
S2	km 250 — Gashuun Sukhait terminal	Battery swap and turnaround charging	Full swap capability; port-side operations
S3	km 170–190 (future expansion)	Additional support for growing fleet	To be installed when fleet exceeds ~20 vehicles

For baseline operating conditions (2.5 kWh/km, 90% usable SOC), stations S0 and S2 are sufficient for full operations. Station S1 becomes operationally necessary for adverse conditions (e ≥ 3.0 kWh/km; winter with reduced battery capacity; headwind conditions). Station S3 is a future provision for fleet expansion.

8.2 Hybrid Backup Strategy

The hybrid CR130EVT can be deployed during the S1 station build-out phase, when terminal infrastructure is under construction but diesel logistics are already established. This provides a risk-managed transition path: begin coal transport electrification immediately with the hybrid variant, accumulate operational experience, and transition to pure electric vehicles as terminal infrastructure is commissioned. The economic cost of the transition period (approximately 3,325 MNT/km more than pure electric) is justified by the operational flexibility and risk reduction it provides.

8.3 Energy Source Comparison

Each 783 kWh battery pack charged in approximately 2 hours requires:

$$P_{charge} = E_{bat} / t_{charge} = 783 / 2 = 391.5 \text{ kW} \quad \text{(average charging power per pack)}$$

For simultaneous charging of 6 packs (estimated for a terminal fleet of 15–20 vehicles):

$$P_{station,6} = 391.5 \times 6 = 2{,}349 \text{ kW} \approx 2.35 \text{ MW}$$

For 8 packs simultaneously:

$$P_{station,8} = 391.5 \times 8 = 3{,}132 \text{ kW} \approx 3.13 \text{ MW}$$

Including auxiliary station loads (lighting, HVAC, control systems, service equipment), each terminal station requires approximately 3–4 MW of installed capacity. Table 8.2 compares energy source options.

Table 8.2: Energy source options for charging station infrastructure

Energy Source Configuration	Advantages	Disadvantages	Recommendation
Grid only (35 kV connection)	Reliable 24/7; consistent power quality	High peak demand charges; single point of failure	Necessary base layer

Solar PV only	Low operational cost; no fuel	Unavailable at night; seasonal variation; intermittent	Insufficient as sole source
Grid + Solar PV	Reduced daytime electricity cost; partial renewable	Peak demand unchanged; overnight gap	Good — moderate improvement
Grid + Solar PV + BESS	Peak demand shaving; renewable integration; outage resilience	Higher CAPEX; complexity	Optimal — recommended configuration

The recommended energy source configuration for TT–GS battery swap stations is Grid + Solar PV + BESS. The South Gobi region has excellent solar resources (high irradiance, minimal cloud cover), making rooftop or adjacent solar PV arrays a cost-effective component. BESS provides peak shaving (reducing grid peak demand charges) and resilience against grid outages — important for a remote corridor where grid reliability may be lower than urban standards.

9. ECONOMIC FEASIBILITY ASSESSMENT

9.1 Assessment Objectives and Input Parameters

This chapter compares the direct operating costs of three transport technology scenarios on the TT–GS corridor: (1) pure electric CR130EVT; (2) hybrid CR130EVT; and (3) conventional diesel heavy-duty truck of equivalent payload capacity. Costs are compared on a per-km, per-500 km-cycle, per-tonne, and per-tonne-km basis. Annual and fleet-level savings are calculated to contextualise the investment payback argument.

Table 9.1: Key input parameters for the economic assessment

Parameter	Symbol	Value	Notes
EV energy consumption	e_EV	2.5 kWh/km	Baseline; sensitivity 2.0–3.0
Electricity tariff	C_el	300 MNT/kWh	Mongolia industrial tariff reference
Hybrid diesel consumption	q_d	0.9 L/km	Estimated hybrid-mode diesel use
Diesel fuel price	C_d	4,250 MNT/L	Mongolia 2024–2025 reference
Hybrid electric consumption	e_H	0.5 kWh/km	Electric component in hybrid mode
EV auxiliary/maintenance cost	C_EV,aux	1,100 MNT/km	Tire, suspension, servicing, insurance
Hybrid maintenance cost	C_H,maint	1,200 MNT/km	EV base + diesel engine service premium
Diesel truck fuel consumption	q_D	1.3 L/km	Comparable diesel truck, 130 t payload class
Diesel truck maintenance cost	C_D,maint	1,500 MNT/km	Higher engine/drivetrain maintenance
Route length (one-way)	L	250 km	Design route length
Round-trip cycle	L_cycle	500 km	Loaded + empty return
Payload per cycle	Q	130 t	Maximum rated payload
Cycles per day (1 vehicle)	n_cycles	2	Both cycles within operating day
Operating days per year	D_year	330 days	Accounting for maintenance and

			downtime

9.2 Per-km and Cycle Cost Comparison

Direct per-km operating costs are calculated as follows:

Pure electric CR130EVT:

$$C_{EV,total} = e_{EV} \cdot C_{el} + C_{EV,aux} = (2.5 \times 300) + 1{,}100 = 750 + 1{,}100 = 1{,}850 \text{ MNT/km}$$

Hybrid CR130EVT:

$$C_{H,total} = q_d \cdot C_d + e_H \cdot C_{el} + C_{H,maint} = (0.9 \times 4{,}250) + (0.5 \times 300) + 1{,}200$$

$$C_{H,total} = 3{,}825 + 150 + 1{,}200 = 5{,}175 \text{ MNT/km}$$

Conventional diesel truck:

$$C_{D,total} = q_D \cdot C_d + C_{D,maint} = (1.3 \times 4{,}250) + 1{,}500 = 5{,}525 + 1{,}500 = 7{,}025 \text{ MNT/km}$$

Table 9.2: Per-km operating cost breakdown — EV, Hybrid, and Diesel

Cost Component	Pure Electric	Hybrid	Diesel	Notes
Electricity cost	750 MNT/km	150 MNT/km	0 MNT/km	e × C_el
Diesel fuel cost	0 MNT/km	3,825 MNT/km	5,525 MNT/km	q × C_d
Maintenance / auxiliary	1,100 MNT/km	1,200 MNT/km	1,500 MNT/km	Tires, service, insurance
Total direct cost per km	1,850 MNT/km	5,175 MNT/km	7,025 MNT/km	
500 km cycle total	925,000 MNT	2,587,500 MNT	3,512,500 MNT	C_total × 500 km

Cost savings relative to diesel:

$$\Delta C_{EV-D} = 7{,}025 - 1{,}850 = 5{,}175 \text{ MNT/km} \quad (\text{EV saves } 73.7\% \text{ vs. diesel})$$

$$\Delta C_{H-D} = 7{,}025 - 5{,}175 = 1{,}850 \text{ MNT/km} \quad (\text{Hybrid saves } 26.3\% \text{ vs. diesel})$$

$$\Delta C_{EV-H} = 5{,}175 - 1{,}850 = 3{,}325 \text{ MNT/km} \quad (\text{EV saves } 64.3\% \text{ vs. hybrid})$$

Per-tonne and per-tonne-km costs (Q = 130 t, loaded leg L_loaded = 250 km, transport work W = Q × L_loaded = 32,500 t·km per cycle):

$$C_{EV,per\ tonne} = 925{,}000 / 130 = 7{,}115\ MNT/t$$

$$C_{H,per\ tonne} = 2{,}587{,}500 / 130 = 19{,}904\ MNT/t$$

$$C_{D,per\ tonne} = 3{,}512{,}500 / 130 = 27{,}019\ MNT/t$$

$$C_{EV,t\cdot km} = 925{,}000 / 32{,}500 = 28.5\ MNT/t\cdot km$$

$$C_{H,t\cdot km} = 2{,}587{,}500 / 32{,}500 = 79.6\ MNT/t\cdot km$$

$$C_{D,t\cdot km} = 3{,}512{,}500 / 32{,}500 = 108.1\ MNT/t\cdot km$$

Table 9.3: Per-tonne and per-tonne-km cost comparison

Metric	Pure Electric	Hybrid	Diesel
Total cost per km	1,850 MNT/km	5,175 MNT/km	7,025 MNT/km
500 km cycle cost	925,000 MNT	2,587,500 MNT	3,512,500 MNT
Cost per tonne (130 t)	7,115 MNT/t	19,904 MNT/t	27,019 MNT/t
Cost per t·km	28.5 MNT/t·km	79.6 MNT/t·km	108.1 MNT/t·km

Figure 9.1: Bar chart comparison of per-km operating costs — Pure Electric, Hybrid, and Diesel scenarios

9.3 Throughput and Productivity Analysis

The transport productivity metric (tonnes per hour, t/h) provides a time-normalised performance measure that accounts for cycle duration differences between variants.

Transport productivity is defined as:

$$P_t = Q / T_{cycle} \quad [t/h] \quad \text{(Eq. derived from productivity definition)}$$

Cycle time components for a 250 km one-way route:

$$T_{loaded} = L / v_{loaded} = 250 / 40 = 6.25\ h \quad \text{(loaded outbound at 40 km/h)}$$

$$T_{empty} = L / v_{empty} = 250 / 50 = 5.00\ h \quad \text{(empty return at 50 km/h)}$$

Stop time for the pure electric variant includes loading, unloading, and battery swap/charge time:

$$T_{stop,EV} = 1.00\ h \quad \text{(estimated: loading 0.3h + unloading 0.3h + swap 0.4h)}$$

$$T_{cycle,EV} = 6.25 + 5.00 + 1.00 = 12.25\ h$$

$$P_{t,EV} = 130 / 12.25 = 10.61\ t/h$$

For the hybrid variant, swap time is replaced by diesel refuelling and pre-checks:

$$T_{stop,H} = 0.80\ h \quad \text{(loading + unloading + refuelling; no swap required)}$$

$$T_{cycle,H} = 6.25 + 5.00 + 0.80 = 12.05\ h$$

$$P_{t,H} = 130 / 12.05 = 10.79\ t/h$$

Table 9.4: Throughput and productivity comparison — pure electric vs. hybrid CR130EVT

Parameter	Pure Electric	Hybrid	Notes
One-way route length	250 km	250 km	
Payload per cycle	130 t	130 t	
Loaded trip speed	40 km/h	40 km/h	
Empty return speed	50 km/h	50 km/h	
Loaded travel time	6.25 h	6.25 h	250/40
Empty return time	5.00 h	5.00 h	250/50
Stop time (loading + unloading + energy)	1.00 h	0.80 h	EV includes swap time
Total cycle time	12.25 h	12.05 h	
Throughput (t/h)	10.61 t/h	10.79 t/h	Hybrid marginally higher
Cost per tonne	7,115 MNT/t	19,904 MNT/t	EV 2.8× cheaper per tonne

The hybrid variant achieves marginally higher throughput (10.79 vs. 10.61 t/h, a difference of 1.7%) due to shorter stop time. However, this marginal throughput advantage is far outweighed

by the hybrid's 2.8× higher cost per tonne (19,904 vs. 7,115 MNT/t). The pure electric variant is economically dominant despite the slightly longer stop time.

Daily and annual throughput per vehicle (2 cycles/day, 330 days/year):

$$Q_{day,1\ vehicle} = 130 \times 2 = 260\ t/vehicle/day$$

$$Q_{year,1\ vehicle} = 260 \times 330 = 85{,}800\ t/vehicle/year$$

Fleet of 10 vehicles:

$$Q_{year,fleet,10} = 85{,}800 \times 10 = 858{,}000\ t/year$$

9.4 Fleet-Level Economics and Payback Period

Annual operating cost saving for one vehicle (EV vs. diesel), assuming 2 cycles/day × 330 days:

$$S_{day,EV-D} = (C_{D,cycle} - C_{EV,cycle}) \times n_{cycles} = (3{,}512{,}500 - 925{,}000) \times 2 = 5{,}175{,}000\ MNT/day$$

$$S_{year,EV-D} = 5{,}175{,}000 \times 330 = 1{,}707{,}750{,}000\ MNT/year \approx 1.71\ billion\ MNT/year\ per\ vehicle$$

Similarly, for hybrid vs. diesel:

$$S_{year,H-D} = (925{,}000 \times 2) \times 330 = 610{,}500{,}000\ MNT/year \approx 0.61\ billion\ MNT/year\ per\ vehicle$$

Table 9.5: Annual and fleet-level cost savings versus conventional diesel transport

Savings Metric	EV vs. Diesel	Hybrid vs. Diesel	EV vs. Hybrid
Per km saving	5,175 MNT/km	1,850 MNT/km	3,325 MNT/km
Per 500 km cycle saving	2,587,500 MNT	925,000 MNT	1,662,500 MNT
Per vehicle, per day (2 cycles)	5,175,000 MNT	1,850,000 MNT	3,325,000 MNT
Per vehicle, per year (330 days)	~1.71 billion MNT	~0.61 billion MNT	~1.10 billion MNT
Fleet of 10 vehicles, per year	~17.08 billion MNT	~6.11 billion MNT	~10.97 billion MNT

Payback period for additional EV infrastructure investment (10-vehicle fleet):

If additional capital investment for EV infrastructure (charging stations, spare battery packs, grid connection, BESS) relative to diesel baseline is approximately 12 billion MNT for a 10-vehicle fleet, and the annual saving of EV vs. diesel for 10 vehicles is approximately 17.08 billion MNT:

$$T_{payback} = \Delta Capex / S_{year,fleet} = 12{,}000{,}000{,}000 / 17{,}080{,}000{,}000 \approx 0.70 \text{ years} \approx 8.5 \text{ months}$$

Alternatively, using the more conservative comparison of EV vs. hybrid (recognising that hybrid is an available alternative):

$$T_{payback} = 12{,}000{,}000{,}000 / 10{,}970{,}000{,}000 \approx 1.09 \text{ years} \approx 13 \text{ months}$$

Both figures represent an extremely compelling financial return on infrastructure investment. Even under conservative sensitivity assumptions (higher CAPEX, lower consumption savings), payback within 2–3 years is highly likely.

Figure 9.2: Payback period as a function of additional capital investment (10-vehicle fleet scenario)

This analysis demonstrates that the pure electric CR130EVT presents not merely an environmental case but an economically dominant solution for the TT–GS corridor, with payback periods measured in months rather than years. The primary risk factor is operating cost uncertainty from variable electricity tariffs and diesel prices — sensitivity analysis on these inputs would be a recommended next step in a more detailed feasibility study.

10. DISCUSSION

10.1 Technical Feasibility

The technical analysis confirms that the CR130EVT pure electric variant is suitable for the TT–GS corridor under normal operating conditions. The 783 kWh battery pack provides sufficient energy for a one-way 250 km trip at consumption rates up to 2.7 kWh/km with a 90% usable SOC window, leaving a positive reserve at the destination terminal. This consumption range is achievable on a well-maintained heavy-haul corridor with rolling resistance coefficient $f_r \leq 0.015$ and sustained gradients below approximately 2–3%.

The critical technical boundary condition is at $e \geq 3.0$ kWh/km — the threshold at which the battery reserve becomes marginal and a mid-route support station at km 110–140 becomes operationally necessary. This threshold is most likely to be approached in winter (cold reduces effective battery capacity by 10–25% in lithium-ion cells at temperatures below −10°C) and during periods of sustained headwinds or extended uphill sections. Battery thermal management is therefore a key engineering requirement for the TT–GS deployment, and the CR130EVT's thermal management system must be validated across the full −40°C to +40°C Gobi temperature range before fleet commitment.

The lateral stability analysis identifies operational speed management as a non-negotiable safety requirement. The theoretical static roll threshold of $\theta_{cr} \approx 34.3°$ appears generous, but the effective operational limit — accounting for dynamic effects, cargo asymmetry, and road surface variation — is much lower. Driver training protocols for the dual-trailer combination must emphasise speed reduction on curves, symmetric cargo loading, and avoidance of high side-slope terrain. These are operational management requirements rather than vehicle design limitations.

10.2 Economic Case

The economic case for the pure electric CR130EVT is unusually strong. A per-km operating cost of 1,850 MNT/km versus 7,025 MNT/km for diesel represents a 73.7% cost reduction — a factor of 3.8× improvement. At this level of difference, the economic case does not depend on optimistic assumptions: even if electricity prices doubled or diesel prices fell by 20%, the EV would still be significantly cheaper to operate per km. The robustness of the economic case is a key finding.

The payback period calculation (approximately 0.7–1.1 years for a 10-vehicle fleet) assumes infrastructure costs of 12 billion MNT — a figure that requires validation through actual procurement quotations from infrastructure suppliers. If infrastructure costs are higher (e.g. 24 billion MNT), payback extends to 1.4–2.2 years — still commercially attractive. A full lifecycle cost analysis (LCA) incorporating vehicle purchase price, battery replacement (likely needed at approximately 7–10 years), vehicle residual value, and financing costs would provide a more complete economic picture and is recommended as a follow-on study.

The comparison of the hybrid variant is also instructive. While significantly cheaper to operate than diesel (5,175 vs. 7,025 MNT/km), the hybrid is 2.8× more expensive than the pure electric variant. This cost premium reflects the continued dependence on diesel fuel. As diesel prices trend upward over the vehicle's service life (reflecting global energy transition dynamics), the hybrid's cost disadvantage versus the pure electric will widen. The hybrid is therefore most appropriately positioned as a 2–3 year transitional technology, not a long-term fleet strategy.

10.3 Infrastructure Strategy

The infrastructure strategy proposed in Chapter 8 — S0 terminal at Tavan Tolgoi, optional S1 mid-route, S2 terminal at Gashuun Sukhait — represents a minimal viable infrastructure footprint for initial fleet operations. The recommended energy source configuration (Grid + Solar PV + BESS) is well-suited to the South Gobi's solar resources and the need for operational resilience on a remote corridor.

A key risk for the TT–GS corridor infrastructure is grid connectivity. If the high-voltage grid does not currently extend to both terminal locations, grid extension or alternative generation capacity (solar + diesel generator + BESS hybrid) will be required. This infrastructure question needs to be resolved in parallel with the vehicle procurement process, as grid connection timelines can be long in remote locations.

The staged deployment strategy — beginning with hybrid vehicles while terminal infrastructure is built, then transitioning to pure electric as infrastructure is commissioned — is operationally prudent and financially risk-managed. It allows the operator to build operational experience with the CR130EVT platform and its maintenance requirements before committing the full fleet to pure-electric operation.

10.4 Limitations and Future Work

This study is a preliminary engineering feasibility study with several important limitations:

(1) Route gradient profile: The simulated sinusoidal gradient profile is an approximation. A proper DEM survey of the TT–GS corridor is required before detailed power and range calculations can be considered definitive. Key outputs to validate: the fraction of the route at gradients > 2.5%, the location and severity of the steepest sections, and whether a mid-route support station is necessary for typical (not adverse) operating conditions.

(2) Battery cold-weather performance: No field data are available for the CR130EVT battery system at −40°C Gobi winter conditions. Battery thermal management pre-conditioning time, effective usable capacity at cold temperatures, and cold-start power limitations must be characterised through field testing before winter operations are commissioned.

(3) Infrastructure cost estimation: The 12 billion MNT infrastructure CAPEX figure is a preliminary estimate. Detailed procurement quotations from infrastructure suppliers for charging station equipment, BESS, grid connection, and civil works are needed for a robust economic case.

(4) Full lifecycle cost analysis: This study covers direct operating costs only. Full LCA incorporating vehicle purchase price (which for an EV is typically higher than diesel), battery replacement cost (estimated at 7–10 year intervals), vehicle residual value, and financing cost is required for a comprehensive investment decision.

(5) Regulatory and safety assessment: Mongolia's regulatory framework for high-voltage electric vehicles on public and semi-public roads, operator licensing requirements, emergency response procedures, and import/customs requirements for the CR130EVT platform have not been addressed in this study.

Recommended future work: (a) 1–2 vehicle pilot operation across all four Mongolian seasons to establish real-world kWh/km consumption; (b) detailed DEM survey of the TT–GS corridor; (c) infrastructure cost quotation exercise; (d) full lifecycle cost analysis; (e) regulatory compliance assessment; (f) driver and maintenance training programme development.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

This thesis has presented a preliminary technical and economic feasibility study of the CR130EVT pure electric and hybrid dual-trailer heavy-duty vehicle for deployment on the 250 km Tavan Tolgoi–Gashuun Sukhait coal transport corridor in Mongolia. Six principal conclusions are supported by the analysis:

Conclusion 1 — Technical suitability confirmed for normal conditions. The CR130EVT is a purpose-designed platform with 120–130 t payload capacity and 783 kWh battery (pure electric) suitable for the TT–GS corridor under normal operating conditions. The 29 m overall length and high axle loads require a dedicated heavy-duty corridor with lane widths of 5.0–5.5 m, turning radii of ≥ 25 m, and pavement designed for dynamic axle loads up to approximately 23 t. These are infrastructure design requirements, not vehicle limitations.

Conclusion 2 — Range adequacy established for normal conditions; conditional for adverse conditions. The 783 kWh battery with 90% usable SOC (704.7 kWh) provides sufficient range for a one-way 250 km trip at consumption rates up to 2.7 kWh/km, leaving a positive SOC reserve. At 3.0 kWh/km (adverse conditions), practical range falls to 234.9 km, making a mid-route support station at km 110–140 operationally necessary. The boundary condition for mid-route station requirement is approximately 2.8 kWh/km at 90% usable SOC.

Conclusion 3 — Hybrid variant is a viable transitional solution only. The hybrid CR130EVT with 400 kW diesel engine provides a risk-managed transition path during infrastructure build-out. However, its direct operating cost of 5,175 MNT/km — 2.8× more expensive than the pure electric (1,850 MNT/km) — makes it economically unsuitable as a long-term primary fleet strategy.

Conclusion 4 — Economic case for pure electric is exceptionally strong. At baseline parameters, the pure electric CR130EVT achieves a per-km cost of 1,850 MNT/km versus 7,025 MNT/km for diesel — a 73.7% reduction. Per-tonne-km cost is 28.5 MNT/t·km versus 108.1 MNT/t·km for diesel. Annual savings per vehicle versus diesel are approximately 1.71 billion MNT. Payback on additional infrastructure investment for a 10-vehicle fleet is estimated at 0.7–1.1 years — exceptionally compelling.

Conclusion 5 — Optimal infrastructure configuration identified. The recommended configuration is: terminal battery swap stations at Tavan Tolgoi (S0) and Gashuun Sukhait (S2); optional mid-

route support station at km 110–140 (S1); Grid + Solar PV + BESS energy source configuration; 3–4 MW installed capacity per terminal station.

Conclusion 6 — Lateral stability requires strict operational protocols. The static analysis demonstrates that the CR130EVT has adequate theoretical roll stability margin ($\theta_{cr} \approx 34.3°$), but dynamic effects, cargo asymmetry, and road surface conditions require strict operational limits: ≤ 20–30 km/h on curves with R ≤ 25 m; maximum working side slope 6–8°; symmetric 60 t loading per trailer body; and level unloading areas.

11.2 Recommendations

Based on the findings of this study, the following recommendations are made:

R1: Conduct a 1–2 vehicle pilot operation across all four Mongolian seasons (preferably a full 12-month programme) before committing to full fleet procurement. Measure actual kWh/km at representative seasonal conditions and validate the mid-route station requirement threshold.

R2: Commission a detailed DEM survey of the TT–GS corridor to establish the actual gradient profile and identify any sections where sustained grades above 3% create range or traction challenges for the pure electric variant.

R3: Engage infrastructure suppliers for detailed CAPEX quotations on terminal battery swap stations (equipment, civil works, grid connection, BESS) and an optional mid-route station. Use these quotes to refine the payback period calculation.

R4: Proceed with hybrid CR130EVT deployment during the 12–24 month infrastructure commissioning window. This generates operational experience and revenue while terminal infrastructure is being built.

R5: Transition to pure electric CR130EVT fleet as terminal infrastructure is commissioned. Target pure electric as the primary fleet variant within 3 years of initial deployment.

R6: Implement mandatory driver training in dual-trailer combination stability management: curve speed protocols, symmetric loading procedure, side-slope avoidance, and high-voltage safety awareness.

R7: Undertake a full lifecycle cost analysis (purchase price, battery replacement, residual value, financing) to complement the direct operating cost analysis presented in this thesis and provide a complete investment case.

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APPENDICES

Appendix A: Range Sensitivity Matrix

Table A.1 provides the complete range and trip feasibility matrix for combinations of energy consumption (2.0–3.0 kWh/km in 0.1 kWh/km increments) and usable SOC window (85%, 90%, 95%, 100%). A "Yes" in the support station column indicates the practical range is less than 250 km and a mid-route station is required.

Table A.1: Complete range sensitivity matrix for the CR130EVT pure electric variant (E_bat = 783 kWh)

e (kWh/km)	SOC_use	E_usable (kWh)	R_practical (km)	Energy for 250 km (kWh)	SOC residual (%)	Station needed?
2.0	100%	783.0	391.5	500.0	36.1%	No
2.0	90%	704.7	352.4	500.0	36.1%	No
2.0	85%	665.6	332.8	500.0	36.1%	No
2.5	100%	783.0	313.2	625.0	20.2%	No
2.5	90%	704.7	281.9	625.0	20.2%	No
2.5	85%	665.6	266.2	625.0	20.2%	No
2.7	90%	704.7	261.0	675.0	13.8%	No (marginal)
2.7	85%	665.6	246.5	675.0	13.8%	Yes
2.8	90%	704.7	251.7	700.0	10.6%	No (marginal)
2.8	85%	665.6	237.7	700.0	10.6%	Yes
3.0	100%	783.0	261.0	750.0	4.2%	No (marginal)
3.0	95%	743.9	247.9	750.0	4.2%	Yes
3.0	90%	704.7	234.9	750.0	4.2%	Yes
3.0	85%	665.6	221.9	750.0	4.2%	Yes

Appendix B: Implementation Roadmap

The following phased implementation roadmap is recommended for CR130EVT fleet electrification on the TT–GS corridor:

Phase 1 (Year 1 — Pilot): Deploy 1–2 hybrid CR130EVT vehicles. Measure actual kWh/km across summer and winter seasons. Commence infrastructure procurement. Develop driver and maintenance training programme.

Phase 2 (Years 1–2 — Infrastructure): Construct terminal battery swap stations at S0 (Tavan Tolgoi) and S2 (Gashuun Sukhait). Commission Grid + Solar PV + BESS energy systems. Validate mid-route station requirement from pilot data.

Phase 3 (Year 2 — EV Transition): Deploy first pure electric CR130EVT vehicles using commissioned terminal infrastructure. Begin hybrid-to-EV fleet transition.

Phase 4 (Years 3–5 — Fleet Scale): Expand to full target fleet size. Commission S1 mid-route station if warranted by operational data. Integrate SCADA monitoring, spare battery logistics, and predictive maintenance systems.

Phase 5 (Ongoing — Optimisation): Annual review of charging infrastructure configuration, energy tariff optimisation, and fleet performance benchmarking. Evaluate catenary ERS when corridor utilisation exceeds 20 vehicles.