RESEARCH NOTE

O&M Note 1: Infrastructure maintenance costs for high-speed rail

Cost structure, methodology, and sensitivity to service frequency

Annual cost (MID)	Per route-km	Fixed share	40-year PV
$1.27B	**$1.27M**	**77%**	**$16.9B**
CAD, real	*per year*	*traffic-independent*	*7% real discount*

Worked example: 1,000 km dedicated double-track HSR corridor under Canadian operating conditions at 80 trains per day baseline. Figures are central (MID) estimates; LOW–HIGH envelope $1.08B–$1.52B per year. See §3.

Purpose

This note sets out a defensible methodology for estimating the steady-state infrastructure maintenance cost of a high-speed passenger rail corridor and applies it to a 1,000 km ALTO-scale alignment under Canadian operating conditions. It also reports the sensitivity of unit and total annual cost to service frequency.

The methodology follows the asset-management practice codified in ISO 55001, the regulatory direct-cost frameworks of the European Union (Directive 2012/34/EU and Implementing Regulation 2015/909), and the published operations-and-maintenance cost models of Network Rail (CP7), DB InfraGO (Trassenpreissystem 2026), SNCF Réseau, the Spanish ADIF, and the California High-Speed Rail Authority.

1. Cost structure

Annual infrastructure cost for fixed assets has three streams. They must be modelled separately to avoid double-counting or omission.

- **Maintenance** — routine inspection, preventive maintenance, and corrective maintenance expenditures incurred annually.
- **Renewal** — periodic replacement of components at the end of their useful life. Renewal is capital expenditure but must be annuitised to produce an annual figure comparable to maintenance spend.
- **Operations** — control centre, dispatching, and energy supply management. Reported separately from maintenance and not the focus of this note.

> *Conflation of renewals into the maintenance line is the most common business-case error in long-life infrastructure analysis. A model that omits the renewal annuity typically understates real life-cycle cost by 40 to 60 per cent.*

Sub-components and their typical weights

The European regulatory benchmarking literature gives a stable proportional breakdown of infrastructure maintenance cost:

Component	Share of infrastructure maintenance
Permanent way (track, ballast, sleepers, switches)	40–67%
Signalling and train control	10–35%
Electrification (OCS, traction power)	third major component
Structures, drainage, fencing, stations, comms	balance

Each asset class has a fixed cost component (independent of traffic, driven by patrol, inspection, and age-based degradation) and a variable component (driven by gross-tonne-kilometres and operating speed).

2. Calculation formula

The total annual infrastructure cost for a single asset class on a single segment is given by:

$$c_{a,i} = Q_{a,i} \cdot \left(\alpha_i + \beta_i \cdot \mathrm{GTKM}_a + \gamma_i \cdot v_a^k \cdot N_a\right) \cdot f_{\mathrm{clim}} \cdot f_{\mathrm{mix}} \cdot f_{\mathrm{terr}}$$

where:

$c_{a,i}$	annual maintenance cost for asset i on segment a ($/year)
$Q_{a,i}$	quantity of asset i on segment a (track-km, count of turnouts, etc.)
α_i	fixed maintenance unit cost ($/unit/year), independent of traffic
β_i	variable maintenance coefficient ($/unit per gross-tonne-km)
γ_i, k	speed-fatigue coefficient and exponent (k typically 2–3 above 200 km/h)
$GTKM_a$	annual gross-tonne-km on segment a
N_a	annual train-km on segment a
v_a	design speed on segment a (km/h)
f_clim, f_mix, f_terr	adjustment factors for climate, mixed traffic, terrain

Renewal annuity

Each long-life asset is replaced periodically. The annualised renewal cost is the equivalent annual cost of the renewal capital expenditure spread over the asset's useful life, discounted at the social discount rate. This is the standard capital recovery factor:

$$A_i \;=\; K_i \cdot \frac{r\,(1+r)^{L_i}}{(1+r)^{L_i}-1}$$

where:

- A_i equivalent annual renewal cost for asset i ($/unit/year)
- K_i unit renewal capital expenditure ($/unit)
- L_i useful life of asset i (years)
- r real social discount rate (Canadian Treasury Board reference: 7%, sensitivities 3% and 10%)

The renewal annuity is added to the maintenance figure for each asset to produce a single comparable annual cost.

Corridor and present-value aggregation

Summing across asset classes and corridor segments gives the annual cost for the whole corridor:

$$C_{\text{year}} \;=\; \sum_a \sum_i \left(c_{a,\,i} \;+\; Q_{a,\,i} \cdot A_i \cdot f_{\text{clim}} \cdot f_{\text{mix}} \cdot f_{\text{terr}}\right)$$

Discounting at the social discount rate over the analysis horizon gives the present value of steady-state operation:

$$\text{PV} \;=\; \sum_{t=1}^{T} \frac{C_{\text{year}} \cdot (1+\pi)^{\,t-1}}{(1+r)^{\,t}}$$

where T is the analysis horizon (typically 40 years) and π is the real escalation rate applied to maintenance and renewal cost relative to general inflation.

Asset inventory at minimum disaggregation

The corridor must be decomposed into the following asset classes. Aggregation above this level produces estimates that cannot be audited against international benchmarks.

Asset class	Unit	Traffic sensitivity (β)	Useful life L (years)
Plain line track	track-km	High	25–40 (rail), 30–50 (ballast)
Switches and crossings	turnout	Very high	20–30
Overhead contact system	OCS-km	Moderate	30–50 (wire 20–30)
Signalling (ETCS L2)	signal-km	Low	20–25
Bridges and viaducts	structure-km	Low	80–120 (periodic refurb)
Tunnels	tunnel-km	Moderate	100+ years
Drainage	route-km	Low	30–50
Fencing and right-of-way	boundary-km	Negligible	25–40
Stations	station	Negligible	40–60
Communications (FRMCS)	route-km	Negligible	10–15

Adjustment factors for Canadian conditions

European and Mediterranean North American unit costs understate the cost of Eastern Canadian operation. Three adjustment factors are applied multiplicatively.

Factor	Central value	Rationale
Climate (f_clim)	**1.25**	Freeze-thaw cycles, snow removal on OCS, switch heaters, ballast fouling from de-icing materials. Range 1.15–1.30.
Mixed traffic (f_mix)	**1.00**	Set to 1.00 for dedicated passenger HSR. Range 1.05–1.13 for shared passenger-freight corridors (European Court of Auditors).
Terrain (f_terr)	**1.10**	Frontenac Arch karst, Canadian Shield bedrock transitions, Leda clay drainage. Range 1.00 (open country) to 1.50 (high tunnel/viaduct).
Combined	**1.375**	Multiplicative product applied to all maintenance and renewal annuity figures.

3. Worked example: 1,000 km HSR corridor

The formula is applied to a 1,000 km dedicated double-track high-speed rail corridor operating under Eastern Canadian conditions. Configuration parameters reflect passenger-only HSR designed for a 300 km/h commercial speed.

3.1 Configuration

Parameter	Value
Route length	1,000 km dedicated double-track (2,000 track-km)
Design speed	300 km/h
Baseline service frequency	80 trains per day (both directions combined)
Average trainset gross mass	450 tonnes
Annual train-km (baseline)	29.2 million
Annual gross-tonne-km (baseline)	13.14 billion
Tunnel percentage	6% (60 km)
Bridge / viaduct percentage	12% (120 km)
Stations	7
Climate × terrain × mixed uplift	1.25 × 1.10 × 1.00 = 1.375
Real discount rate	7% (Canadian Treasury Board CBA standard)
Analysis horizon	40 years

3.2 Annual cost breakdown (MID scenario)

Asset-class results for the central scenario, with maintenance and renewal annuity components shown separately. All figures in millions of CAD per year after climate and terrain uplifts.

Asset class	Quantity	Maint $M	Renewal $M	Total $M	Share
Plain line track	2,000 track-km	247.5	265.9	513.4	40.6%
Signalling (ETCS L2)	2,000 km	96.2	165.2	261.4	20.6%

Asset class	Quantity	Maint $M	Renewal $M	Total $M	Share
Overhead contact system	2,000 km	55.0	110.8	165.8	13.1%
Bridges / viaducts	120 km	16.5	59.8	76.3	6.0%
Tunnels	60 km	20.6	35.3	55.9	4.4%
Communications	1,000 km	13.8	34.6	48.4	3.8%
Fencing	2,000 km	8.2	33.2	41.5	3.3%
Stations	7	24.1	14.4	38.5	3.0%
Drainage	1,000 km	6.9	30.9	37.8	3.0%
Switches and crossings	220	7.6	19.5	27.0	2.1%
TOTAL		**496.4**	**769.7**	**1,266.1**	**100.0%**

Composition: maintenance 49.2%, renewal annuity 50.8%. The almost-even split is consistent with steady-state asset management practice. Any business case showing renewal below 30 per cent of M+R implicitly assumes the system will be handed back degraded.

3.3 Sensitivity envelope

The LOW–MID–HIGH envelope reflects the uncertainty band on unit maintenance costs across published international comparables.

Scenario	Maintenance	Renewal	Total / year	$/route-km	40-yr PV
LOW	$310.8M	$769.7M	$1,080M	$1.08M	$14.4B
MID	$496.4M	$769.7M	**$1,266M**	**$1.27M**	**$16.9B**
HIGH	$746.6M	$769.7M	$1,516M	$1.52M	$20.2B

3.4 Cross-check against international benchmarks

Stripping the 1.375 combined uplift leaves an underlying figure of approximately $920k per route-km per year. This is at the top end of the European HSR range, which is the appropriate position given Canadian labour rates and the absence of a domestic HSR supply chain.

System	M+R ($/route-km/yr)
Spanish ADIF (HSR network)	~$300–400k
California HSRA (2020 Plan, infra only)	~$600–800k
Network Rail HS1	~$700–900k
SNCF Réseau LGV network	~$800–950k
This model, underlying (uplift stripped)	*$920k*
This model, MID (with Canadian uplift)	**$1.27M**

4. Sensitivity to service frequency

The total annual cost can be expressed as the sum of a fixed component (traffic-independent) and a variable component that scales linearly with service frequency:

$$C_{\text{year}}(N) = C_{\text{fixed}} + c_{\text{var}} \cdot N$$

where:

N	service frequency (trains per day, both directions combined)
C_fixed	traffic-independent annual cost (patrol, inspection, age-based renewals)
c_var	variable cost per train-per-day per year

Decomposing each asset class using fixed-fraction coefficients from the CATRIN study, UK VTISM analysis, and IRG-Rail methodologies gives, at the 80 trains-per-day baseline:

- **C_fixed = $980M per year.** 77 per cent of the MID total. Incurred regardless of service frequency.
- **c_var = $3.6M per year per train-per-day.** Scales linearly with traffic volume.

4.1 Sensitivity curves

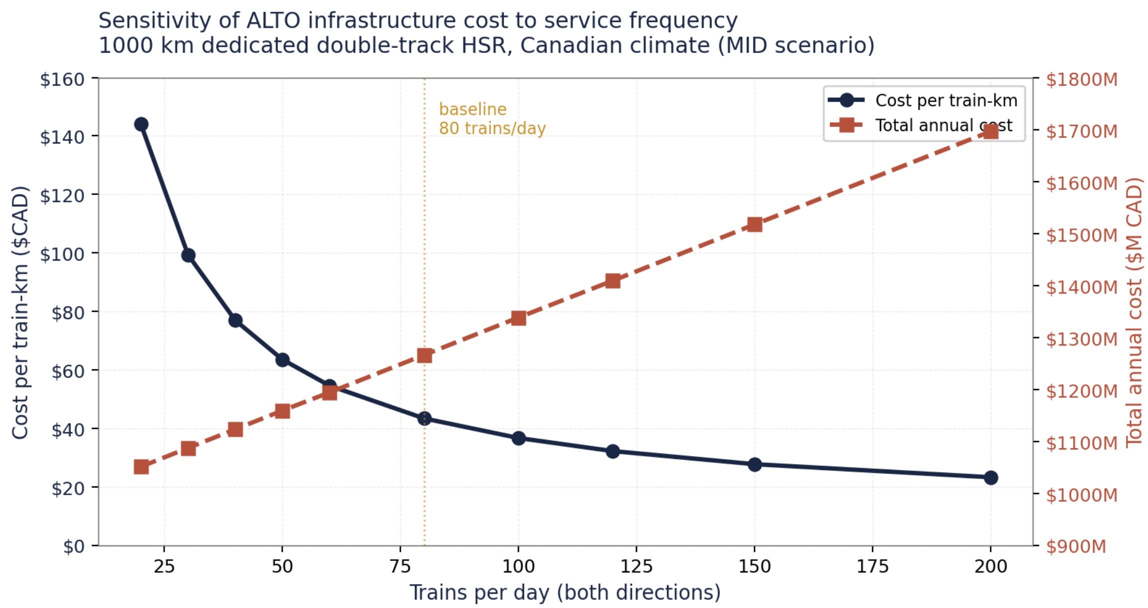

Figure 1. Sensitivity of unit and total annual infrastructure cost to service frequency. Total cost rises modestly with frequency; unit cost falls hyperbolically.

4.2 Sensitivity table

Trains/day	Total $M/yr	$/train-km	$/1000 GTKM
20	1,051	144.01	320.0
30	1,087	99.28	220.6
40	1,123	76.91	170.9
50	1,159	63.49	141.1
60	1,194	54.54	121.2
80	**1,266**	**43.36**	**96.4**
100	1,338	36.65	81.4
120	1,409	32.17	71.5
150	1,517	27.70	61.6
200	1,696	23.23	51.6

Baseline 80 trains/day row highlighted.

4.3 Two findings

The sensitivity displays an asymmetric structure that is the central economic fact about high-speed rail infrastructure cost.

1. **Total annual cost is nearly inelastic to traffic.** Quadrupling frequency from 20 to 200 trains per day raises annual cost from $1.05B to $1.70B — only 61 per cent for a tenfold increase in service. The elasticity of total cost to trains per day between 40 and 80 trains is +0.128. A 10 per cent increase in trains per day raises total cost by 1.3 per cent.
2. **Unit cost falls hyperbolically.** Each fixed-cost line item is spread across more train movements as frequency rises. Cost per train-km halves roughly every time frequency doubles. The elasticity of $/train-km to trains per day between 40 and 80 trains is −0.436. At the 80 trains-per-day baseline, infrastructure cost is $43 per train-km; at 200 trains per day it falls to $23; below 40 trains per day it rises sharply.

> *"The infrastructure cost a high-speed corridor must recover is set by the asset base, not by the traffic. Whether the corridor is built or not is the economic decision; how many trains run on it once built is largely a rounding error in the cost line."*

5. Implications and diagnostic framework

5.1 Implications for ALTO's economic case

The trains-per-day sensitivity is where ALTO's economic case lives or dies. Three observations follow directly from the results above.

1. **Per-train-km cost is structurally high.** Across the plausible operating frequency range (40 to 100 trains per day), unit infrastructure cost lies between $37 and $77 per train-km. The German freight benchmark for 2027 is approximately $8 per train-km; SNCF LGV sits in the $15–25 range. ALTO's per-train-km infrastructure cost is three to ten times higher than mature European peers across that frequency range.
2. **Cost recovery requires very high frequency or perpetual subsidy.** At the 80 trains-per-day MID scenario, fixed infrastructure cost recovery is approximately $1.27 billion per year. Either the operator pays far higher track access charges than European peers, the taxpayer subsidises infrastructure perpetually, or the corridor operates at far higher traffic density than 80 trains per day to spread fixed cost — which the proponent's own ridership forecasts must support.
3. **The renewal annuity does not get easier with traffic.** The $980M fixed-cost floor persists across the entire range. No ridership scenario reduces it. This is what makes shared-corridor approaches such as the High Performance Rail (HPR) framework structurally more cost-defensible: a corridor that already exists and is being maintained for

some traffic does not add a new $980M-per-year fixed cost merely because passenger services are added to it.

5.2 Diagnostic framework for proponent cost claims

When reviewing any HSR operations-and-maintenance cost figure, the following questions should be applied. Failure to disclose any of them indicates the figure is not auditable.

1. **What service frequency is assumed?** Without an explicit trains-per-day figure, a dollar total is meaningless.
2. **What is the implied cost per train-km?** Divide claimed annual O&M by claimed annual train-km. If the result is below $30 per train-km at fewer than 100 trains per day, either the cost is understated or the frequency is overstated.
3. **What is the fixed/variable split?** Any figure that does not disclose this is hiding the sensitivity. Real-world ratios are 70 to 80 per cent fixed at typical traffic levels.
4. **Is maintenance separated from renewal?** Bundled figures understate the second by definition. The two should be approximately equal at steady state. Renewal reported as less than 30 per cent of M+R indicates assumed asset degradation.
5. **What is the maintenance-of-way facility density?** Industry benchmark is approximately one MOI facility per 240 km. Fewer indicates under-provisioning.
6. **What climate and terrain uplift is applied?** European or Mediterranean unit costs without a Canadian climate uplift of at least 1.15 understate cost.
7. **Has a break-even frequency analysis been published?** Ask for the unit-cost curve from 20 to 200 trains per day. The shape of that curve, not the headline number, indicates whether the business case is robust or built on a single ridership assumption.

6. Caveats and limitations

- The model is steady-state. Ramp-up years (the first five to ten years of operation) typically have lower renewal spend and higher early-life defect costs.
- Unit costs are central estimates from international comparables. Firm Canadian unit costs would require Access to Information disclosure on VIA/CN engineering rate cards, Metrolinx project cost data, or the proponent’s own assumptions if obtainable.
- The model assumes a uniform corridor. Real costs vary by segment: urban approaches and tunnelled sections typically two to three times the average; open-country sections below average.
- No allowance is made for catastrophic events (flooding, ice storms, derailments). Historical experience in cold-climate jurisdictions adds five to ten per cent to long-run cost.

- The model does not include rolling stock maintenance, energy, dispatching, station operations, security, or general and administrative costs. These typically add 30 to 50 per cent to the infrastructure figures.
- The variable-cost decomposition uses fixed-fraction coefficients from the European literature; Canadian-specific elasticities are not available in the public domain and would require infrastructure-manager data to refine.

Sources

Council of European Union, Directive 2012/34/EU and Implementing Regulation (EU) 2015/909. CATRIN (Cost Allocation of Transport Infrastructure cost), Deliverable 8: Rail Cost Allocation for Europe. IRG-Rail, Overview of the Implementation of Direct Costs in Europe. Office of Rail and Road (UK), Network Rail Access Charging Framework, CP7 (2024–29). Bundesnetzagentur, Trassenpreissystem 2026 (December 2025). European Court of Auditors, Special Report 19/2018: A European high-speed rail network. California High-Speed Rail Authority, 2020 Business Plan Operations and Maintenance Cost Model. Federal Railroad Administration, Rail Planner's Handbook: Technical Monograph on Mixed High-Speed Passenger and Freight Rail Corridors. International Union of Railways, Asset Management Working Group guidance on ISO 55001. Spanish ADIF, infrastructure management financial reporting. Treasury Board of Canada Secretariat, Canadian Cost-Benefit Analysis Guide.