

Article

Sustainable Performance-Cost-GWP Pareto Optimization of RAP-Modified High-Performance Asphalt Pavements: An Alberta Design Case Study

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Abstract

Road construction contributes to embodied carbon in infrastructure, with asphalt-bound layers often dominating construction-stage greenhouse gas emissions in flexible pavements. Reclaimed asphalt pavement (RAP) and high-modulus asphalt concrete can reduce virgin material demand and improve structural efficiency, but their sustainability benefit depends on maintaining equivalent pavement performance. This study develops a climate-informed, mechanistic, environmental, and economic Pareto optimization framework for RAP-modified high-performance asphalt concrete (RAP-HPAC) pavement sections in Alberta. The framework couples fitted dynamic modulus master curves, monthly pavement temperature inputs, ALVA layered elastic analysis, Asphalt Institute fatigue and rutting criteria, A1–A5 global warming potential (GWP), and Alberta 2026 installed unit-price cost data. The RAP-HPAC mixture contains 50% RAP and was designed through a balanced mix design to target approximately 80% effective RAP binder activation. Three traffic classes were evaluated: 731, 1300, and 5426 ESAL/day/direction, each with 2% annual compound growth over a 20-year design period. Relative to independently optimized conventional HMA controls, Pareto-selected RAP-HPAC sections reduced P50 construction-stage GWP by approximately 19–30% and first cost by approximately 6–11% at a conservative 0.90× RAP-HPAC cost multiplier. The results show that RAP-HPAC is most beneficial when used as a structural-bound base that replaces conventional asphalt-bound capacity while preserving sufficient granular support. The framework provides a reproducible design-stage approach for comparing recycled high-modulus asphalt mixtures using performance, carbon, and cost criteria simultaneously.

Keywords: reclaimed asphalt pavement; high-performance asphalt concrete; layered elastic analysis; ALVA; life-cycle assessment; A1–A5 GWP; pavement design optimization; Alberta; construction cost

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1. Introduction

Transportation infrastructure represents one of the largest embodied-carbon categories in civil construction. Flexible pavements, in particular, rely on bitumen-bound asphalt layers that carry substantial cradle-to-gate greenhouse gas intensities owing to the energy demands of crude oil refining, asphalt plant heating, and regional material transport. At a network scale, even modest reductions in asphalt layer thickness or emission intensity

per ton of material translate into meaningful reductions in construction-stage GWP. Recognition of this relationship has driven increasing interest in two distinct but related directions: the use of reclaimed asphalt pavement to reduce virgin material demand and the use of high-modulus asphalt mixes to achieve structural efficiency through higher layer stiffness.

Reclaimed asphalt pavement (RAP) contains aged binder and aggregate that retain most of their structural value when properly reactivated. At RAP contents below roughly 25%, conventional plants can incorporate RAP with few modifications to the mix design or quality control. At higher RAP contents—commonly designated as high-RAP mixes when RAP exceeds 30% by mass—activation of the aged binder requires rejuvenators, warm-mix additives, soft-binder blends, or plant-heating adjustments, and the performance characteristics of the resulting mixture become less predictable without mixture-level testing. The environmental incentive for high-RAP mixes is substantial: substituting reclaimed aggregate and binder for virgin materials reduces cradle-to-gate GWP roughly in proportion to the fraction of virgin asphalt displaced. However, the environmental benefit is only realized if the high-RAP mixture performs adequately in the pavement structure and does not require rehabilitative overlays earlier than a conventional section would.

High-modulus asphalt concretes—developed originally in France as *enrobé à module élevé* (EME) and later adapted in various cold-region and North American forms—achieve structural efficiency through dense aggregate packing, relatively stiff binders, and high binder content. The result is a layer modulus substantially above that of conventional HMA, which reduces tensile strain at the base of the asphalt-bound stack and, in principle, allows thinner pavement structures under equivalent traffic demand. Reported thickness reductions in the high-modulus asphalt literature commonly fall in the range of 15 to 30%, though the magnitude depends on climate, traffic, and the governing distress mode. Applying this concept in cold climates requires care because very stiff binders can increase low-temperature cracking susceptibility; the high-performance asphalt concrete (HPAC) approach addresses this by retaining the structural intent of high-modulus design while using mixture-design tools—binder modification, fiber reinforcement, warm-mix additives, and binder activation management—to maintain cold-region durability.

A logical extension of both concepts is to combine high RAP content with high-modulus structural intent: producing a bound layer that reduces virgin material demand, reactivates aged binder, and achieves the high stiffness needed for structural efficiency in the layer stack. This RAP-HPAC concept has been demonstrated at the mixture level, but its integration into a complete mechanistic pavement design workflow—one that enforces performance equivalence across fatigue and rutting criteria simultaneously, propagates environmental and cost impacts, and compares alternatives on a common structural basis—has not been widely presented in the published literature. That integration is the contribution of the present paper.

The cold-region Alberta context matters for several reasons. First, Edmonton's pronounced seasonal temperature variation produces a dynamic modulus range spanning nearly an order of magnitude over the course of a year. A design that ignores monthly climate states will either underperform in summer or overperform in winter, both of which distort the structural optimization. Second, Alberta highway traffic includes a range of conditions from upper-highway demands of a few hundred ESAL/day/direction to observed heavy-corridor ESAL values above 5000, and the optimal RAP-HPAC cross-section is not independent of traffic class. Third, Alberta Transportation and Economic Corridors publishes unit price average data from historical tender bids, providing an auditable cost basis for the economic comparison. Fourth, the Alberta Pavement Design Manual describes staged construction practice that is directly relevant to how thick asphalt-bound sections are delivered in practice.

The gap this paper addresses is the frequent disconnection among three elements that must be evaluated together: structural performance, construction-stage environmental impact, and first cost. Studies of RAP mixtures often terminate at mixture performance or cradle-to-gate impact without linking to a mechanistic structural optimization. High-modulus pavement studies often focus on thickness reduction without propagating GWP

or cost implications. Life-cycle assessment studies of pavements often use fixed section geometries without optimizing them mechanistically. When the three elements are treated separately, the apparent environmental benefit of RAP or high-modulus layers may be overstated if the structural design is not properly constrained, or understated if the design is not optimized for the new material's properties.

This paper addresses the gap by coupling measured dynamic modulus data, climate-informed ALVA layered elastic batch analysis, Asphalt Institute fatigue and rutting damage criteria, a construction-stage A1–A5 GWP model with P10/P50/P90 uncertainty bounds, and Alberta 2026 installed unit-price cost modeling into a Pareto selection framework. The result is a set of independently optimized control and RAP-HPAC sections for each of three Alberta-representative traffic classes, compared on a common structural, environmental, and economic basis.

2. Literature Review

2.1. RAP and High-RAP Asphalt Mixtures

The environmental rationale for RAP use in asphalt pavements has been well established over the past two decades. Reclaimed material displaces both virgin aggregate and virgin binder, and because asphalt binder carries a substantially higher carbon intensity than aggregate, even modest RAP contents produce measurable reductions in cradle-to-gate GWP. At lower RAP contents, the structural and durability impacts are generally small, and RAP is broadly accepted in agency specifications in North America and Europe. At high RAP contents (typically defined as above 25–30% by mass of total mixture), the degree of binder activation becomes a critical variable. The reclaimed binder is partially blended with the new binder depending on mixing temperature, RAP particle size, and blend mechanics; incomplete activation leaves portions of the reclaimed binder contributing less to mixture performance than the virgin binder would [1,2].

Balanced mix design (BMD) approaches attempt to address high-RAP performance risks by targeting performance thresholds directly rather than relying solely on volumetric targets. High RAP contents can reduce virgin binder and aggregate demand, but they also introduce aged binder, blending uncertainty, stiffness increase, and cracking-risk concerns. Recent reviews of waste-material use in road upper layers similarly note that recycled-material benefits depend on performance verification, material availability, environmental accounting, and implementation constraints rather than on material substitution alone [3]. Alberta's RAP amendment to Specification 3.50 also reflects this caution: RAP/virgin aggregate blends greater than 10/90 require binder grade adjustment and/or RAP/virgin binder rheology testing, and the specified RAP additive categories are bracketed up to the >20% to ≤30% range [4]. The mixture evaluated here therefore should not be interpreted as an ordinary high-RAP substitution: it is a 50% RAP mixture designed through BMD to achieve approximately 80% effective RAP binder activation while meeting a high-modulus requirement. This material basis is important because the study evaluates a measured, performance-screened RAP-HPAC mixture rather than extrapolating from typical 25–35% RAP mixtures without corresponding dynamic modulus and LCA data.

2.2. High-Modulus Asphalt Concrete and Cold-Region HPAC

High-modulus asphalt concretes were developed in France as part of the EME (enrobé à module élevé) specification [5]. The structural argument is straightforward: a stiffer asphalt-bound layer distributes load over a larger area, reducing tensile strain at the bottom of the bound stack and compressive strain at the top of the subgrade. Leiva-Villacorta, Taylor, and Willis (2017) reviewed international high-modulus asphalt applications and reported thickness reductions commonly in the range of 15 to 30% relative to conventional asphalt bases, depending on climate, traffic, and subgrade conditions [6]. Guyot (2021) summarized French practice and noted that EME layers are typically placed in the base

position, below a conventional surface course, precisely because their stiffness advantage is most effective at depth [7].

Applying high-modulus concepts in cold regions introduces additional complexity because low-temperature cracking risk increases with binder stiffness. Pszczola, Rys, and Jaczewski (2022) reviewed this tension and noted that the structural efficiency of high-modulus mixes can be negated in cold climates if thermal cracking is not controlled [8]. The HPAC concept responds to this problem by retaining the structural intent of high-modulus design while selecting binders and mix parameters that maintain adequate low-temperature performance [9]. Ahmed et al. (2024) [10] demonstrated that fiber reinforcement and warm-mix additives can extend the low-temperature performance range of high-RAP, high-modulus mixes, and Enoyoze et al. (2025) reported similar findings for cold-region Alberta conditions [11]. In the present study, RAP-HPAC is treated as a bound structural base layer—placed below a conventional HMA surface course—rather than as a direct substitute for the surface layer.

2.3. Dynamic Modulus as Structural Design Input

The shift from empirical to mechanistic-empirical pavement design in North America has placed dynamic modulus at the center of asphalt material characterization. Dynamic modulus $|E^*|$ relates stress amplitude to strain amplitude under sinusoidal loading at a given temperature and frequency, and it is the primary input to layered elastic and viscoelastic pavement response models used in mechanistic-empirical design. At the mixture level, dynamic modulus is also a performance indicator: high-RAP mixes generally exhibit higher modulus than conventional HMA at intermediate and elevated temperatures, which is structurally advantageous for rutting resistance, while their low-temperature modulus behavior depends more on the binder activation level and rejuvenator selection.

Dynamic modulus testing characterizes asphalt mixtures as linear viscoelastic materials under sinusoidal loading, where the complex modulus E^* includes both storage and loss components, and the design input commonly used in layered response analysis is its magnitude $|E^*|$. In the present workflow, the measured dynamic modulus data for the control HMA and RAP-HPAC were represented as temperature-frequency master-curve inputs, shifted to the monthly layer temperatures, and evaluated at the design loading frequency of 15 Hz. The resulting $|E^*(T,f)|$ values were then used as equivalent elastic moduli for each monthly ALVA response state. The 10 Hz value reported for RAP-HPAC is therefore a mixture-design target used to confirm high-modulus behavior, whereas the ALVA response calculations use the modulus corresponding to the analysis frequency and monthly pavement temperature.

2.4. Mechanistic-Empirical Pavement Design and Layered Elastic Analysis

Layered elastic theory, originating with Burmister in 1945, provides the analytical foundation for most mechanistic pavement response tools. For a given set of layer thicknesses, moduli, and Poisson's ratios, and for a known surface load, layered elastic theory yields closed-form or numerically integrated solutions for stress, strain, and deflection at any point in the pavement structure. The critical responses for asphalt fatigue design are the maximum horizontal tensile strain at the bottom of the asphalt-bound layers, and for subgrade rutting design, the maximum vertical compressive strain at the top of the subgrade [12].

Programs such as KenPave implement layered elastic solutions and are widely used for individual design checks; however, the present workflow required a fully scriptable batch environment for thousands of candidate sections [13]. The Adaptive Layered Viscoelastic Analysis (ALVA) package (version 1.3.0.0), developed by Skar and Andersen in 2020 and published as open-source software through the Journal of Open Source Software, provides a scriptable, batch-executable environment for layered elastic and viscoelastic pavement response. ALVA allows full programmatic control over layer geometry, material properties, load configuration, response coordinates, and numerical integration parameters, and the original ALVA publication reports validation against analytical half-

space solutions and the ELLEA, ELLVA, and GAMES benchmark programs [14,15]. The scriptability of ALVA is important to the present study's design sweep: an enumeration of HMA thickness, RAP-HPAC thickness, GBC thickness, and monthly climate state across three traffic classes produces several thousand candidate sections per pavement family, a scale for which a transparent scripted workflow is more reproducible than manual case-by-case entry.

The present study uses ALVA's layered elastic response mode. Seasonal asphalt behavior is represented through measured temperature-frequency dynamic modulus values assigned month by month, rather than through a moving-load viscoelastic simulation. This is a deliberate scope choice: a full Pavement ME implementation would require a complete Level 1 input package, local calibration, and additional assumptions for distress evolution, aging, and project-specific reliability that are beyond the measured design-stage dataset used here. The ALVA layered elastic approach provides a transparent, reproducible structural response calculation at a scale appropriate for design-stage screening.

2.5. Pavement LCA: Boundaries, EPDs, and Construction-Stage Modules

Life-cycle assessment of pavements follows ISO 14040/14044 [16,17] and is increasingly structured according to EN 15978 [18] module designations. For a construction-stage boundary, modules A1–A3 cover raw material supply, transport to the plant, and plant production; module A4 covers transport from plant to site; and module A5 covers construction installation, including equipment fuel and any site waste. The A1–A5 boundary, sometimes termed cradle-to-handover or upfront carbon, is the scope most commonly required by green building certification schemes and owner-specified EPD requirements for embodied carbon reduction in infrastructure.

Environmental product declarations (EPDs) for asphalt mixtures report cradle-to-gate GWP (modules A1–A3) based on plant-specific or industry-average inventory data. Canadian asphalt EPDs have become more available in recent years, though with meaningful variability across facilities and supply regions. de Bortoli, Rahimy, and Levasseur (2024) published a systematic review of bitumen LCA with new Canadian models, reporting that the carbon footprint of Canadian asphalt binders spans a wide range depending on crude source, processing route, and geographic context, and that transportation impacts within Canada add further regional variability [19]. This variability motivates the use of P10/P50/P90 uncertainty bounds in the present study rather than single-point GWP estimates.

Module A4 transport GWP depends on haul distance, vehicle type, load factor, road grade, and fuel type. Generic ton-kilometer emission factors abstract away these physics, but for a material like asphalt-heavy, requiring heated transport in some conditions and hauled over distances that vary significantly by facility location—a physics-based truck model captures the relevant sensitivity more faithfully. Module A5 construction equipment GWP covers paving trains, rollers, water trucks, and emulsion distributors; emission factors are typically derived from equipment productivity rates and diesel fuel consumption per unit area paved.

2.6. Construction Cost and LCCA for Pavement Screening

Life-cycle cost analysis (LCCA) for pavements is described in FHWA (1998, 2002) guidance and in NCHRP Report 703 [20–22]. The fundamental approach is to multiply construction quantities by unit prices from historical bid data and to discount future maintenance and rehabilitation events to a common base year. For design-stage screening comparisons—where the goal is to distinguish which alternative offers better value, not to produce a contractor bid estimate—AACE International's Class 4 cost estimation guidance is appropriate: it acknowledges uncertainty in the ± 30 to $\pm 50\%$ range and is specifically intended for feasibility and alternative screening applications [23]. AASHTO's pavement design guidance identifies agency historical bid data as the appropriate source of unit costs for this purpose [24].

For Alberta, Transportation and Economic Corridors publishes Unit Price Averages (UPAs) compiled from submitted tender bids, providing a publicly available, quantity-weighted basis for conventional HMA and granular base course pricing. RAP-HPAC does not yet appear as an independent Alberta bid item, which makes a parametric multiplier approach appropriate: the multiplier spans the range of outcomes reported in the RAP-cost literature, from modest savings when virgin binder and aggregate costs dominate to near-parity when rejuvenator, processing, and quality-control costs are substantial [1,2].

2.7. Multi-Criteria and Pareto Selection in Pavement Design

Multi-criteria decision frameworks in pavement design typically involve at least two competing objectives: structural performance and cost. Adding environmental impact as a third dimension creates a three-objective problem that does not have a unique optimal solution but rather a Pareto front of non-dominated alternatives. The approach adopted here—filtering structurally feasible candidates by CrDR, then selecting the Pareto-optimal candidate minimizing GWP, cost, material thickness, and distance from the CrDR = 1.0 efficiency limit—applies multi-criteria Pareto logic specifically to a batch structural design sweep rather than a post hoc comparison of pre-specified alternatives [25–27].

3. Materials and Experimental Inputs

Two pavement material families were characterized for this study. The control family represents conventional hot-mix asphalt placed over a granular base course—the standard structural approach on Alberta highways. The RAP-HPAC family represents a bound structural base layer composed of 50% reclaimed asphalt pavement (with 80% RAP binder active) combined with a binder system selected to achieve high-modulus performance while maintaining cold-region durability.

The RAP-HPAC mixture was developed through an iterative balanced mix design process targeting high-modulus performance. The mixture contained 50% RAP and was formulated to achieve approximately 80% effective RAP binder activation. The key mixture-level requirement was a dynamic modulus of approximately 14,000 MPa at 10 °C and 10 Hz, consistent with high-modulus asphalt specifications. This target provided the stiffness basis for evaluating RAP-HPAC as a bound base layer intended to reduce tensile strain at the base of the asphalt-bound stack relative to a conventional HMA layer.

Beyond dynamic modulus, the RAP-HPAC mixture was characterized using four-point bending (4PB) fatigue testing as part of the mixture validation program. Table 1 summarizes the principal material characteristics and measured inputs used for the conventional HMA and RAP-HPAC mixtures. Those data support the material characterization but were not used as the design transfer function because the objective was to compare conventional and RAP-HPAC sections under a common agency-style structural criterion. The design equations are therefore the Asphalt Institute fatigue and rutting transfer functions described in Section 4.4.

Table 1. Material and laboratory inputs used in the design framework.

Input	Control HMA	RAP-HPAC	Role in Framework
RAP content	0%	50% RAP by mass; approximately 80% effective RAP binder activation	Defines recycled mixture basis and binder-activation target
Layer position in stack	Surface and structural	Bound base below thin HMA surface	Structural layer in optimized sections
Dynamic modulus basis	Conventional measured mix	~14,000 MPa at 10 °C, 10 Hz	High-modulus criterion; ALVA layer input
Dynamic modulus method	Monthly $E^*(T,f)$ from fitted master-curve input	Monthly $E^*(T,f)$ from fitted master-curve input	Climate-dependent stiffness per layer

4PB fatigue	Characterized	Characterized	Mixture validation, not the design equation
Design transfer functions	Asphalt Institute (1991) [28]	Asphalt Institute (1991) [28]	Common structural criteria for both families
A1–A3 GWP factor (P50)	75.54 kg CO _{2e} /t	49.70 kg CO _{2e} /t	Material production emission intensity
Density	2.26 t/m ³	2.39 t/m ³	Layer mass calculation

Figure 1 presents the measured temperature-dependent dynamic modulus for both the control HMA and the RAP-HPAC across the monthly Edmonton pavement temperature range.

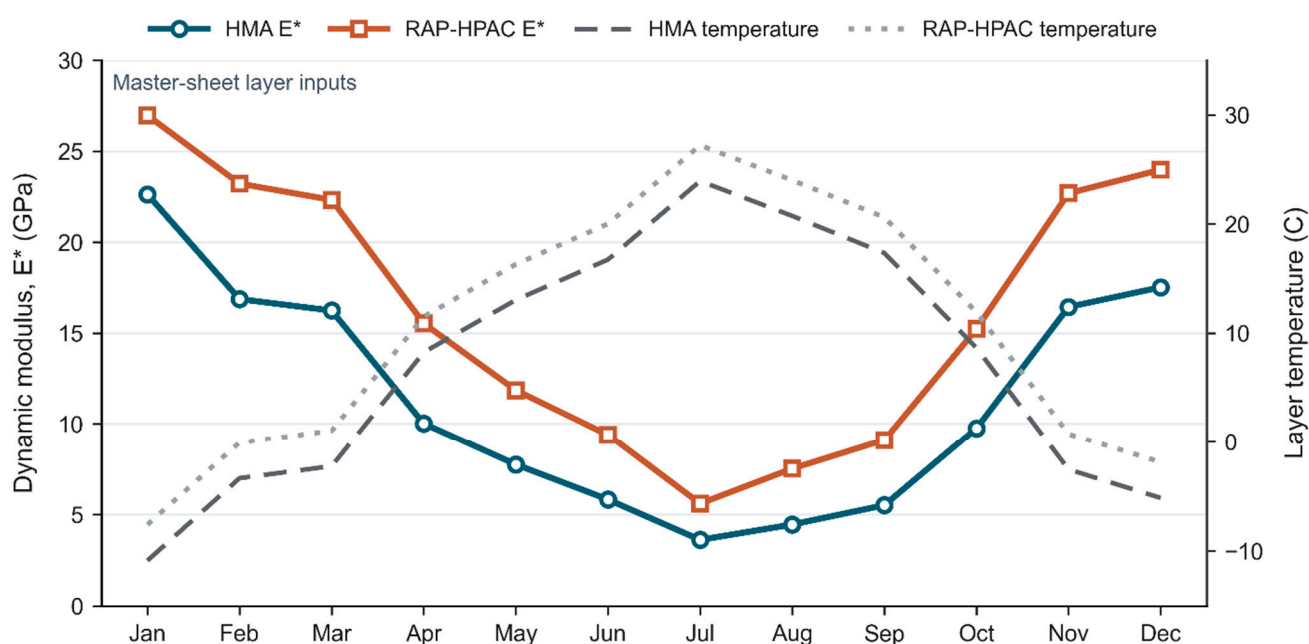


Figure 1. Monthly temperature-dependent dynamic modulus for the control HMA and RAP-HPAC layers used in ALVA. Layer temperatures were estimated from Edmonton monthly mean air temperatures using the SHRP/LTPP depth-temperature relationship applied at each layer midpoint. The RAP-HPAC layer is represented by its own depth-adjusted temperature and fitted $E^*(T,f)$ input.

4. Methods

4.1. Framework Overview and Functional Unit

The analytical framework integrates five coupled components: climate-informed layered elastic structural analysis, a traffic accumulation model, Asphalt Institute damage criteria, an A1–A5 GWP model, and a construction cost model. Figure 2 presents the framework workflow. The functional unit is one lane-kilometer of new pavement with a 3.5 m lane width. All GWP results are reported in kg CO_{2e} per lane-km; all cost results are reported in 2026 Canadian dollars per lane-km.

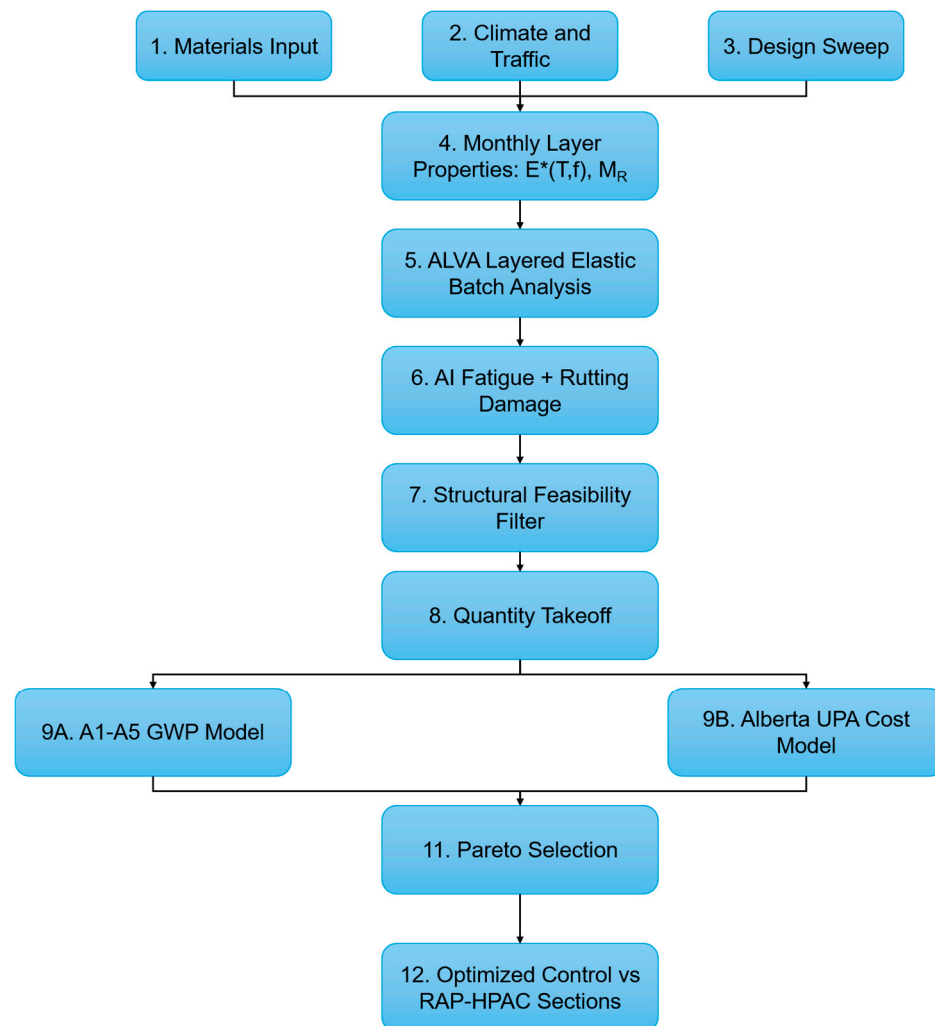


Figure 2. Climate-informed ME-LCA-cost Pareto optimization workflow linking material inputs, ALVA structural response, A1–A5 GWP, construction cost, and feasible section selection.

Two pavement families were optimized independently for each traffic class:

- Control: HMA surface and structural layer over granular base course (GBC); no bound intermediate layer.
- RAP-HPAC: Thin HMA surface course over a RAP-HPAC bound base, over GBC.

Optimizing both families independently for each traffic class avoids the bias of comparing an optimized alternative against an unadjusted reference. Each control section is the Pareto-optimal conventional section for its traffic class; each RAP-HPAC section is the Pareto-optimal recycled-material section for the same traffic class.

4.2. Climate-Dependent Modulus Assignment

Monthly Edmonton mean air temperatures were converted to asphalt-layer temperatures using the SHRP/LTPP seasonal asphalt concrete pavement temperature relationship used in the project workbook and developed from Canadian pavement-temperature data [29]. For month m and layer midpoint depth z in mm, the pavement temperature was calculated as $T_p(m,z) = T_{air}(m) + 0.051z - 0.000063z^2$, where temperatures are in degrees Celsius. This depth-adjusted monthly pavement temperature was evaluated separately at the HMA and RAP-HPAC layer midpoint depths. The resulting layer temperatures were then used with the fitted dynamic modulus master curves to assign monthly $E^*(T,f)$ values for ALVA.

For each month, the resulting layer temperature and a representative loading frequency of 15 Hz were used to evaluate the temperature-frequency dynamic modulus

master curves for the HMA and RAP-HPAC layers. The resulting monthly moduli were passed to ALVA for structural response calculation. The 15 Hz analysis frequency differs from the 10 Hz mixture-design reporting point because the former represents the design loading condition, while the latter is the high-modulus mixture acceptance reference.

4.3. ALVA Layered Elastic Response

Structural response was computed using ALVA [13] in its layered elastic mode. ALVA is capable of layered viscoelastic analysis; however, the present study uses its layered elastic response mode because the objective is a design-stage batch sweep rather than a full moving-load viscoelastic simulation. The available measured data support temperature-frequency-dependent material characterization through $|E^*(T,f)|$, but not a fully calibrated viscoelastic structural-response model with relaxation spectra, load-history representation, aging evolution, and local distress calibration. ALVA was selected because it is open, scriptable, and has published benchmark comparisons against established layered response programs, including KENLAYER, BISAR, and GAMES, in the ALVA software documentation and validation examples [13,14]. The previously reported KenPave-era strain ranges from the earlier project manuscript which was used only as historical context for the original design basis; the present revision does not claim a new KenPave rerun or a project-specific KenPave calibration.

To make the response-engine evidence explicit, Table 2 reproduces the key R1–R8 layered elastic benchmark comparisons reported in the ALVA repository documentation for BISAR, KENLAYER, GAMES, and ALVA [13,14]. R1 and R5 are vertical stress responses; R2 and R6 are horizontal tensile strains at the bottom of layer 1; R3 and R7 are vertical strains at the top of layer 2; and R4 and R8 are vertical strains at the top of layer 3. The table is not presented as a new project-specific KenPave rerun; it documents the published benchmark basis for the open response engine used in the batch sweep.

Table 2. Published ALVA layered elastic benchmark comparison for key pavement response points [14].

Case	Software	R1	R2	R3	R4	R5	R6	R7	R8
Single wheel, bonded	BISAR	0.7	−100.5	251.7	185	0.4	−61.9	192.2	177.5
Single wheel, bonded	KENLAYER	0.8	−100.5	251.6	185.3	0.3	−62	192.2	177
Single wheel, bonded	GAMES	0.7	−100.5	251.6	185.1	0.3	−61.9	192.2	177.5
Single wheel, bonded	ALVA (Slip)	0.7	−100.4	251.6	185.1	0.3	−61.8	192.3	177.5
Single wheel, bonded	ALVA (Bonded)	0.7	−100.4	251.6	185.1	0.3	−61.8	192.3	177.5
Single wheel, unbonded L1–L2	BISAR	0.7	−120	1	217	0.4	−78	−10	205
Single wheel, unbonded L1–L2	KENLAYER	0.7	−120	1	216	0	−78	−10	205
Single wheel, unbonded L1–L2	GAMES	0.7	−119	11	217	0	−77	−1	205
Single wheel, unbonded L1–L2	ALVA (Slip)	0.7	−119.5	0.7	216.5	0.3	−77.8	−9.7	204.7
Dual wheel, bonded	BISAR	0.7	N/A	186	170	0	N/A	182	177
Dual wheel, bonded	KENLAYER	1.5	−85	186	170	0	−89	183	177
Dual wheel, bonded	GAMES	0.7	−85	186	170	0	−89	183	177
Dual wheel, bonded	ALVA (Slip)	0.7	−84.9	186	169.7	0	−88.8	183.2	177.2
Dual wheel, bonded	ALVA (Bonded)	0.7	−84.9	186	169.7	0	−88.8	183.2	177.2
Dual wheel, unbonded L1–L2	BISAR	0.7	N/A	9	193	0	N/A	−12	204
Dual wheel, unbonded L1–L2	KENLAYER	0.7	−120	−1	216	0	−78	−10	205
Dual wheel, unbonded L1–L2	GAMES	0.7	−101	−3	194	0	−106	1	205

Dual wheel, unbonded L1–L2	ALVA (Slip)	0.7	−102.6	−9.2	193.4	0	−107	−11.5	204.1
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The standard 80 kN equivalent single axle load was modeled as dual tires with 20 kN per tire, 690 kPa inflation pressure, and 330 mm center-to-center dual-tire spacing. Two response points were evaluated for each candidate section: one directly beneath a tire centerline and one at the midpoint between the two tires. The fatigue-governing response was the maximum positive horizontal tensile strain at the bottom of the asphalt-bound layer across both evaluation points. The rutting-governing response was the maximum vertical compressive strain at the top of the subgrade across both points.

The layer stack for the control family comprised, from top to bottom: HMA (variable thickness), granular base course (variable thickness), and semi-infinite subgrade. For the RAP-HPAC family, the stack comprised: HMA (variable surface thickness), RAP-HPAC bound base (variable thickness), granular base course (variable thickness), and semi-infinite subgrade. Poisson's ratios were set to 0.35 for asphalt-bound layers, 0.40 for GBC, and 0.45 for subgrade, consistent with standard layered elastic practice for Alberta conditions.

4.4. Structural Feasibility Criteria

Structural adequacy was evaluated against two independent distress modes using the Asphalt Institute transfer functions [28]:

$$N_f = 0.0796 \cdot \varepsilon_t^{-3.291} \cdot E^{-0.854} \quad (1)$$

$$N_d = 1.365 \times 10^{-9} \cdot \varepsilon_c^{-4.477} \quad (2)$$

where N_f is the allowable load repetitions for asphalt fatigue cracking, N_d is the allowable load repetitions for subgrade permanent deformation, ε_t is the horizontal tensile strain at the bottom of the asphalt-bound layer (dimensionless), ε_c is the vertical compressive strain at the top of the subgrade (dimensionless), and E is the asphalt-bound modulus in psi. Strains were converted from microstrain to strain, and modulus was converted from MPa to psi before substitution, consistent with the unit conventions embedded in the Asphalt Institute coefficients.

Monthly damage fractions were accumulated using Miner's linear damage rule [30]. The 20-year design traffic was distributed equally across the 12 monthly climate states (one-twelfth of annual ESALs per month). For each month m , ALVA strains at the corresponding temperature-dependent moduli were used to compute monthly allowable repetitions $N_{f,m}$ and $N_{d,m}$. Two cumulative damage ratios were then accumulated:

$$DR_{fatigue} = \sum_m \frac{n_m}{N_{f,m}} \quad (3)$$

$$DR_{rutting} = \sum_m \frac{n_m}{N_{d,m}} \quad (4)$$

where n_m is the number of 80 kN ESAL applications in month m over the 20-year period. Fatigue and rutting were retained as independent structural constraints because they represent mechanistically distinct failure modes at different critical response locations, governed by different transfer functions. A design was treated as structurally feasible only when both constraints were simultaneously satisfied:

$$DR_{fatigue} \leq 1.0 \quad \text{and} \quad DR_{rutting} \leq 1.0 \quad (5)$$

For compact reporting, the critical distress ratio was defined as follows:

$$CrDR = \max(DR_{fatigue}, DR_{rutting}) \quad (6)$$

CrDR is a governing limit-state indicator, not a combined or weighted damage index; it identifies which distress mode controls and how much structural margin remains. Both component damage ratios are reported for all selected sections so that the governing mode and the margin in the non-governing mode are both visible. Sections with CrDR in the

range of 0.90 to 1.00 were classified as structurally efficient: they satisfy both distress constraints without substantial overdesign relative to the binding mode.

The Asphalt Institute transfer functions were applied to both the control HMA and the RAP-HPAC without mixture-specific calibration adjustment. The measured dynamic modulus characterizes the structural contribution of the RAP-HPAC bound layer; any additional fatigue resistance arising from a specific binder blend, fiber content, or activation level that is not captured by the modulus alone is not credited in the structural calculation. This is a conservative choice: if RAP-HPAC has better fatigue resistance than the Asphalt Institute equations predict at its measured modulus, the structural advantage reported here represents a lower bound on actual performance.

4.5. Traffic Growth and Design-Period ESALs

Traffic was evaluated using year-1 ESAL/day/direction values drawn from Alberta Transportation and Economic Corridors traffic and pavement management system records [31,32]. The 20-year cumulative ESALs were calculated as follows.

To test the influence of the selected growth assumption, the candidate pool was re-selected at 0%, 2%, and 4% annual compound growth. Because Miner damage is linear in cumulative ESAL demand for a fixed response state, the sensitivity rescales the fatigue and rutting damage ratios for each candidate and then repeats the same feasibility filter and Pareto selection rule used in the main analysis. Across the redesigned cases in Table 3, the selected RAP-HPAC sections remain thinner than the independently selected conventional controls by 40–130 mm, indicating that the material-saving conclusion is not controlled by the single 2% growth assumption.

$$ESALs_{20} = ESAL_{day,1} \times 365 \times \frac{(1 + g)^{20} - 1}{g} \quad (7)$$

where $g = 0.02$ is the annual compound growth rate. A 2% growth rate was adopted as the central assumption because it is consistent with the long-term growth order of magnitude described in the Alberta Pavement Design Manual and avoids overstating demand for already high-volume corridors. Three traffic classes were evaluated, as summarized in Table 4.

Table 3. Traffic growth redesigned section sensitivity for Pareto-selected sections.

Traffic Class	Family	0% Growth	2% Growth	4% Growth
5426 ESAL/day/direction	Control	380/0/400 (CrDR 0.998)	400/0/400 (CrDR 0.957)	400/0/600 (CrDR 0.990)
5426 ESAL/day/direction	RAP-HPAC	90/250/400 (CrDR 0.978)	90/270/400 (CrDR 0.907)	90/270/550 (CrDR 0.978)
731 ESAL/day/direction	Control	150/0/560 (CrDR 0.978)	190/0/430 (CrDR 0.989)	170/0/540 (CrDR 0.976)
731 ESAL/day/direction	RAP-HPAC	50/120/430 (CrDR 0.977)	50/140/360 (CrDR 0.975)	50/140/390 (CrDR 0.992)
1300 ESAL/day/direction	Control	190/0/500 (CrDR 0.988)	170/0/600 (CrDR 0.962)	270/0/520 (CrDR 0.991)
1300 ESAL/day/direction	RAP-HPAC	50/155/360 (CrDR 0.932)	50/140/470 (CrDR 0.994)	90/120/470 (CrDR 0.980)

Table 4. Traffic classes used in the Alberta design sweep.

Traffic Class	Year-1 ESAL/Day/Direction	Growth Rate	20-Year ESALs	Context
High	731	2%	6.48 million	Upper-range Alberta highway demand
Very high	1300	2%	11.53 million	High-volume heavy corridor
Observed heavy corridor	5426	2%	48.12 million	PMS record from Hwy 2:24; heavy-corridor sensitivity

The 5426 ESAL/day/direction case was based on an observed Alberta PMS record from Highway 2 direction 24 and was treated as a heavy-corridor sensitivity rather than a typical network design condition. Extreme urban freeway records above this range were not used in the main sweep, as the published traffic table reports total ESAL/day/direction rather than lane-specific design ESALs, and final design for such segments would require project-specific lane distribution, geometric, drainage, and agency standard-section input.

4.6. A1–A5 GWP Model

The environmental assessment used a construction-stage A1–A5 boundary for the functional unit. Modules B, C, and D were not included because the paper is framed as a pavement design case study: alternatives are first required to meet similar structural serviceability through the same fatigue and rutting damage-ratio criteria, and the comparison then asks which initial design delivers that equivalent serviceability with lower construction-stage GWP and cost. Including maintenance, end-of-life, or future reuse credits would require assumed service lives, rehabilitation schedules, and future material-management scenarios that are not measured in this design-stage dataset.

The tack/prime emulsion contribution was estimated through a transparent A1–A3 parametric sweep rather than a product-specific EPD. The recipe bounds were checked against local CSS-type emulsion evidence: Alberta’s CSS-1H micro-surfacing specification requires residue after distillation of at least 62%, and an Alberta/Edmonton CSS-1H emulsion example reported 61% hard binder and 39% water [33,34]. The sweep therefore used bitumen fractions of 0.55, 0.62, and 0.70; emulsifier fractions of 0.003, 0.005, and 0.010; and a fixed additive fraction of 0.003. Bitumen GWP was varied using Canadian bitumen LCA scenarios from de Bortoli et al. [19], with 826 and 1098 kg CO₂e/t as the base Canadian range and 2680 kg CO₂e/t retained only as a fugitive-methane stress case. The resulting base emulsion A1–A3 factors were P10 = 533.55, P50 = 665.28, and P90 = 838.04 kg CO₂e/t emulsion; the P50 value was used as the central value in the A1–A5 model, while P10/P90 were used as uncertainty bounds. The stress-case median was 1736.03 kg CO₂e/t and is reported only as a sensitivity case. Table 5 summarizes the local CSS-type emulsion recipe ranges and corresponding A1–A3 emission factors used in the LCA.

Table 5. Emulsion A1–A3 recipe bounds and emission-factor outputs used in the pavement LCA.

Input or Output	Range/Value	Role in Model
Local CSS-1H residue/composition evidence	Alberta CSS-1H micro-surfacing specification requires residue after distillation $\geq 62\%$; Alberta/Edmonton CSS-1H emulsion example reports 61% hard binder and 39% water.	Supports a residual bitumen fraction near 0.60 for local CSS-type emulsions.
Recipe sweep	Bitumen fraction, 0.55, 0.62, 0.70; emulsifier fraction, 0.003, 0.005, 0.010; additive fraction, 0.003.	Covers local CSS-type residue levels and adjacent tack/prime emulsion formulations.
Bitumen GWP sweep	826, 1098, and 2680 kg CO ₂ e/t bitumen.	Low and mid cases from Canadian bitumen scenarios; 2680 kg CO ₂ e/t is a fugitive-methane stress case.
Base A1–A3 emulsion outputs	P10 533.55, P50 665.28, P90 838.04 kg CO ₂ e/t emulsion.	P50 is the central value propagated into the pavement A1–A5 model; P10/P90 defines the uncertainty band.
Fugitive-methane stress output	Median 1736.03 kg CO ₂ e/t emulsion.	Reported as a stress test only, not as the base case.

4.6.1. A1–A3 (Material Production)

Layer masses were calculated from geometry as follows:

$$M_i = L \cdot W \cdot h_i \cdot \rho_i \quad (8)$$

where $L = 1000$ m, $W = 3.5$ m, h_i is layer thickness, and ρ_i is material density. GWP was then the following:

$$GWP_{A1-A3} = \sum_i M_i \cdot EF_i + GWP_{emulsion} \quad (9)$$

Material emission factors were developed from Canadian asphalt EPD data [35] and the project LCA inventory. Conventional HMA was assigned P10/P50/P90 factors of 68.74/75.54/84.60 kg CO₂e/t, reflecting the range of Canadian plant-level asphalt production intensities. RAP-HPAC was assigned 41.64/49.70/57.76 kg CO₂e/t, reflecting the lower virgin material burden of the 50% RAP mixture with approximately 80% effective binder activation. Granular base course was assigned 2.09/2.96/5.28 kg CO₂e/t. Densities were 2.26 t/m³ for HMA, 2.39 t/m³ for RAP-HPAC, and 2.30 t/m³ for GBC.

Prime and tack coat emulsions were included to avoid omitting ancillary materials. Because Canadian EPDs for asphalt emulsions were not available, emulsion factors were estimated using a parametric sweep anchored to recent Canadian bitumen LCA ranges [19] and Alberta/Western Canadian asphaltic-crude inventory assumptions. For a 3500 m² lane-km area, 3.50 t of prime coat was included for sections requiring priming, and 1.225 t of tack coat was included where a bound RAP-HPAC layer was present. The control family prime-coat contribution was 1867/2328/2933 kg CO₂e per lane-km for P10/P50/P90. The RAP-HPAC family prime and tack coat combined were 2521/3143/3960 kg CO₂e per lane-km.

4.6.2. A4 (Transport to Site)

Transport GWP was computed using a truck-physics model rather than a generic ton-kilometer factor. For each material stream and vehicle type, traction demand was calculated from rolling resistance, aerodynamic drag, and road grade:

$$F_{trac} = C_{rr} \cdot M \cdot g + 0.5 \cdot \rho_{air} \cdot C_d A \cdot v^2 + M \cdot g \cdot \sin\theta \quad (10)$$

Round-trip energy, including loaded outbound and empty return legs, auxiliary power, and vehicle-specific payload, was converted to fuel consumption and then to GWP using fuel-specific emission factors. The sweep used a 32.2 km regional haul distance with haul speeds of 60–90 km/h, ± 2 –4% grade variation, and a 5–30 °C ambient temperature range for paving-season conditions.

A differentiated-haul sensitivity was added because aggregate sources may be closer to a project than asphalt plants. The base model uses 32.2 km for all materials; the sensitivity keeps asphalt materials at 32.2 km and tests GBC haul distances of 20 km and 10 km. The RAP-HPAC GWP advantage remains in all cases, indicating that the result is not driven by the common-haul assumption. Table 6 presents the sensitivity of RAP-HPAC construction-stage GWP reductions to alternative GBC haul-distance assumptions across the three traffic classes.

Table 6. A4 differentiated-haul sensitivity for P50 A1–A5 GWP.

Traffic Class	GBC Haul Distance	RAP-HPAC GWP Change vs. Control
731 ESAL/day/direction	10.0 km	−22.9%
731 ESAL/day/direction	20.0 km	−23.5%
731 ESAL/day/direction	32.2 km	−24.2%
5426 ESAL/day/direction	10.0 km	−29.9%
5426 ESAL/day/direction	20.0 km	−30.1%

5426 ESAL/day/direction	32.2 km	−30.3%
1300 ESAL/day/direction	10.0 km	−16.3%
1300 ESAL/day/direction	20.0 km	−17.4%
1300 ESAL/day/direction	32.2 km	−18.7%

4.6.3. A5 (Construction Installation)

Equipment-based A5 emission factors from an Athena pavement analysis and project-specific productivity assumptions were applied to the paving, compaction, and aggregate placement operations. The A5 module contributes a smaller fraction of total A1–A5 GWP than A1–A3 for asphalt-bound sections but is retained for completeness and because it varies with section thickness and the number of construction lifts.

All GWP results are reported at P50 (median) unless otherwise stated. The P10–P90 range reflects uncertainty in emission factors, not in the structural or geometric design variables.

4.7. Construction Cost Model

Construction cost was modeled using Alberta 2026 Unit Price Averages published by Transportation and Economic Corridors [36]. The primary prices used were:

- HMA (Q998 Superpave): \$147.89 CAD/t (five contracts, 173,100 t; provincial average)
- GBC (B282, Des. 2 Cl. 25): \$34.27 CAD/t (ten contracts, 811,950 t; provincial average)

These installed bid prices include material supply, plant-to-site haul, placement, compaction, and contractor markup. They do not require separate addition of equipment, labor, or overhead, as these are embedded in the contractor bid. The cost analysis is a parallel assessment of the same physical construction activities evaluated in the LCA; cost and GWP are assessed in different units (dollars versus kg CO₂e) across the same A1–A5 equivalent scope without double-counting.

RAP-HPAC was not available as an independent Alberta bid item. Its cost was therefore modeled parametrically as a multiplier applied to the HMA unit price. The multiplier range—0.65, 0.75, 0.90, 1.00, and 1.15—spans the spectrum from meaningful savings (when reclaimed binder and aggregate cost offsets exceed processing premiums) to a modest cost premium (when rejuvenator, polymer modification, quality control, and contractor familiarity costs dominate). The main cost comparison uses the 0.90× multiplier (\$133.10 CAD/t) as a conservative central estimate; multiplier sensitivity is presented separately.

Traffic control, mobilization, and preliminary engineering were excluded from both alternatives' cost calculations because they are common to both and produce no differential cost relevant to the design comparison.

Table 7 summarizes the key inputs, assumptions, and their rationale.

Table 7. Key inputs, assumptions, and rationale.

Parameter	Value/Range	Rationale
Functional unit	1 lane-km, 3.5 m width	Standard lane-km basis for pavement LCA
Design period	20 years	Alberta PDM standard design period
Traffic growth	2% per year compound	Alberta PDM long-term central assumption
Loading	80 kN ESAL; dual tire, 690 kPa, 330 mm spacing	Standard Alberta design axle
Loading frequency	15 Hz at asphalt layer depth	Typical Alberta highway truck speed
Subgrade modulus	Seasonal; warm-season governs damage	Alberta silty clay representative conditions

GBC modulus	Seasonal; 125–1000 MPa with 200 MPa warm-season baseline	Seasonal granular stiffness factors from Alberta PDM-style support adjustment
HMA A1–A3 GWP (P50)	75.54 kg CO ₂ e/t	Canadian asphalt EPD range; project inventory
RAP-HPAC A1–A3 GWP (P50)	49.70 kg CO ₂ e/t	Parameterized A1–A3 factor for 50% RAP mixture with approximately 80% effective binder activation
GBC A1–A3 GWP (P50)	2.96 kg CO ₂ e/t	Canadian aggregate production EPD range
Transport haul	32.2 km regional	Regional plant-to-site haul assumption
HMA unit price	\$147.89 CAD/t	Alberta 2026 UPA, Q998 Superpave
GBC unit price	\$34.27 CAD/t	Alberta 2026 UPA, B282
RAP-HPAC multiplier (main)	0.90× HMA	Conservative central estimate; no Alberta bid history
RAP-HPAC multiplier range	0.65–1.15×	Full literature range for high-RAP processing costs
CrDR feasibility threshold	CrDR ≤ 1.0	Both DR _{fatigue} ≤ 1.0 and DR _{rutting} ≤ 1.0 required
CrDR efficiency band	0.90–1.00	Structurally efficient without substantial overdesign

4.8. Design Sweep and Pareto Selection

A full enumeration of HMA thickness, RAP-HPAC thickness, and GBC thickness was conducted for both pavement families and all three traffic classes, generating several thousand candidate cross-sections per family. HMA thickness was varied from 50 to 400 mm in 10 mm steps; RAP-HPAC thickness from 50 to 350 mm in 10 mm steps (RAP-HPAC family only); and GBC thickness from 200 to 650 mm in 10 mm steps. For each candidate, ALVA was called 12 times (once per monthly climate state) and damage was accumulated as described in Section 4.4.

Candidates with CrDR > 1.0 were removed as structurally infeasible. Among the feasible candidates, Pareto selection identified non-dominated sections minimizing simultaneously: total P50 A1–A5 GWP, construction cost at the 0.90× multiplier, total pavement thickness (a proxy for material demand), and distance of CrDR from 1.0 (to reward efficiency without overdesign). Where multiple sections lay on the Pareto front, the section with CrDR closest to 1.0 in the 0.90–1.00 band was selected as the primary reported section, as it represents the most material-efficient structurally adequate design.

5. Results

5.1. Seasonal Modulus and Temperature Behavior

The climate-informed modulus model produces a pronounced seasonal variation for both asphalt-bound layers. The monthly HMA and RAP-HPAC stiffness values reflect the SHRP/LTPP depth-adjusted pavement temperatures and the fitted temperature-frequency modulus inputs assigned to each layer. Both materials are stiffest in winter and softest during the summer damage-critical months, when reduced asphalt modulus increases the tensile and subgrade strain responses used in the damage calculations.

Figure 2 illustrates the monthly dynamic modulus and layer temperatures for both materials. The most damage-critical months are June through August, when both layers are at minimum stiffness and tensile strain at the base of the bound stack reaches its peak. In contrast, winter months contribute little cumulative damage despite carrying the same

traffic fraction because the high-modulus stiffness of both layers keeps strains well below the allowable limits.

5.2. Monthly ALVA Strain Behavior

Figure 3 presents the monthly ALVA tensile and subgrade compressive strains for the representative 731 ESAL/day/direction optimized pair: the conventional control section and the Pareto-selected RAP-HPAC section. The comparison shows that the RAP-HPAC section reduces or maintains comparable critical strain response while satisfying both fatigue and rutting constraints after GBC thickness is co-optimized with the asphalt-bound layers.

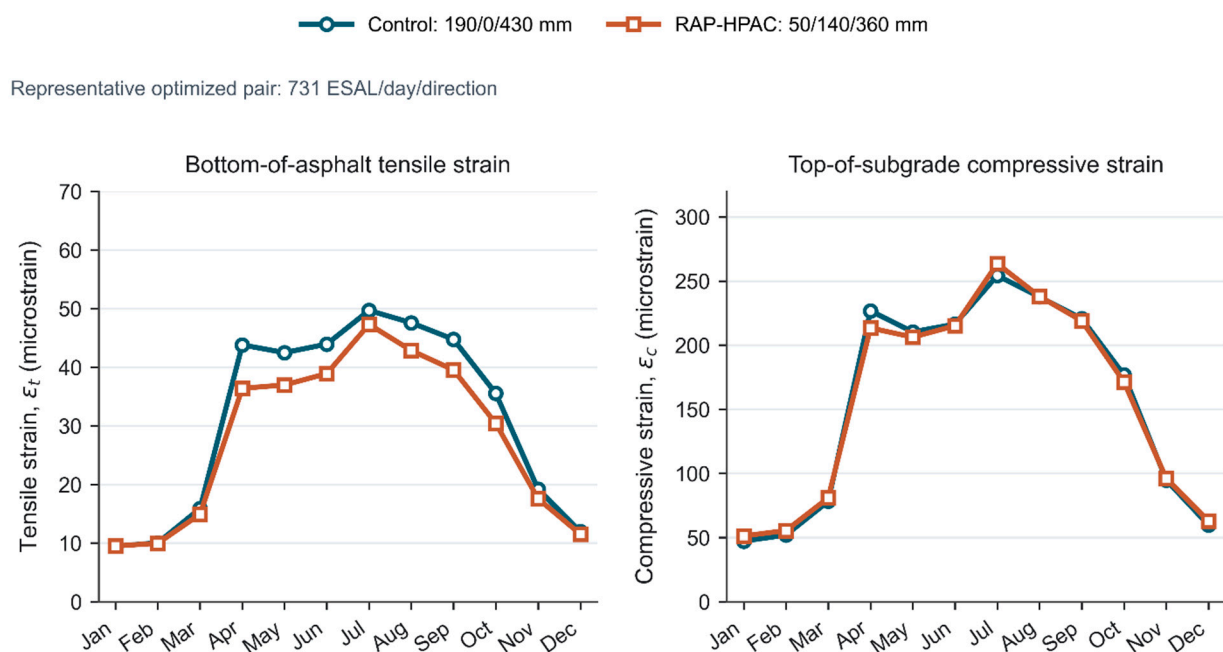


Figure 3. Monthly ALVA tensile and subgrade compressive strains for optimized control and RAP-HPAC sections at 731 ESAL/day/direction. Layer thicknesses are reported as HMA/RAP-HPAC/GBC.

The optimized 731 ESAL/day/direction pair illustrates the main mechanistic behavior without relying on an infeasible trial design. The RAP-HPAC section uses the recycled high-modulus layer below a thin HMA surface and reduces tensile strain at the bottom of the asphalt-bound stack while maintaining acceptable subgrade compressive strain. This response supports the interpretation that the high-modulus layer is structurally useful when the bound stack and GBC are co-optimized.

The Pareto-selected RAP-HPAC section therefore should be interpreted as a coupled cross-section design rather than a direct material replacement. Its performance advantage comes from assigning stiffness to the bound base while retaining sufficient granular support to control subgrade response under warm-season loading.

This is the primary mechanistic message of the paper: RAP-HPAC does not automatically improve both fatigue and rutting performance through higher stiffness alone. The GBC layer must be designed in conjunction with the bound stack to distribute load adequately to the subgrade, and the design sweep identifies the combinations where both constraints are satisfied simultaneously.

5.3. Optimized Section Geometries

Table 8 presents the Pareto-selected control and RAP-HPAC section geometries for all three traffic classes. Layer thicknesses are expressed as HMA/RAP-HPAC/GBC in mm.

Table 8. Pareto-selected pavement cross-sections for control and RAP-HPAC families.

Traffic Class	Control Section (HMA/-/GBC, mm)	RAP-HPAC Section (HMA/HPAC/GBC, mm)	Control CrDR	RAP-HPAC CrDR	Governing Dis- tress (HPAC)
731 ESAL/day/dir	190/0/430	50/140/360	0.989	0.975	Rutting
1300 ESAL/day/dir	170/0/600	50/140/470	0.962	0.994	Fatigue
5426 ESAL/day/dir	400/0/400	90/270/400	0.957	0.907	Fatigue

Several patterns are apparent. First, the optimized control sections respond to increasing traffic by increasing either asphalt-bound thickness or granular support, depending on the governing distress mode. The control sections range from 190/0/430 mm at 731 ESAL/day/direction to 400/0/400 mm at the observed 5426 ESAL/day/direction case. Second, the RAP-HPAC sections retain a thin HMA surface layer of 50–90 mm and place the recycled high-modulus material in the bound base position, with RAP-HPAC thickness increasing from 140 mm at 731 and 1300 ESAL/day/direction to 270 mm in the heavy-corridor sensitivity. Third, the governing distress mode changes with traffic: rutting governs the 731 ESAL/day/direction RAP-HPAC section, while fatigue governs the 1300 and 5426 ESAL/day/direction RAP-HPAC sections. This supports the need to select RAP-HPAC thickness and GBC thickness jointly rather than optimizing for tensile strain alone.

The total bound-layer thicknesses also merit comment. At 731 ESAL/day/direction, the RAP-HPAC section uses 190 mm of combined bound material, the same as the optimized control HMA thickness, but reduces GBC by 70 mm. At 1300 ESAL/day/direction, the RAP-HPAC section uses 190 mm of combined bound material compared with 170 mm of HMA in the control but reduces GBC by 130 mm, producing a net 110 mm reduction in total thickness. For the observed 5426 ESAL/day/direction sensitivity, the RAP-HPAC section uses 360 mm of combined bound material compared with 400 mm of HMA in the control, while keeping GBC equal at 400 mm; this produces a net 40 mm reduction in total thickness. The environmental and cost benefit therefore comes from a combination of lower RAP-HPAC emission intensity and structural redistribution, not simply from making every layer thinner.

5.4. GWP and Construction Cost Comparisons

A fixed-traffic diagnostic was also extracted from the feasible candidate pool to separate traffic demand from governing distress mode. At the same 731 ESAL/day/direction demand, the selected RAP-HPAC section (50/140/360 mm) was rutting-governed, with CrDR = 0.975 and fatigue and rutting ratios of 0.694 and 0.975, respectively. A feasible fatigue-governed RAP-HPAC alternative at the same ESAL demand (90/170/470 mm) had CrDR = 0.987 and fatigue and rutting ratios of 0.987 and 0.257, respectively. This diagnostic illustrates that the governing distress mode can change with layer balance and stiffness distribution even when ESAL demand is held constant.

Table 9 compares the Pareto-selected sections on P50 A1–A5 GWP, construction cost at the 0.90× RAP-HPAC multiplier, and total pavement thickness change.

Table 9. GWP and construction cost comparison for Pareto-selected sections (0.90× HMA cost scenario).

Traffic Class	GWP Change (RAP-HPAC vs. Control)	Cost Change at 0.90×	Total Thickness Change
731 ESAL/day/direction	−24.2%	−8.0%	−70 mm
1300 ESAL/day/direction	−18.7%	−5.7%	−110 mm
5426 ESAL/day/direction	−30.3%	−10.7%	−40 mm

RAP-HPAC reduced both GWP and first cost in all three traffic classes. At 731 ESAL/day/direction, the RAP-HPAC section reduced P50 A1–A5 GWP by 24.2% and cost by 8.0%. At 1300 ESAL/day/direction, the corresponding reductions were 18.7% and 5.6%. At 5426 ESAL/day/direction, the reductions were 30.3% and 10.7%. The results show that the benefit is not controlled by thickness alone; it comes from replacing conventional asphalt-bound material with lower-emission RAP-HPAC while preserving structural feasibility.

Figure 4 plots the P50 A1–A5 GWP against construction cost at the 0.90× multiplier for all six selected sections.

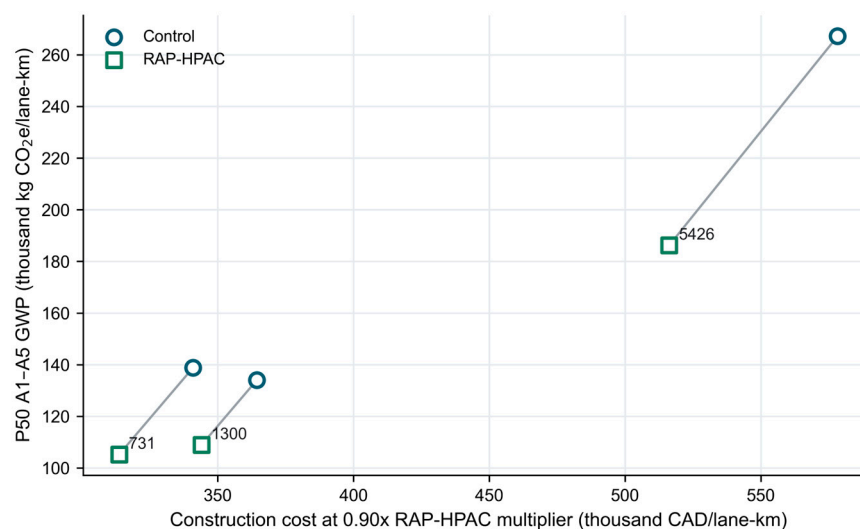
**Figure 4.** P50 A1–A5 GWP versus construction cost for Pareto-selected control and RAP-HPAC sections at the 0.90× RAP-HPAC cost scenario. RAP-HPAC reduces both GWP and cost across all three traffic classes while satisfying structural feasibility.

Figure 5 presents the relative changes in GWP, cost, and total thickness across all three traffic classes.

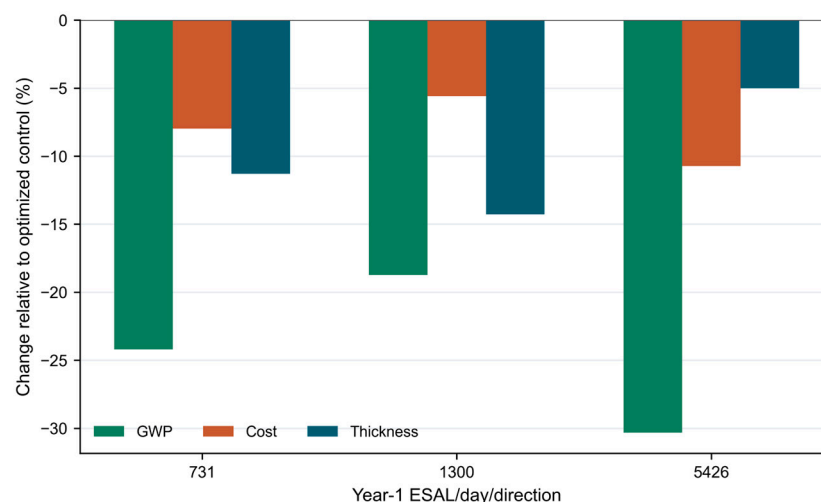


Figure 5. Relative changes in P50 A1–A5 GWP, construction cost, and total thickness for Pareto-selected RAP-HPAC sections compared with optimized controls. RAP-HPAC reduces all three metrics across the evaluated traffic classes at the 0.90× cost scenario.

5.5. Cost Multiplier Sensitivity

Table 10 presents the cost comparison across the full RAP-HPAC multiplier range for all three traffic classes.

Table 10. Construction cost change (%) for RAP-HPAC sections relative to control across RAP-HPAC cost multiplier scenarios.

Multiplier	Approximate RAP-HPAC Price (CAD/t)	Cost Change, 731 ESAL	Cost Change, 1300 ESAL	Cost Change, 5426 ESAL
0.65×	\$96.13/t	−20.7%	−17.5%	−25.2%
0.75×	\$110.92/t	−15.6%	−12.7%	−19.4%
0.90×	\$133.10/t	−8.0%	−5.6%	−10.7%
1.00×	\$147.89/t	−2.9%	−0.8%	−4.9%
1.15×	\$170.07/t	+4.7%	+6.3%	+3.7%

At a 0.90× multiplier, treated here as a conservative central estimate for RAP-HPAC production cost, the optimized RAP-HPAC sections reduce first cost in all three traffic classes. The cost reductions are approximately 8.0%, 5.6%, and 10.7% for the 731, 1300, and 5426 ESAL/day/direction cases, respectively. At parity with conventional HMA pricing (1.00×), all three RAP-HPAC sections remain slightly cost-favorable, with reductions of approximately 2.9%, 0.8%, and 4.9%, respectively. This indicates that the cost advantage is not dependent solely on assuming large RAP material discounts; it also reflects structural material redistribution, particularly the replacement of conventional HMA thickness with a thinner HMA surface and RAP-HPAC-bound base.

At a 1.15× multiplier, representing a stress-test case where rejuvenator use, quality-control requirements, contractor familiarity, or production risk make RAP-HPAC more expensive per ton than conventional HMA, the selected RAP-HPAC sections become modestly more expensive than the optimized controls. The cost premiums are approximately 4.7%, 6.3%, and 3.7% for the 731, 1300, and 5426 ESAL/day/direction cases, respectively. The practical interpretation is that RAP-HPAC is cost-competitive over a wide but not unlimited price range: it remains favorable at parity, but its economic advantage can be erased if the production premium exceeds the structural material savings. Table 11

summarizes the principal sources and evidence supporting the construction cost model and RAP-HPAC cost multiplier assumptions.

Table 11. Cost evidence basis used in the construction cost model.

Source	Use in This Study
Alberta 2026 Unit Price Averages (TEC) [36]	Installed bid-price basis for HMA (Q998) and GBC (B282)
Alberta Pavement Design Manual (1997) [37]	Supports UPA data as an appropriate basis for LCC-stage Alberta design comparisons
NCHRP Report 703 (2011) [22]	Methodology for historical-bid-based LCCA; supports UPA approach
FHWA LCCA guidance (1998, 2002) [20,21]	Agency historical unit prices appropriate for screening-level comparison
AACE 18R-97 (2016) [23]	Class 4 feasibility framing; ± 30 –50% accuracy appropriate for design screening
FHWA high-RAP cost evidence (2011) [1]	Supports RAP-HPAC multiplier range
NCAT high-RAP cost review (2012) [2]	Supports multiplier range; includes rejuvenator and QC cost components
FHWA/NCAT high-RAP evidence (2011, 2012) [1,2]	Supports RAP-HPAC cost multiplier range; RAP-HPAC cost modeled parametrically

6. Discussion

6.1. The Structural Case for Performance-Equivalent Design

The results demonstrate that RAP-HPAC's environmental and economic advantages are not intrinsic properties of the mixture alone; they emerge from the structural role the layer plays in an optimized cross-section. This distinction matters because a common assumption in RAP sustainability arguments is that substituting high-RAP material for conventional HMA at the same geometry will reduce GWP. That may be true at the material level, but the substitution also changes the structural response of the pavement. A high-stiffness recycled-bound layer must therefore be evaluated within the complete layer system, where asphalt-bound thickness, GBC thickness, subgrade support, and traffic demand jointly determine feasibility.

The design sweep makes this tradeoff explicit. Only candidates satisfying both fatigue and rutting constraints were retained, and Pareto selection then identified the candidates that minimized GWP, cost, total thickness, and distance from the structural efficiency limit. RAP-HPAC's high stiffness is an asset because it can reduce tensile strain at the bottom of the asphalt-bound stack, but this benefit must be balanced against subgrade compressive strain through appropriate GBC support. The final selected sections therefore reflect system-level optimization rather than direct material substitution.

Retaining fatigue and rutting damage ratios as separate constraints is analytically important. In the selected RAP-HPAC sections, the governing distress mode changes with traffic: rutting governs the 731 ESAL/day/direction section, while fatigue governs the 1300 and 5426 ESAL/day/direction sections. A single combined index would obscure this shift and could mislead the reader about which layer or mechanism controls the optimized design. Reporting both ratios keeps the structural interpretation transparent.

6.2. Traffic Demand and the Value of Structural Recycling

The GWP and cost benefits of RAP-HPAC scale with traffic, but not in a simple linear way. At 731 ESAL/day/direction, the optimized control section is 190/0/430 mm, while the RAP-HPAC section is 50/140/360 mm. Both designs use 190 mm of asphalt-bound material, but the RAP-HPAC option replaces most of the conventional HMA thickness with lower-

emission recycled high-modulus material and reduces GBC by 70 mm. This produces a 24.2% GWP reduction and an 8.0% cost reduction.

At 1300 ESAL/day/direction, the optimized control section is 170/0/600 mm, while the RAP-HPAC section is 50/140/470 mm. The RAP-HPAC design uses slightly more bound material than the control, but the bound material is lower-emission RAP-HPAC rather than conventional HMA, and the total section is 110 mm thinner. This produces an 18.7% GWP reduction and a 5.6% cost reduction at the 0.90× cost multiplier.

In the observed 5426 ESAL/day/direction heavy-corridor sensitivity, the optimized control section is 400/0/400 mm, while the RAP-HPAC section is 90/270/400 mm. Here the benefit comes primarily from replacing a large conventional HMA package with a thinner HMA surface over a thick recycled high-modulus bound base. The total section is 40 mm thinner, and the GBC thickness is unchanged. This produces the largest GWP reduction, 30.3%, and the largest cost reduction, 10.7%. The result indicates that RAP-HPAC is most valuable where it can replace substantial conventional asphalt-bound structural capacity without requiring additional granular support.

6.3. The Role of GBC as a Co-Optimized Layer

A finding that may initially seem counterintuitive is that the largest GWP reduction occurs in the heaviest traffic case even though both alternatives require substantial structural capacity. In the 5426 ESAL/day/direction sensitivity, the optimized control section is 400/0/400 mm, while the RAP-HPAC section is 90/270/400 mm. The RAP-HPAC design keeps the same GBC thickness as the control but replaces 310 mm of conventional HMA with 270 mm of lower-emission RAP-HPAC plus a 90 mm HMA surface. The resulting section is 40 mm thinner overall and reduces P50 A1–A5 GWP by 30.3%. The mechanism is therefore not simply thickness reduction; it is the substitution of high-GWP conventional HMA with lower-GWP recycled high-modulus bound material while preserving structural feasibility.

This is also practically significant for Alberta highway agencies. In Alberta's staged construction approach, asphalt-bound structural capacity can be delivered through initial construction and subsequent overlay stages rather than as a single construction lift. The optimized RAP-HPAC sections should therefore be interpreted as total structural asphalt packages that could be staged in practice and refined using pavement condition and FWD-based structural assessment before later lifts, consistent with the Alberta Pavement Design Manual.

6.4. Framework Transferability

The framework developed here is parameterized with Edmonton climate conditions, Alberta traffic and PMS records, and Alberta 2026 unit prices. The workflow can be transferred to other cold-region jurisdictions, but the monthly pavement temperature model, fitted dynamic modulus data, traffic ESAL distribution, seasonal support assumptions, GWP factors, and installed unit prices should be replaced with local inputs before project-level decisions are made.

The framework is not a substitute for full Pavement ME Design, which requires a complete Level 1 input package, locally calibrated distress transfer functions, and project-specific inputs for drainage, subgrade variability, pavement layer aging, and distress calibration. Its role is design-stage screening: identifying structurally feasible candidate cross-sections and comparing them on construction-stage environmental and economic criteria before advancing to project-level design.

6.5. Scope and Boundary Notes

The A1–A5 boundary used here covers construction-stage design consequences only. Modules B, C, and D are not included because the study is explicitly a design case study under equivalent serviceability: both pavement families are filtered to satisfy the same fatigue and rutting damage-ratio criteria before GWP and costs are compared. This

boundary keeps the comparison anchored to quantities directly determined by the selected cross-section, rather than adding assumed maintenance schedules, end-of-life treatments, or future recycling credits that have not yet been established for RAP-HPAC at the Alberta network scale.

The cost analysis follows the same design-stage boundary and addresses initial construction only. Because the compared alternatives are selected to provide similar structural serviceability at the design stage, future maintenance costs are not assigned differently without field evidence that one family would require earlier intervention. Long-term monitoring would be the appropriate basis for extending the framework from this design case study to a full service-life LCCA. A further development path is to use ALVA as a scriptable stress–strain response kernel within locally customized mechanistic-empirical design workflows, including regional climate and traffic inputs, measured viscoelastic asphalt characterization, and locally calibrated fatigue and rutting transfer functions. In that extension, viscoelastic continuum damage or related mixture-specific damage models could eventually replace generic fatigue equations when sufficient laboratory and field calibration data are available.

7. Conclusions

The principal contribution of this paper is a reproducible, climate-informed, mechanistic–environmental–economic framework that couples measured RAP-HPAC dynamic modulus, ALVA layered elastic batch analysis, Asphalt Institute fatigue and rutting criteria, a construction-stage A1–A5 GWP model, and Alberta bid-price cost modeling into a unified Pareto selection workflow. Applied to Alberta highway traffic conditions, the framework shows how recycled high-modulus asphalt can be evaluated as a structural design material rather than only as a lower-carbon mixture substitute.

RAP-HPAC's environmental advantage is structural in origin, not merely material. The lower cradle-to-gate emission intensity of the RAP blend produces the strongest benefit when the mixture is placed in a cross-section where its high stiffness replaces conventional asphalt-bound structural capacity while still satisfying both fatigue and rutting constraints. The analysis shows that RAP-HPAC and GBC thickness must be co-optimized; tensile-strain reduction alone is not sufficient evidence of structural equivalence.

Across the three Alberta traffic classes examined, 731, 1300, and 5426 ESAL/day/direction with 2% annual growth, Pareto-selected RAP-HPAC sections reduced construction-stage P50 GWP by approximately 19 to 30% relative to independently optimized conventional controls, while reducing first cost by approximately 6 to 11% at the 0.90× RAP-HPAC cost multiplier. The traffic growth and haul-distance sensitivities indicate that these conclusions are not controlled by a single growth or transport assumption.

The cost advantage is sensitive to the RAP-HPAC unit price multiplier but remains favorable at the 0.90× scenario used for the central comparison. At parity with conventional HMA pricing, the selected sections remain close to cost-neutral or favorable, while the 1.15× premium case becomes unfavorable for the lower two traffic classes.

The governing distress mode is traffic-dependent. Rutting governs the 731 ESAL/day/direction RAP-HPAC section, while fatigue governs the 1300 and 5426 ESAL/day/direction sections. Reporting fatigue and rutting damage ratios separately is therefore essential: a single combined indicator would hide the transition in the controlling mechanism and weaken the design interpretation.

The framework is parameterized for Alberta but is not Alberta-specific in structure. Climate records, fitted dynamic modulus master curves, traffic ESALs, seasonal support assumptions, emission factors, and unit prices are the jurisdiction-specific inputs; the ALVA response engine, damage-ratio filtering, A1–A5 accounting, and Pareto-selection workflow are transferable to other cold-region contexts where high-RAP, high-modulus asphalt is being considered as a structural layer.

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