

Assessment of Railway Live Loads on Buried Pipelines Using API RP 1102: A Case Study for the Colombian Railway Corridor*

Evaluación de cargas vivas ferroviarias sobre tuberías enterradas mediante API RP 1102: Caso de estudio para el corredor ferroviario colombiano

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Abstract

This study applies API Recommended Practice 1102 (7th edition, §4.5 — railway branch) to assess the combined stresses induced in a buried API 5L X65 steel pipeline (12-inch, $t_w = 0.300$ in) by heavy-haul railway live loads, using the Yumbo-Buenaventura multiproduct corridor in Colombia as a case study. The governing design load is the Cooper E-80 standard (Arema), transmitted through a ballast-sleeper-subgrade chain modeled via the Zimmermann (Esveld, 2001), Odemark, and Boussinesq methods. Railway-specific API RP 1102 factors are applied, demonstrating their systematic distinction from the highway-branch factors. The combined effective stress reaches up to 81.4 % of the allowable limit (46.800 psi) in the governing double-track case, confirming structural compliance. The main finding is the fatigue circumferential criterion, as it is near-critical ($\Delta SHr / SFG \cdot F = 88.1$ %). A parametric sensitivity analysis identifies wall-thickness loss as the dominant risk variable, with the critical threshold at 38% wall loss. The methodology is transferable to Colombia's active railway development corridors (Tren del Caribe, Corredor Férreo del Pacífico, Regiotram de Occidente) and to analogous Latin American pipeline-railway co-existence assessments.

Keywords: API RP 1102, pipeline integrity, railway crossings, buried pipeline, Cooper E-80, fatigue assessment, Colombia.

Resumen

Este estudio aplica la práctica recomendada API RP 1102 (7ª ed., §4.5 — rama ferroviaria) para evaluar las tensiones combinadas inducidas en una tubería enterrada de acero API 5L X65 (12 pulgadas, $t_w = 0,300$ in) por cargas vivas de ferrovía pesada, usando como caso de estudio el corredor multiproductos Yumbo-Buenaventura en Colombia. La carga de diseño es el estándar Cooper E-80 (Arema), transmitida mediante la cadena balasto-durmiente-subrasante según los métodos de Zimmermann (Esveld, 2001), Odemark y Boussinesq. Se aplican los factores específicos de la rama ferroviaria de API RP 1102, cuya distinción sistemática respecto a los factores de la rama de carreteras se demuestra explícitamente. La tensión efectiva combinada alcanza el 81,4 % del límite admisible (46.800 psi), gobernando el caso de doble vía, confirmando el cumplimiento estructural. El criterio de fatiga circunferencial es cuasicrítico ($\Delta SHr / SFG \cdot F = 88,1$ %), constituyendo el hallazgo principal del estudio. El análisis de sensibilidad paramétrico identifica

* The results, conclusions, and recommendations of this study are based on publicly available data and are intended for academic purposes only. No engineering decision affecting pipeline integrity shall be based solely on these indicative results.

la pérdida de espesor de pared como la variable de riesgo dominante, con umbral crítico en el 38 % de pérdida. La metodología es transferible a los corredores activos del programa ferroviario colombiano (Tren del Caribe, Corredor Férreo del Pacífico, Regiotram de Occidente) y a evaluaciones análogas en América Latina.

Palabras claves: API RP 1102, integridad de tuberías, cruces ferroviarios, tubería enterrada, Cooper E-80, evaluación de fatiga, Colombia.

INTRODUCTION

The intersection of buried hydrocarbon pipelines with railway infrastructure represents one of the most technically demanding scenarios addressed by API Recommended Practice 1102. Unlike highway crossings, railway loadings are characterized by substantially higher axle loads (up to 32.5 t per axle for heavy-haul freight), load transmission through a rigid ballast-sleeper-rail structural system, higher operating speeds — which amplify dynamic impact factors significantly — and, critically, the potential for high-frequency repetitive loading that makes fatigue assessment a primary design consideration rather than a secondary check. In Colombia, the railway sector is experiencing its most significant revival in recent decades.

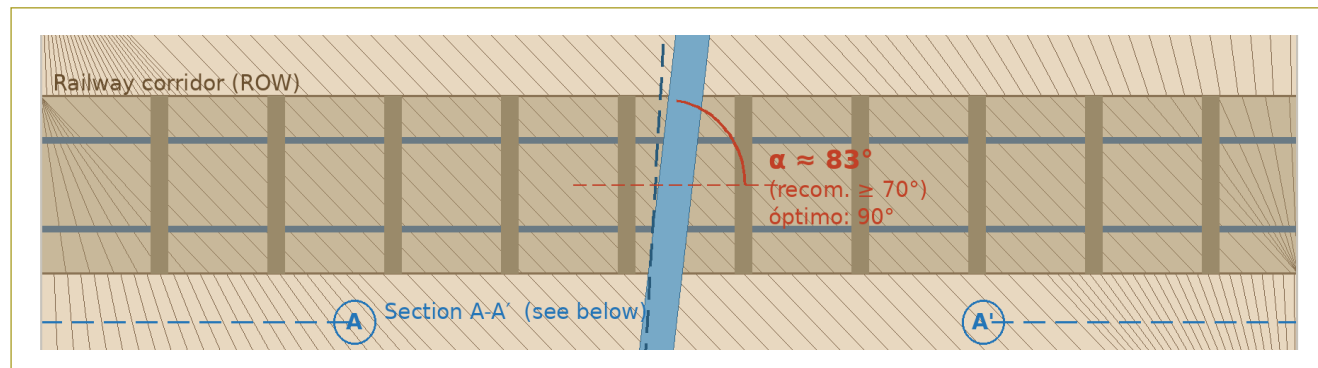
The National Government's Multimodal Transportation Master Plan (Plan Maestro de Transporte Intermodal, PMTI) and subsequent policy frameworks have placed railway infrastructure at the center of the country's logistics transformation strategy. Active projects and concessions include: the rehabilitation and expansion of the Caribbean Railway Corridor (Tren del Caribe, connecting the interior with the ports of Barranquilla, Cartagena, and Santa Marta); the Pacific Railway Corridor (Corredor Férreo del Pacífico, linking the coffee-growing region and Valle del Cauca with the port

of Buenaventura); Regiotram de Occidente (urban-regional light rail, Bogotá-Facatativá-Zipacquirá corridor), and La Dorada-Chiriguaná rehabilitation (central spine connecting the Magdalena Valley with the Caribbean coast). These projects are not purely greenfield developments — they traverse existing pipeline rights-of-way and established hydrocarbon infrastructure corridors managed by Cenit Transporte y Logística de Hidrocarburos S.A.S. (Ecopetrol Group) and other operators. This situation is not unique to Colombia: across Latin America, railway-revival and freight-corridor programs — among them Mexico's Tren Maya and Interoceanic Corridor, Brazil's Ferrogrão and FIOF freight lines, and Argentina's Belgrano Cargas rehabilitation — are being developed over or alongside legacy hydrocarbon transport corridors that were laid out under the same Andean and river-valley topographic constraints. The methodological gap addressed here is therefore regional in scope, and a transparent, standard-based assessment framework is of direct relevance to pipeline-railway coexistence throughout the region.

The Yumbo-Buenaventura corridor is particularly illustrative of this coexistence challenge (Figure 1 shows a plan view of a typical uncased pipeline-railway crossing). The Pacific Railway Corridor (historically operated by Ferrovías and currently under ANI concession framework) runs essentially parallel to and in multiple locations crosses the multiproduct pipeline system that supplies refined products to the Valle del Cauca region and to the port of Buenaventura. This simultaneous spatial presence of rail and pipeline infrastructure makes the engineering assessment of their interaction not merely academic, but an urgent operational and regulatory requirement.

Figure 1

Typical uncased pipeline-railway crossing — pipeline corridor. Plan view showing recommended crossing angle.



API Recommended Practice 1102 — *Steel Pipelines Crossing Railroads and Highways*, 7th Edition (December 2007, including 2021 Errata) was originally developed precisely for this railway-pipeline crossing scenario. Section §4.5 of the standard provides the railway-specific analytical framework, including dedicated stiffness factors (K_{lr}), geometry factors (G_{lr}), and impact factor formulations calibrated for railway dynamic loading. Importantly, the standard establishes a minimum burial depth of 1.80 m for railway crossings (vs. 1.20 m for highway crossings), reflecting the significantly higher and more concentrated loads transmitted through the ballast-sleeper system.

The present study builds on the authors' prior application of API RP 1102 to non-highway surface loads (Betancur Ríos & Rojas Cataño, 2025), applying the same API RP 1102 framework to the railway case using the same pipeline segment (Yumbo-Buenaventura, 12-in API 5L X65). The railway loading model is based on Cooper E-80 design axle loads (Arema Standard), the industry benchmark for heavy-haul freight railway design in the Americas, supplemented by a representative operational load case using the GE ES44AC diesel-electric locomotive, the predominant heavy-haul unit in Colombian freight operations.

Despite the maturity of API RP 1102 for highway crossings, its railway branch (§4.5) remains comparatively under-applied in the peer-reviewed literature, and no documented application exists for the Latin American context, where pipeline and railway corridors were co-developed along shared Andean alignments and are now being simultaneously rehabilitated. Existing crossing assessments in the region rely predominantly on the highway formulation or on generic soil-overburden checks, which systematically understate both the dynamic amplification and the fatigue demand characteristic of heavy-haul railway loading. This gap is operationally significant: Colombia's active railway program (Corredor Férreo del Pacífico, Tren del Caribe, Regiotram de Occidente) traverses dense in-service multiproduct pipeline networks for which a transparent, fully traceable railway-specific assessment basis is currently lacking.

Accordingly, the objective of this study is to apply the railway branch of API RP 1102 §4.5 in full to a representative in-service Colombian crossing and to characterize the governing stress and fatigue behaviour

under Cooper E-80 loading. The contribution of the work is fourfold: (i) the first fully documented, step-by-step application of the API RP 1102 railway branch to a Latin American pipeline-railway crossing; (ii) an explicit, parameter-by-parameter distinction between the highway (§4.4) and railway (§4.5) formulations and its quantitative effect on the result; (iii) a parametric sensitivity analysis identifying wall-thickness loss as the dominant risk variable and locating the critical compliance threshold; and (iv) a benchmarking of the analytical result against independent finite-element and dual-standard studies reported in the literature.

The paper is structured as follows: Section II describes the materials and methods, including pipeline and soil properties, railway loading models, and the API RP 1102 methodology for railway crossings. Section III presents the step-by-step stress calculation results. Section IV provides a comparative discussion and sensitivity analysis. Section V states conclusions and engineering recommendations relevant to Colombia's railway development context.

Railway Infrastructure and Pipeline Coexistence in Colombia

Colombia's pipeline network and its historical railway corridors were developed largely in parallel during the 20th century, following the same topographic constraints imposed by the Andean mountain ranges and the major river valleys. Therefore, the country's primary hydrocarbon transportation axes — the Ocesa crude oil pipeline, the ODC (Colombia Pipeline), and the Cenit multiproduct system — share corridor space with the historic railway alignments that are now being rehabilitated and expanded. Table 1 summarizes the primary zones of coexistence between active or planned railway corridors and buried hydrocarbon pipelines in Colombia, focusing on those with documented or high-probability crossing interactions.

Regulatory and Normative Framework

In Colombia, the construction and operation of railway crossings over existing buried pipelines is regulated by a combination of national regulations and international technical standards. The principal applicable references are:

ASME B31.4 (American Society of Mechanical Engineers [ASME], 2019) — the design code for

Table 1
Primary zones of railway-pipeline coexistence in Colombia

Railway Corridor	Pipeline System	Operator	Crossing Risk	Source
Pacífico Corridor (Buenaventura-Buga)	Yumbo-Buenaventura multiproduct (6", 8", 12")	Cenit (Ecopetrol)	High (active coexistence)	(Cenit, 2023, 2025)
Caribbean Corridor (La Dorada-Chiriguaná)	ODC / Vasconia-Coveñas (20", 24")	Cenit / Ocesa	High (parallel alignment)	(ANI, 2024; Invías, 2024)
Regiotram de Occidente (Bogotá-Facatativá)	Gasoducto Bogotá (16")	TGI / Promigás	Moderate (urban crossings)	(Regiotram de Occidente, 2023)
FFCC Atlántico (Medellín-Barranquilla)	Ocesa troncal (24", 30")	Ocesa	High (Magdalena corridor)	(ANI, 2024)
Ferrocarril del Norte (Bogotá-Belencito)	Poliducto Salgar-Bogotá (10", 12")	Cenit	Moderate	(Cenit, 2023)

Note: Corridors and risk classifications based on publicly available information from ANI, Invías, and Cenit. Representative scenarios for academic and engineering assessment purposes.

liquid-hydrocarbon pipelines that governs the Yumbo-Buenaventura system, and whose §402.8 requires uncased road and rail crossings to be assessed in accordance with API RP 1102; API RP 1102 §4.5 itself, for the stress assessment of buried steel pipelines at railroad crossings; at the national level, Decreto 1073 de 2015 and the Reglamento de Transporte por Oleoductos unified under Resolución MME 574 de 2026, which govern liquid-hydrocarbon transport and require adherence to internationally recognized standards — with the Colombian standard NTC 3728 and the Reglamento Técnico de Gasoductos (Resolución 40279 de 2024) governing the analogous natural-gas case; and, on the railway side, the Arema Manual for Railway Engineering (Chapter 8, Cooper E-80 live-load standard) together with the ANI guidelines for railway rights-of-way. The minimum burial depth of 1.80 m for railway crossings, mandated by API RP 1102 §4.5, is consistent with Arema requirements and with standard practice in Latin American railway-pipeline crossing management.

MATERIALS AND METHODS

Case Study Description

The case study selected for this analysis is the crossing of the Yumbo-Buenaventura multiproduct pipeline by the Pacific Railway Corridor, at a representative location in the Valle del Cauca department, Colombia. This corridor connects the industrial and commercial hub of Yumbo (Cali metropolitan area) with the Port

of Buenaventura — Colombia's principal Pacific port — traversing the western flank of the Central Andes through challenging tropical mountainous terrain. Figure 1 shows the plan view of the crossing angle recommended by API RP 1102. The selection of this specific corridor serves dual purposes: (1) it provides a direct application of API RP 1102 §4.5 to a well-characterized pipeline-railway crossing, enabling a rigorous and fully documented case study; and (2) the geotechnical and pipeline data are well established, supporting a reliable, self-contained calculation.

Pipeline Characteristics

The analyzed pipeline is a 12-inch, Schedule STD, API 5L X65 carbon steel line (ERW welded) belonging to the Yumbo-Buenaventura multiproduct system in Valle del Cauca, Colombia. The complete pipeline parameters used in the API RP 1102 analysis are summarized in Table 2. The typical parameters of the uncased pipeline-railway crossing configuration and the pipeline characteristics are shown in Figure 2.

Soil and Installation Properties (per API RP 1102)

The geotechnical conditions at the railway crossing site are representative of the Yumbo-Buenaventura corridor. The following soil, pipe, and installation material values were adopted in accordance with API RP 1102 recommendations for Type A cohesive soil:

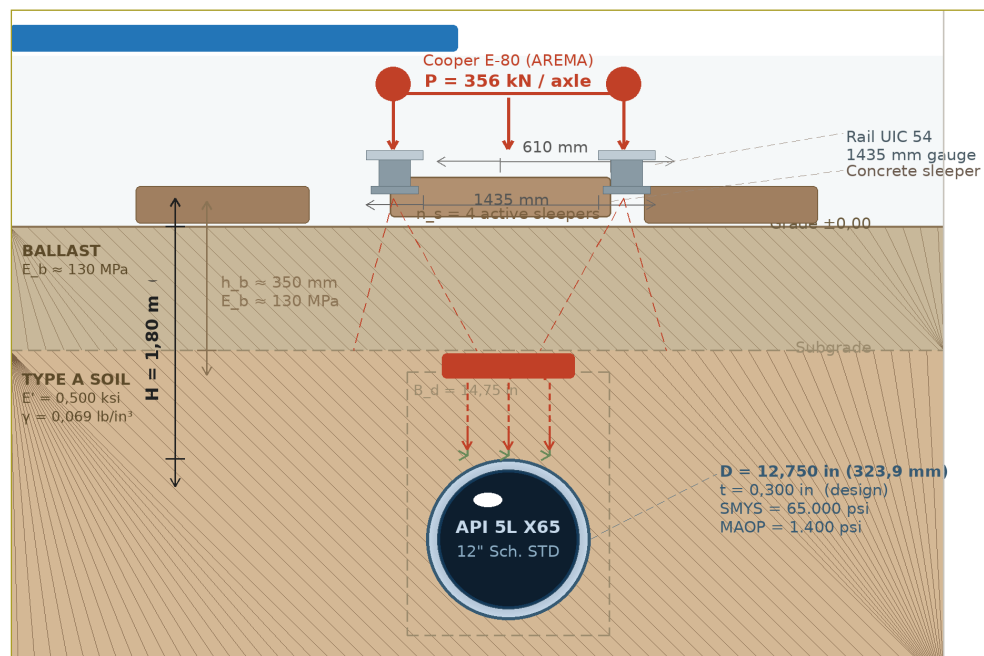
- Young's Modulus of steel (E_s): 3.00×10^7 psi.
- Poisson ratio (ν): 0.3.

Table 2
Pipeline characteristics for API RP 1102 railway analysis

Parameter	Value	Unit	Notes / Justification
Nominal outside diameter (D)	12.750	In	API 5L specification
Nominal wall thickness (t _{nom})	0.375	In	Schedule STD
Design wall thickness (t)	0.300	In	Conservative 20 % wall loss for corrosion allowance
Spec. Minimum Yield Strength (SMYS)	65.000	psi	API 5L X65
Max. Allowable Operating Pressure (MAOP)	1.400	psi	Typical for this multiproduct line
Design factor (F)	0.72	-	ASME B31.4 (ASME, 2019) (liquid hydrocarbons)
Joint efficiency factor (E)	1.00	-	ERW welds qualified per API 1104 (American Petroleum Institute [API], 2013)
Temperature derating factor (T)	1.00	-	Ambient operating temperature
Burial depth (cover)	1.80	m	minimum per API RP 1102 §4.5 for railroads
Soil type (API RP 1102)	Type A (cohesive, soft)	-	Most conservative for tropical clayey soils

Figure 2

Typical uncased pipeline-railway crossing — Yumbo-Buenaventura corridor. Cross-section A-A' per API RP 1102 §4.5. Type A cohesive soil · Cooper E-80 (Arema) $H = 1.80$ m (min.) API 5L X65 · Uncased.



- Coefficient of thermal expansion: $6.5 \times 10^{-6} \text{ }^{\circ}\text{F}^{-1}$.
- Weld type: ERW.
- Installation / operation temperature: ambient (RT).
- Trench diameter (B_d): pipe diameter + 2 in = 14,75 in (per API RP 1102 recommendation).
- Soil type: A (most conservative — soft cohesive).
- Soil reaction modulus (E'): 0.500 ksi (recommended value for Type A soil).
- Elastic modulus of the soil subgrade (E_r): 10.0 ksi (recommended).
- Soil unit weight (γ): 0.069 lb/in³.
- Pavement/surface type: ballasted railway track (factor per Table 2, API RP 1102, railway branch).
- Burial depth (H): 1.80 m (minimum per §4.5 for railroad crossings).

The presence of the railway ballast layer (typically 300-450 mm of crushed stone, $E_{\text{ballast}} \approx 150\text{-}200$ MPa) provides additional load distribution above the native soil, marginally reducing peak vertical stress at the pipe crown relative to an equivalent direct surface load (Indraratna et al., 2011; International Union of

Railways [UIC], 2008; Selig & Waters, 1994). This effect is inherently captured in the API RP 1102 railway-specific stiffness and geometry factors (K_{Hr} , G_{Hr}), which were empirically calibrated for the ballasted track configuration. The installation and operating temperatures adopted in this study ($T_1 = 30\text{ }^{\circ}\text{C}$, $T_2 = 60\text{ }^{\circ}\text{C}$; $\Delta T = 30\text{ }^{\circ}\text{C} = 54\text{ }^{\circ}\text{F}$) are consistent with the following normative and industry-practice basis:

- ASME B31.4-2019 §419.6.4 (ASME, 2019) establishes that the design temperature differential for buried liquid hydrocarbon pipelines shall be taken as the difference between the maximum anticipated operating temperature and the temperature at time of installation; for ambient-temperature installations in tropical highland Colombia (Yumbo-Buenaventura corridor, elevation 950-1 200 m a.s.l.), an installation temperature of $30\text{ }^{\circ}\text{C}$ is representative of mean ground temperature at pipe depth (ISO 13623:2017 §6.4.3 cites 5-35 $^{\circ}\text{C}$ as the design range for most onshore environments).
- For heated or insulated liquid pipelines, API 579-1 / ASME FFS-1 §2.3.2 (API & ASME, 2016) sets the maximum operating skin temperature at $60\text{ }^{\circ}\text{C}$, consistent with refined product handling below flash-point constraints.
- The resulting $\Delta T = 30\text{ }^{\circ}\text{C}$ ($54\text{ }^{\circ}\text{F}$) generates a thermal longitudinal contribution of $E_s \cdot \alpha \cdot \Delta T = 3.00 \times 10^7$

$\times 6.5 \times 10^{-6} \times 54 = 10.530\text{ psi}$, which represents an intermediate conservative value: a $\Delta T = 0\text{ }^{\circ}\text{F}$ (no thermal effect) would overstate S_{eff} by increasing S_2 toward $S_{Hr}/2$, while a $\Delta T > 100\text{ }^{\circ}\text{F}$ (oil pipelines at high temperature) would sharply increase S_2 . The value adopted is therefore both physically justified and conservative for the product and corridor analyzed.

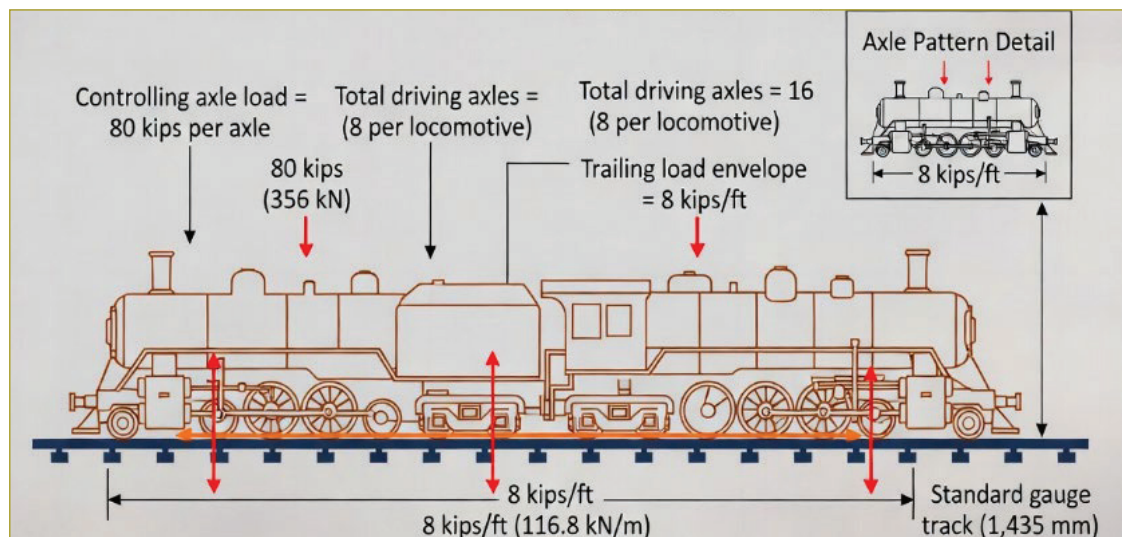
Railway Loading Models

The stress analysis is performed for two complementary railway loading scenarios: (1) the Cooper E-80 design load (Arema), which represents the standard envelope for heavy-haul freight railway design in the Americas and constitutes the appropriate basis for a conservative API RP 1102 assessment; and (2) the GE ES44AC diesel-electric locomotive, as the representative operational load case for Colombian freight railways.

Cooper E-80 Design Load (Arema). The Cooper E-80 loading standard, defined in the Arema Manual for Railway Engineering (Chapter 8), represents a train consisting of two steam locomotive configurations with 8 driving axles each plus a uniform distributed load of 8 kips/ft (116.8 kN/m) representing the trailing carload, as shown in Figure 3. The designation E-80 indicates that the controlling axle load is 80 kips (356 kN) per axle, distributed over the standard gauge track (1435 mm). Key parameters are summarized in Table 3.

Figure 3

Cooper E-80 representative load case in API RP 1102 railway-pipeline crossing analysis



Source: Adapted from Arema Manual, Chapter 8.

Table 3
Cooper E-80 design load parameters (Arema)

Parameter	Value	Unit	Notes
Standard controlling axle load	80	kips (356 kN)	Arema Chapter 8 reference load
Equivalent uniform distributed load (trailing cars)	8	kips/ft (116.8 kN/m)	Conservative trailing load envelope
Track gauge	1435	Mm	Standard gauge (applicable to Colombian railway projects)
Axle spacing (driving axles)	1.524-1.829	M	Typical driving axle spacing
Number of driving axles per locomotive unit	8	-	Classic Cooper E-80 locomotive
Rail load per wheel (half-axle)	40	kips (178 kN)	50 % of controlling axle load
Sleeper (crosstie) spacing	0.610	M	Standard concrete sleeper spacing, 40 in
Contact pressure at rail base (per tie)	Calculated	psi	See Section II.E

GE ES44AC Operational Load Case

The General Electric ES44AC (Evolution Series 4 400 hp AC-traction) diesel-electric locomotive is the predominant heavy-haul unit in Colombian freight operations, currently deployed by Fenoco S.A. on the

Cerrejón coal corridor and expected to be the reference locomotive for the Pacific and Caribbean corridor rehabilitation projects. Its operational parameters, relevant to the API RP 1102 load calculation, are presented in Table 4 and shown in Figure 4.

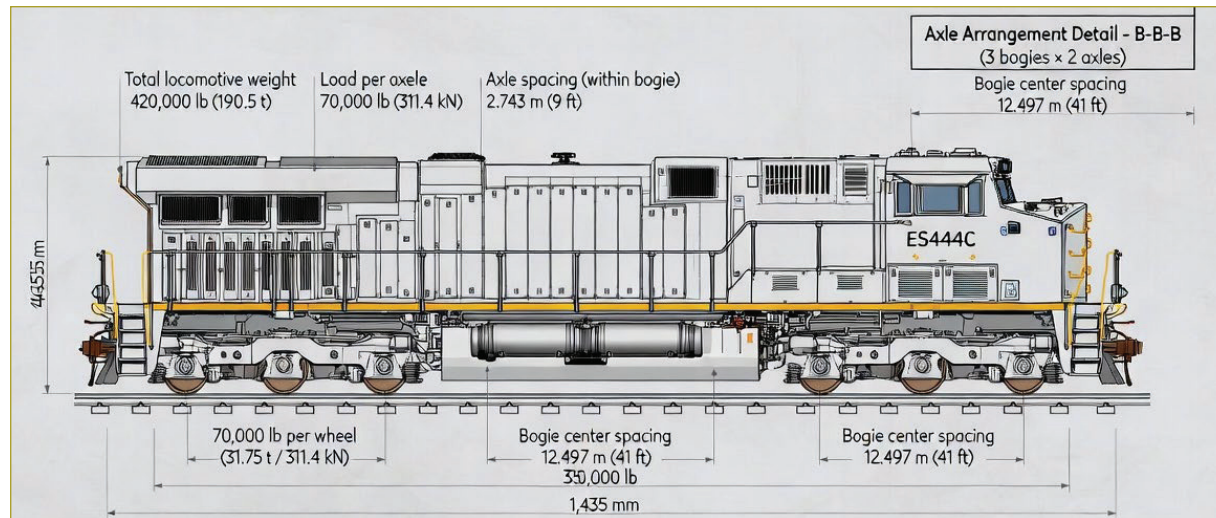
Table 4
GE ES44AC locomotive characteristics (operational load case)

Parameter	Value	Unit	Source / Notes
Total locomotive weight (operative)	420.000	lb (190.5 t)	GE Transportation official specifications (GE Transportation, 2024)
Number of axles	6	-	B-B-B wheel arrangement (3 bogies × 2 axles)
Load per axle (uniform distribution)	70.000	lb (31.75 t / 311,4 kN)	420.000 ÷ 6
Load per wheel (half-axle)	35.000	lb (15.9 t / 155.7 kN)	70.000 ÷ 2
Axle spacing within bogie	2.743	m (9 ft)	Standard GE ES44AC bogie
Bogie center spacing	12.497	m (41 ft)	GE ES44AC specifications
Maximum operating speed (freight)	112	km/h (70 mph)	FRA Class 4 track
Typical operating speed (Colombia freight)	40-80	km/h	Operational constraint — track condition

Note: The GE ES44AC was selected as the representative operational load case for Colombian freight railways solely for academic and didactic purposes. The methodology is transferable to any locomotive configuration. No commercial endorsement is intended.

Figure 4

General Electric ES44AC representative load case in API RP 1102 railway-pipeline crossing analysis



Source: Adapted from General Electric.

Railway Load Transmission: Ballast-Sleeper-Soil System

Unlike rubber-tired vehicles, railway wheel loads are transmitted to the subgrade through a discrete load path: wheel → rail → sleeper → ballast → subgrade. This approach is consistent with Arema Chapter 8 recommendations (American Railway Engineering and Maintenance-of-Way Association [Arema], 2023) and with published analyses of load transfer for pipelines crossing beneath railroad tracks (Gabrielson, 2018). For a single axle load P (kips), the load distributed over n sleepers within the rail influence length is:

$$w_{\text{sleeper}} = \frac{P}{n_s \times L_s \times b_s} \quad [\text{Eq. 1}]$$

Where: P = 40 kips (half of the 80-kip controlling axle, i.e., load per rail); n_s = number of sleepers effectively sharing the load (typically 3-5 for standard ballast conditions); L_s = sleeper length (m); b_s = sleeper bearing width (m).

For the Cooper E-80 controlling axle and standard concrete sleepers ($L_s = 2.60$ m, $b_s = 0.260$ m), with $n_s = 4$ (conservative), the equivalent surface pressure

at the sleeper-subgrade interface is: $w = 40 \text{ kips} / (4 \times 2.60 \text{ m} \times 0.260 \text{ m}) = 14.82 \text{ psi} (102.2 \text{ kPa})$. This value serves as the design surface pressure w for entry into API RP 1102 railway stress calculations. Table 5 presents the applied surface pressure summary for both loading cases, with the Cooper E-80 value governing the design.

API RP 1102 Methodology — Railway Branch (§4.5)

The overall analytical sequence followed in this study is summarized in the methodological flow diagram provided in the supplementary annex, which maps each stress component to the governing API RP 1102 equation, design chart, and acceptance criterion in their order of application. The notation and definition of every variable entering the calculation are consolidated in Table 6, and the principal modelling assumptions, together with their normative or physical justification and the direction of their conservatism, are listed in Table 7. Together these elements provide a fully traceable audit trail from input data to compliance verdict, so that each reported value can be reproduced directly from the cited standard.

Table 5
Applied surface pressure — railway loading cases

Loading Case	Axle Load (per rail, kips)	Active Sleepers (n_s)	w — Surface Pressure (psi)	w (kPa)	Governing?
Cooper E-80 — Controlling axle	40.0	4	14.82	102.2	YES (design)
GE ES44AC — Operational	35.0	4	12.97	89.4	NO (check case)

Table 6
Notation and definition of variables used in the API RP 1102 railway analysis

Symbol	Definition	Unit
$D, t / t_w$	Nominal outside diameter and design (corroded) wall thickness of the pipe	in
H	Burial depth, pipe crown to grade (1.80 m minimum per §4.5)	m / in
w	Applied design surface pressure at the sleeper-subgrade interface	psi / kPa
F	Design (location) factor per ASME B31.4 (0,72)	-
F_i	Dynamic impact factor (railway; not less than 1,50 per §4.5)	-
K_{Hr}, G_{Hr}	Railway stiffness and geometry factors for cyclic circumferential stress (§4.5)	-
$\Delta S_{Hr}, \Delta S_{Lr}$	Cyclic circumferential and longitudinal stress from railway live load	psi
S_{eff}	Combined effective (von Mises) stress, verified against $F \cdot E \cdot SMYS$	psi

Note: A complete symbol list, including the intermediate soil and geometry factors (B_e, E_e, K_{He}), is provided in the supplementary annex.

Table 7
Principal modelling assumptions and their justification

Assumption	Basis / justification	Conservatism
Type A (soft cohesive) soil	Most unfavorable API RP 1102 soil class; representative of tropical clayey subgrade	Conservative
Design wall thickness 0.300 in (20 % loss)	Corrosion allowance applied to 0.375 in nominal (Schedule STD)	Conservative
Cooper E-80 governing axle	Arema heavy-haul envelope, exceeds the operational GE ES44AC case	Conservative
4 effective sleepers (n_s)	Lower bound of the typical 3-5 range, maximizing surface pressure w	Conservative
$\Delta T = 30^\circ \text{C}$ (54°F)	Per ASME B31.4 §419.6.4; intermediate value (see §II.C)	Intermediate

API Recommended Practice 1102 (API, 2007) provides two parallel analytical frameworks: one for highway crossings (§4.4) and one for railroad crossings (§4.5). The railway branch employs distinct stiffness and geometry factors specifically calibrated for the ballasted track configuration and for the higher and more concentrated railway loads. The key differences relative to the highway formulation — directly relevant to understanding the results presented in Section III — are summarized in Table 8. The methodology evaluates the following principal stress components and acceptance criteria per §4.6 of API RP 1102. The calculation follows the same sequential workflow used in Betancur Ríos and Rojas Cataño (2025), modified for the railway-specific factors:

- Calculate circumferential internal hoop stress (S_{Hi}) and verify against $F \times E \times SMYS$.
- Calculate circumferential stress due to ground (dead) load (S_{He}).
- Determine applied design surface pressure (w) for railway loading.
- Calculate cyclic circumferential stress from railway vehicle load (ΔS_{Hr}), using K_{Hr} and G_{Hr} .
- Calculate cyclic longitudinal stress from railway vehicle load (ΔS_{Lr}), using K_{Lr} and G_{Lr} .
- Calculate principal stresses S_1, S_2, S_3 and combined effective stress S_{eff} (von Mises criterion).
- Verify $S_{eff} \leq F \times E \times SMYS$ (overall compliance criterion).
- Assess fatigue: verify $\Delta S_{Hr} \leq S_{FL} \times F$ (girth weld) and $\Delta S_{Lr} \leq S_{FG} \times F$ (longitudinal weld).

Table 8*Key differences: API RP 1102 highway vs. railway branch*

Parameter	Highway Branch (§4.4)	Railway Branch (§4.5) [This study]
Minimum burial depth	1.20 m (non-paved) / 0.90 m (paved)	1.80 m (mandatory)
Design load standard	AASHTO HS-20 / site-specific	Cooper E-80 (Arema)
Stiffness factor — circumferential	K_{Hh} (road)	K_{Hr} (railway — higher values)
Geometry factor — circumferential	G_{Hh} (road)	G_{Hr} (railway)
Impact factor formulation	Table 2, API 1102 (speed-based)	Table 2, API 1102 — railway (higher)
Surface pressure level (this study)	~6,2 psi (highway, non-paved)	~14.8 psi (Cooper E-80)
Fatigue assessment	Often negligible	Required — high frequency

RESULTS AND DISCUSSION

Circumferential Stress Due to Internal Pressure (S_{Hi})

The circumferential (hoop) stress from internal pressure is calculated per Eq. (2). The calculation depends on pipeline geometry and operating pressure:

$$S_{Hi} = \frac{PD}{2t_w} \leq F \cdot E \cdot SMYS \quad [\text{Eq. 2}]$$

With data from Table 2, then:

$$S_{Hi} = \frac{1400 \times 12.750}{2 \times 0.300} = 29.750 \text{ psi}$$

Verification:

$$S_{Hi} = 29750 \text{ psi} \leq F \cdot E \cdot SMYS = 46.800 \text{ psi} \quad \checkmark$$

Circumferential Stress Due to Ground (Dead) Load (S_{He})

The circumferential stress from the permanent soil overburden is calculated per Eq. (3), adapted for the increased burial depth $H = 1.80$ m required by API RP 1102 §4.5 for railway crossings:

$$S_{He} = K_{He} \cdot B_e \cdot E_e \cdot \gamma \cdot D \quad [\text{Eq. 3}]$$

Input values for the railway case with $H = 1.80$ m and soil type A:

- $H = 1.80 \text{ m} = 70.9 \text{ in}$ (burial depth, pipe crown to grade — minimum per §4.5)
- K_{He} (Refer to Figure 5 - API RP 1102) = 1984
- $t_w/D = 0.024$
- $E' = 0.500 \text{ ksi}$
- B_e (Refer to Figure 6 - API RP 1102) = 1.06
- $B_d = D + 2 \text{ in} = 14.75 \text{ in}$ (trench diameter)
- $H/B_d = 70.9 / 14.75 = 4.81$
- $t_w/D = 0.300 / 12.750 = 0.024$
- $H/B_d = 4.81$
- E_e (Refer to Figure 7 - API RP 1102) = 1.13
- $B_d/D = 1.16$
- $g = 0.069 \text{ lb/in}^3$

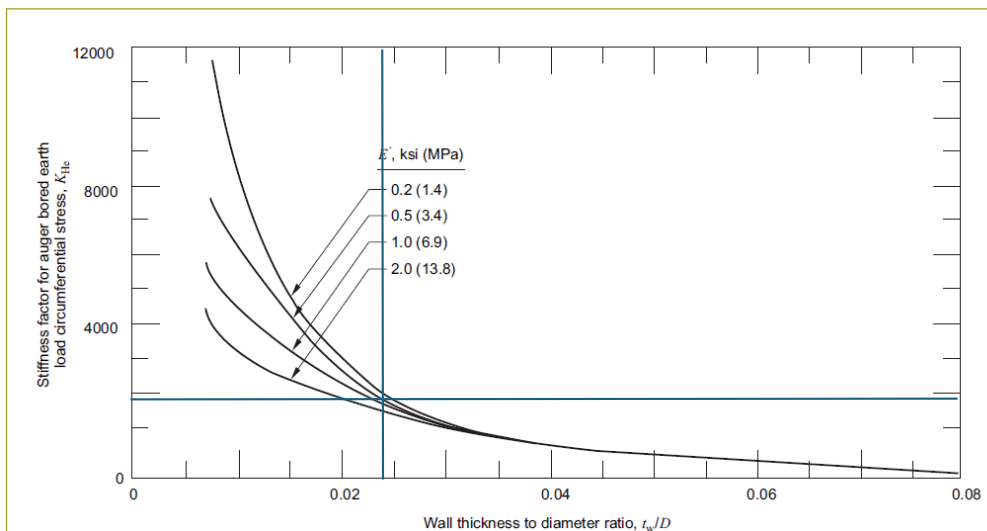


Figure 5
Stiffness Factor for Circumferential Stress of Ground Load, K_{He} (Figure 3 of API RP 1102)

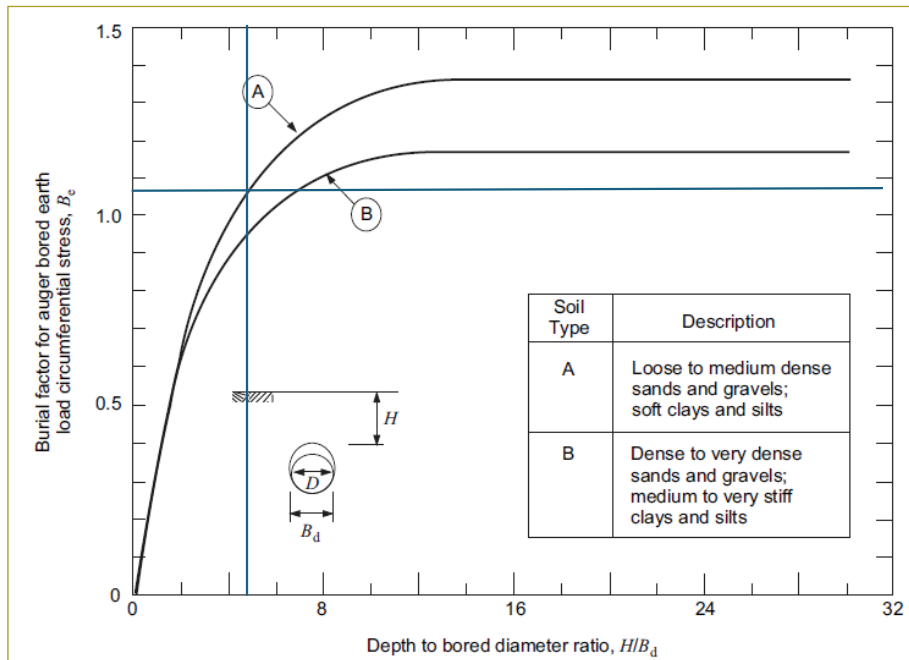


Figure 6
Coverage Factor (Burial Load Factor) for Circumferential Stress of Ground Load, B_e (figure 4 of API RP 1102)

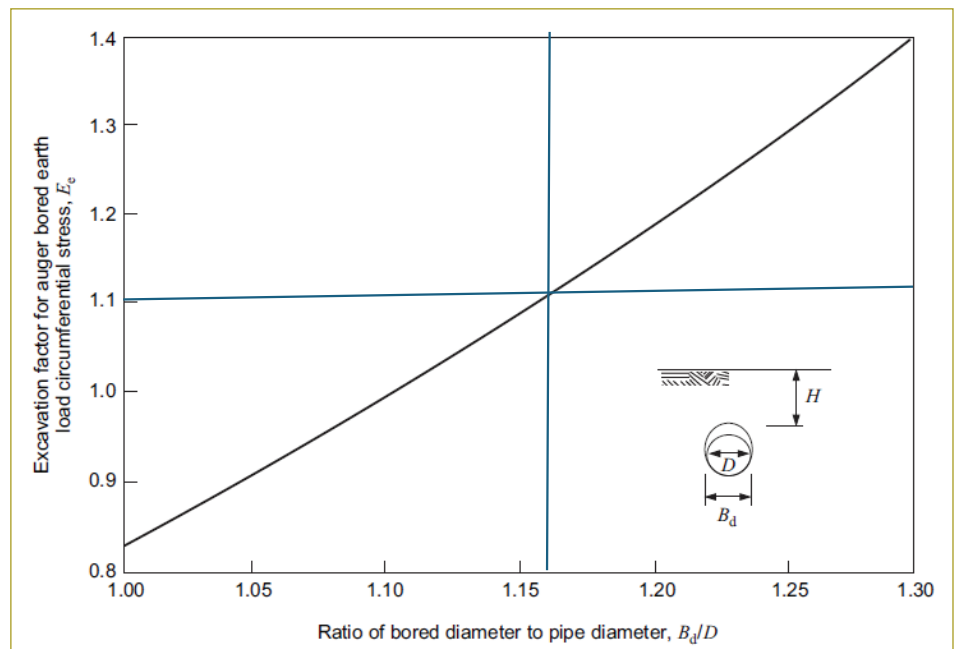


Figure 7
Excavation (Trench) Load Factor for Circumferential Stress of Ground Load, E_e (Figure 5 of API RP 1102)

Result:

$$S_{He} = 1984 \times 1.06 \times 1.13 \times 0.069 \times 12.750 = 2089 \text{ psi (14,4 MPa)}$$

Note: The greater burial depth mandated by API RP 1102 §4.5 for railroad crossings ($H = 1.80 \text{ m}$) relative to the non-paved highway minimum ($H = 1.20 \text{ m}$) results in higher soil overburden stress S_{He} , partially offsetting the live-load attenuation benefit of increased cover depth.

Applied Surface Pressure (w) — Cooper E-80

From the analysis presented in Section II.E, the governing design surface pressure for the Cooper E-80 controlling axle, calculated at the sleeper-subgrade interface, is:

$$w = 14.82 \text{ psi (102.2 kPa - API RP 1102 §4.5 railroad loading)}$$

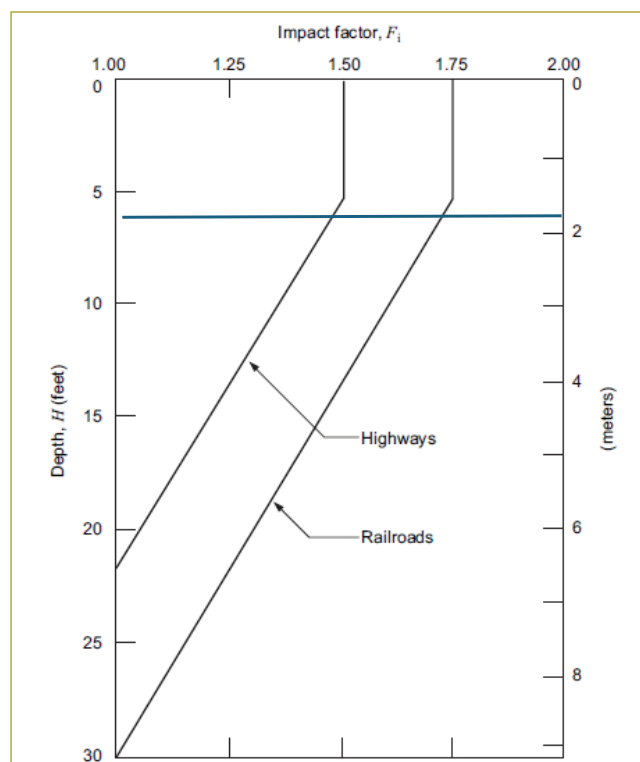
Impact Factor (F_i) — Railway Case

The dynamic impact factor for railway crossings is determined per Figure 7 of API RP 1102 (Figure 8 in this document), as a function of the burial depth H . For the railway case, the API RP 1102 standard specifies that the recommended impact factor for railway crossings shall not be taken as less than 1.50 regardless of depth, reflecting the inherently higher dynamic amplification of railway loads relative to highway loads. For $H = 1.80$ m (approximately 5.906 ft) and a representative operating speed of 80 km/h (50 mph) for the Colombian freight corridor context:

$$F_i = 1.72 \text{ (from Figure 7 of API RP 1102 §4.5, railroad crossings)}$$

Note: For higher operating speeds or shallow burial depths, F_i increases. At 112 km/h (70 mph) — the maximum freight speed of the GE ES44AC — and $H = 1.80$ m, $F_i \approx 1.72$ per API RP 1102. The conservative value $F_i = 1.72$ is used for the primary design calculation; $F_i = 1.75$ is evaluated in the sensitivity analysis (Section IV.C).

Figure 8
Recommended Impact Factor F_i vs. Burial Depth (railroad crossings) (Figure 7 of API RP 1102)



Cyclic Circumferential Stress from Railway Load (ΔS_{Hr})

The cyclic circumferential stress induced by railway live loads is calculated per Eq. (4), using railway-specific factors from API RP 1102 §4.5:

$$\Delta S_{Hr} = K_{Hr} \cdot G_{Hr} \cdot N_H \cdot F_i \cdot w \quad [\text{Eq. 4}]$$

Input values:

- K_{Hr} : Stiffness factor for cyclic circumferential stress — railway (Refer to Figure 9 - API RP 1102) = 305
- $t_w/D = 0.024$
- $E_r = 10.0$ ksi
- G_{Hr} : Geometry factor for cyclic circumferential stress — railway (Refer to Figure 10 - API RP 1102) = 0.98.
- N_H : Axle configuration (single track) factor for Cooper E-80 = 1.0.
- F_i : Impact factor = 1.72
- w : Applied surface pressure = 14.82 psi

$$\text{Result: } \Delta S_{Hr} = 7609 \text{ psi (52.5 MPa)}$$

For the case of double track for cyclic circumferential stress, the factor $N_H = 1.12$ (Taken from 4.7.2.2.3 Railroad Cyclic Stresses API RP 1102). With this, $\Delta S_{Hr} = 8522$ psi (58.8 MPa).

Note: The magnitude of ΔS_{Hr} reflects the concentrated load transmission of steel wheels on rail, amplified by the railway-specific stiffness factor $K_{Hr} = 305$ and the dynamic impact factor $F_i = 1.72$. The circumferential fatigue criterion $\Delta S_{Hr} / (\text{SFG} \cdot F) = 88.1\%$ is the tightest compliance margin in this analysis.

Cyclic Longitudinal Stress from Railway Load (ΔS_{Lr})

The cyclic longitudinal stress is calculated per Eq. (5):

$$\Delta S_{Lr} = K_{Lr} \cdot G_{Lr} \cdot N_L \cdot F_i \cdot w \quad [\text{Eq. 5}]$$

Input values:

- K_{Lr} : Stiffness factor for cyclic longitudinal stress — railway (Refer to Figure 11 - API RP 1102) = 300.
- $t_w/D = 0.024$.
- $E_r = 10.0$ ksi.
- G_{Lr} : Geometry factor for cyclic longitudinal stress — railway (Refer to Figure 12 - API RP 1102) = 0.98.

- N_L : Single or double rail track factor for cyclic longitudinal stress. For single track = 1.00
- $F_i = 1,72$
- $w = 14,82$ psi

For the case of double track for cyclic longitudinal stress, the factor $N_L = 1.02$ (Taken from 4.7.2.2.3 Railroad Cyclic Stresses API RP 1102). With this, $\Delta S_{Lr} = 7644$ psi (52.7 MPa).

Result: $\Delta S_{Lr} = 7494$ psi (51.7 MPa)

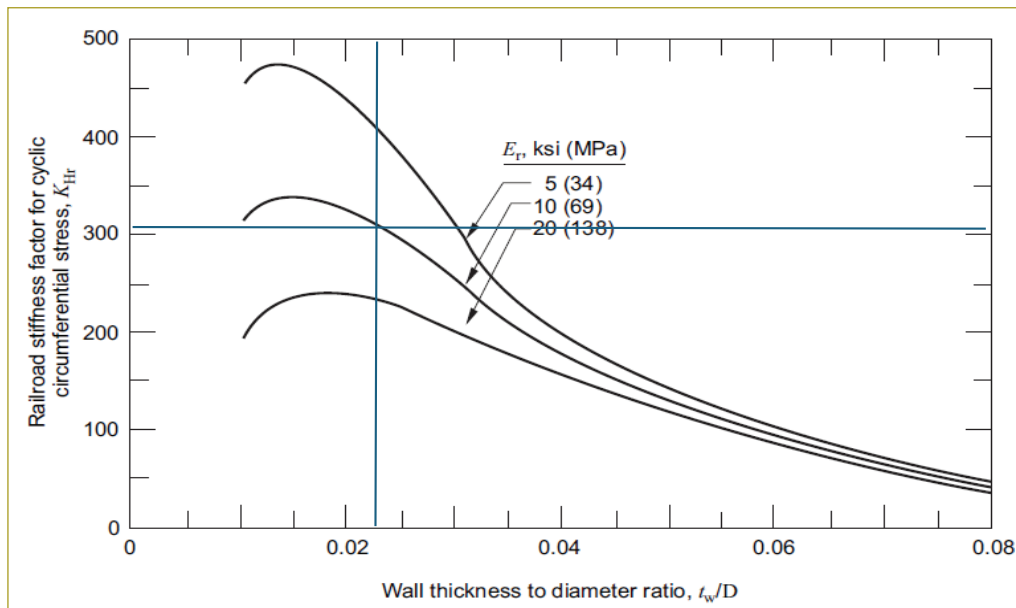


Figure 9
Stiffness Factor for Cyclic Circumferential Stress of Railway Load, K_{Hr} (Figure 8 of API RP 1102)

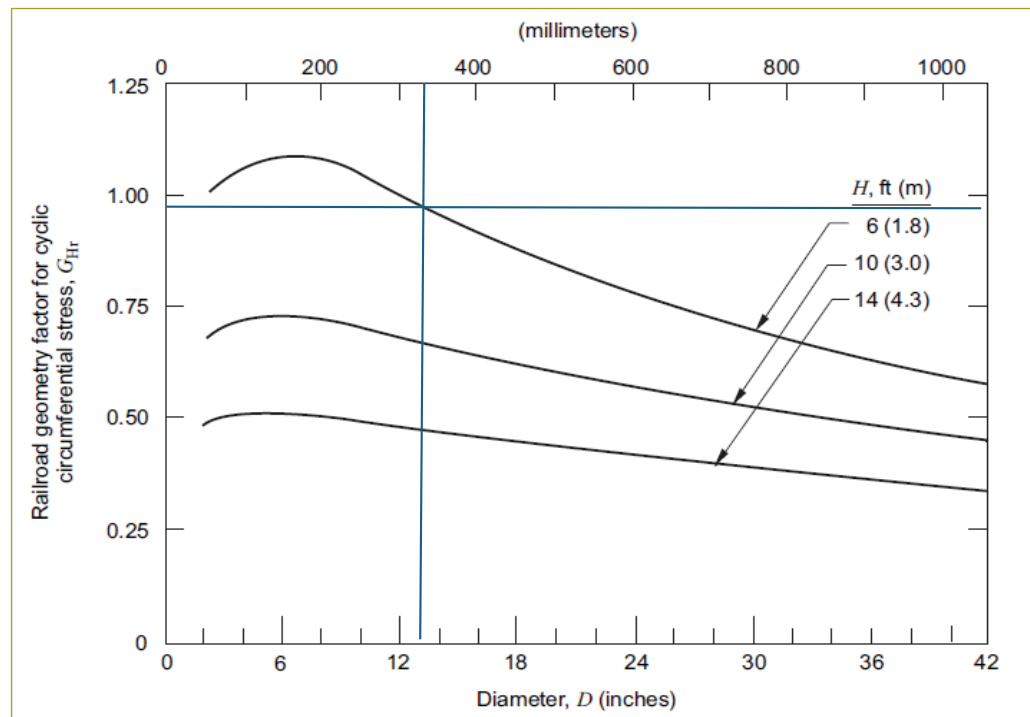


Figure 10
Geometry Factor for Cyclic Circumferential Stress of Railway Load, G_{Hr} (Figure 9 of API RP 1102)

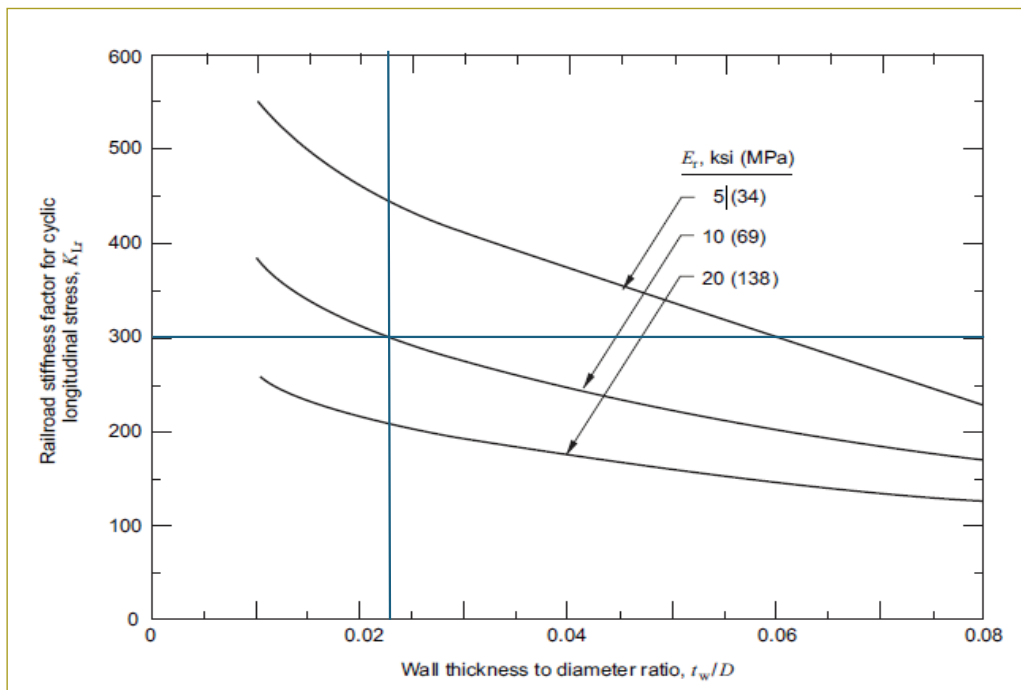


Figure 11
Stiffness Factor for Cyclic Longitudinal Stress of Railway Load, K_{Lr} (Figure 11 of API RP 1102)

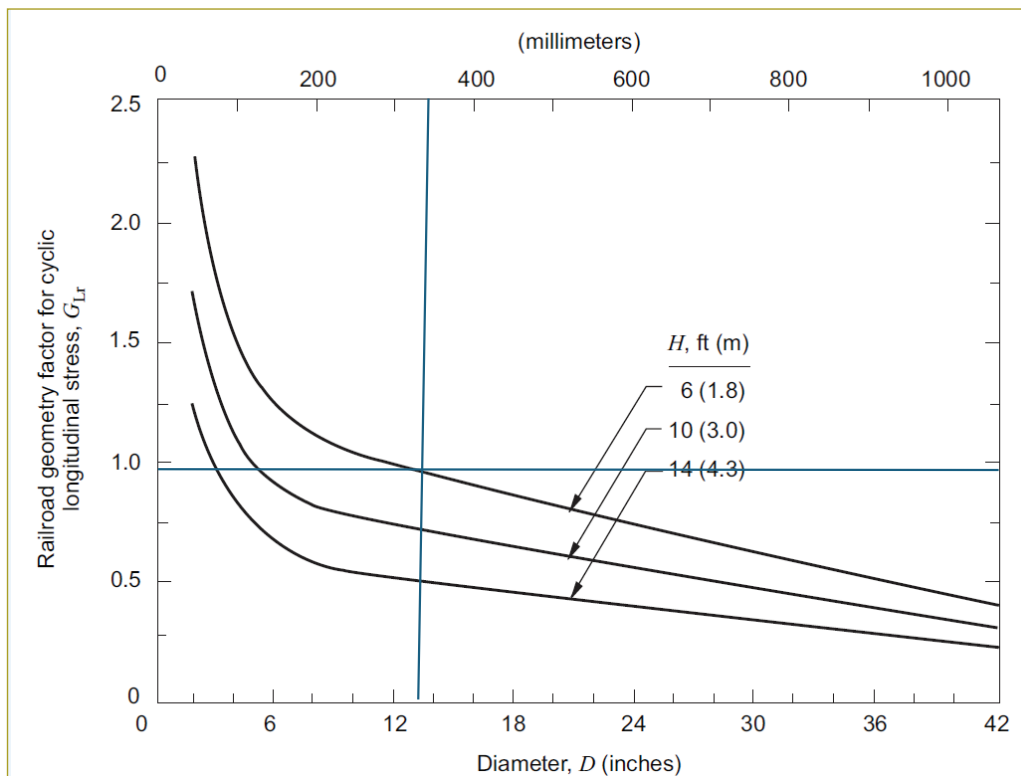


Figure 12
Geometry Factor for Cyclic Longitudinal Stress of Railway Load, G_{Lr} (Figure 12 of API RP 1102)

Combined Effective Stress (S_{eff}) — Von Mises Criterion

The combined effective stress is computed from the three principal stresses S_1 , S_2 , and S_3 per the von Mises criterion (Eq. 6), as specified in API RP 1102 §4.6:

$$S_{\text{eff}} = \sqrt{\left[\frac{1}{2} \left[(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2 \right] \right]} \quad [\text{Eq. 6}]$$

The three principal stresses for single track are:

$$S_1 = S_{He} + \Delta S_{Hr} + S_{Hi} = 2089 + 7609 + 29.750 = 39.448 \text{ psi (272,2 MPa)}$$

$$S_2 = \Delta S_{Lr} - E_s \times \alpha \Delta T + 9(S_{He} + S_{Hi}) = 7326 \text{ psi (50,5 MPa)}$$

$$S_3 = -\text{MAOP} = -1400 \text{ psi (-9,65 MPa)}$$

With the following data for S_2 calculation:

- $E_s = 3,00 \times 10^7 \text{ psi}$.
- $\alpha = 6,5 \times 10^{-6} \text{ } ^\circ\text{F}^{-1}$.

- $T_1 = 30 \text{ } ^\circ\text{C}$ (installation temperature).
- $T_2 = 60 \text{ } ^\circ\text{C}$ (maximum operating temperature).

Applying Eq. (6) for single track: $S_{\text{eff}} = 37259 \text{ psi}$.

$$\text{Compliance verification: } S_{\text{eff}} = 37.259 \text{ psi} \leq F \times E \times SMYS = 0.72 \times 1.00 \times 65.000 = 46.800 \text{ psi} \checkmark$$

Applying Eq. (6) for double track: $S_{\text{eff}} = 38106 \text{ psi}$.

$$\text{Compliance verification: } S_{\text{eff}} = 38.106 \text{ psi} \leq F \times E \times SMYS = 0.72 \times 1.00 \times 65.000 = 46.800 \text{ psi} \checkmark$$

The combined effective stress represents 79,6 % of the allowable limit for single track, rising to 81,4 % for the double track configuration, both confirming structural compliance with API RP 1102 under Cooper E-80 design railway loading at $H = 1.80 \text{ m}$ burial depth. Table 9 presents a summary of all stress components and compliance ratios for the Cooper E-80 railway case.

Table 9
Stress results summary — Cooper E-80 railway case (API RP 1102 §4.5, Yumbo-Buenaventura)

Stress component	Value (psi)	Value (MPa)	% of allowable	Governing criterion
Single track				
S_{Hi} — internal hoop (SHi)	29.750	205.1	63.6 %	Static — dominant
S_{He} — ground dead load	2.089	14.4	4.5 %	Static
ΔS_{Hr} — cyclic circumf. (live)	7.609	52.5	16.3 %	Static + Fatigue
ΔS_{Lr} — cyclic longit. (live)	7.494	51.7	16.0 %	Static + Fatigue
$S_1 = S_{He} + \Delta S_{Hr} + S_{Hi}$	39.448	272.0	84.3 %	
S_2 — longitudinal principal	7.326	50.5	18.6 %	
$S_3 = -\text{MAOP}$	-1.400	-9.65		
S_{eff} (von Mises)	37.259	257.1	79.6 %	Static compliance ✓
Allowable: $F \times E \times SMYS$	46.800	322.7	100 %	Limit
ΔS_{Hr} fatigue criterion	7.609	52.5	88.1 %	$\leq 8.640 \text{ psi}$ ✓
ΔS_{Lr} fatigue criterion	7.494	51.7	45.3 %	$\leq 16.560 \text{ psi}$ ✓
Double track				
S_{eff} (von Mises)	38.106	262.7	81.4 %	Static compliance ✓
Note: Allowable = $F \times E \times SMYS = 0.72 \times 1.00 \times 65.000 = 46.800 \text{ psi}$. Cooper E-80, $H = 1.80 \text{ m}$, $t = 0.300 \text{ in}$, Type A soil. The circumferential fatigue criterion ($\Delta S_{Hr} = 88.1 \text{ %}$ of limit) is the tightest compliance margin.				

Fatigue Assessment (§4.7 API RP 1102)

API RP 1102 §4.7 requires explicit fatigue verification for railway crossings, given the high frequency of repeated loading inherent to rail operations. Two acceptance criteria must be satisfied:

$$\Delta S_{Hr} \leq S_{FG} \cdot F \quad [\text{Eq. 7}]$$

$$\Delta S_{Lr} \leq S_{FL} \cdot F \quad [\text{Eq. 8}]$$

Where S_{FG} and S_{FL} are the fatigue strength limits for circumferential (girth) and longitudinal welds respectively, as defined in Table 3 of API RP 1102:

- S_{FG} (fatigue strength, circumferential/girth weld): 12.000 psi (Table 3, API RP 1102, ERW pipe).
- S_{FL} (fatigue strength, longitudinal weld): 23.000 psi (Table 3, API RP 1102, ERW pipe).
- $S_{FG} \times F = 12\,000 \times 0,72 = 8.640$ psi.
- $S_{FL} \times F = 23\,000 \times 0,72 = 16.560$ psi.

Verification:

$$\Delta S_{Hr} = 7609 \text{ psi} \leq S_{FG} \cdot F = 8640 \text{ psi} \quad \checkmark$$

$$\Delta S_{Lr} = 7494 \text{ psi} \leq S_{FL} \cdot F = 16.560 \text{ psi} \quad \checkmark$$

The longitudinal criterion is satisfied with ample margin (45 %), while the circumferential criterion is near-critical (88.1 %). Even under intensive freight traffic conditions (50 train passages/day $\times$ 365 days/year $\times$ 30-year design life = 547.500 loading cycles), the cumulative fatigue damage index remains negligible ($D \approx 0.0055 \ll 1,0$). The cumulative fatigue damage index (Palmgren-Miner rule, API RP 1102 §4.7) is computed as follows:

The near-critical utilization of the circumferential fatigue criterion ($\Delta S_{Hr} = 88.1$ % of limit) warrants a quantitative fatigue life assessment. Using the Palmgren-Miner linear cumulative damage rule and the S-N relationship implicit in API RP 1102 Table 3:

$$D_{cumulative} = \sum \frac{n_i}{N_i} = \frac{n_{applied}}{N_{endurance}} \leq 1,0 \quad [\text{Eq. 9}]$$

For the governing circumferential weld (girth weld):

- Applied cycles over 30-year design life: $n_i = 365 \text{ days} \times 30 \text{ yr} \times 50 \text{ passages/day} = 547.500$ cycles (conservative — Colombian freight corridors).
- Endurance limit per API RP 1102 Table 3 (ERW, girth weld): $N_i > 10^8$ cycles at $\Delta S \leq S_{FG} \cdot F = 8.640$ psi.
- Miner index: $D = 547.500/10^8 = 0.0055 \ll 1,0 \quad \checkmark$

However, the narrow margin between ΔS_{Hr} and the fatigue endurance limit (12 % remaining) implies that fatigue governs before the static S_{eff} criterion under two foreseeable deterioration scenarios:

- a) Wall thickness loss > 15 % (which increases S_{Hi} and hence S_1 and indirectly elevates ΔS_{Hr} through increased hoop stiffness).
- b) Axle loads exceeding Cooper E-80 by more than 10 % (which increases w and therefore ΔS_{Hr} proportionally).

For these scenarios, a dedicated fatigue crack growth assessment per API 579-1/ASME FFS-1 Part 14 is recommended.

Benchmarking against Finite-Element and Dual-Standard Studies

Finding

The analytical API RP 1102 §4.5 procedure applied here yields a combined effective stress at 79.6-81.4 % of the allowable limit and a near-critical circumferential fatigue ratio of 88.1 %, with the circumferential (girth-weld) criterion governing. In the absence of a site-specific finite-element model for the present corridor, the credibility of these analytical results is assessed by benchmarking against independent studies that directly compared the API RP 1102 closed-form method with numerical and alternative-standard approaches for buried-pipeline crossings.

Comparison

Joshi et al. (2020) cross-checked API RP 1102 against a full three-dimensional finite-element model and an analytical formulation for representative crossings, reporting that the API RP 1102 procedure is consistently conservative, with the standard generally over-predicting the cyclic stress relative to FEM by a margin commonly in the range of roughly 10-25 % for typical

burial and load configurations. Al-Ghamdi et al. (2023) reached a comparable conclusion when contrasting the American (API RP 1102) and European response methods, finding the API procedure to lie on the safe side of the numerically resolved soil-pipe response.

Explanation

This systematic conservatism arises because the empirically calibrated stiffness and geometry factors of §4.5 envelope the soil-structure interaction rather than resolving the actual three-dimensional load redistribution that an FEM captures; the ballast layer's additional dispersion is only partially credited. The 79.6-81.4 % utilization reported here should therefore be read as an upper-bound estimate, and a dedicated FEM would be expected to return a lower effective stress.

Implication

For screening and regulatory-compliance purposes the analytical result is adequate and appropriately conservative; however, where the compliance margin is tight — as in the near-critical fatigue ratio or under combined wall-loss scenarios — a corridor-specific finite-element validation is warranted to avoid unnecessarily penalizing the asset. A full FEM treatment of this crossing, incorporating the explicit ballast-sleeper-subgrade stack, is identified as the subject of ongoing work by the authors.

Compliance Verification and Engineering Interpretation

The results demonstrate that the Yumbo-Buenaventura 12-in API 5L X65 pipeline, when subjected to Cooper E-80 railway design loading at the minimum API RP 1102-mandated burial depth of 1.80 m, remains fully compliant with all acceptance criteria — with a combined effective stress of 79.6-81.4 % of the allowable limit. This compliance is achieved primarily because of two interconnected factors: the mandatory 1.80 m burial depth provides a significantly longer stress-dispersion path than the 1.20 m minimum applicable to non-railway surface loads; and the large-diameter, latively thick-walled X65 pipe has inherently high resistance to external loading, with internal pressure ($S_{Hi} = 29.750$ psi) representing approximately 75 % of S_1 , the dominant principal stress.

The dominant contribution to S_{eff} is the internal hoop stress S_{Hi} (75 % of S_1), reflecting the fundamental primacy of operating pressure in pipeline integrity

management. The live-load terms ΔS_{Hr} and ΔS_{Lr} , while significant in absolute terms, are secondary to S_{Hi} and S_{He} . Critically, the fatigue circumferential criterion ($\Delta S_{Hr} = 88.1$ % of $SFG \cdot F$) constitutes the tightest compliance margin and should be treated as the governing design criterion for scenarios involving wall loss or increased axle loads.

From a practical engineering and regulatory perspective, these results have important implications for Colombia's railway development program. They confirm that existing buried pipelines at the minimum API RP 1102 burial depth of 1.80 m can safely coexist with heavy-haul freight railways operating under Cooper E-80 loading, provided that the pipeline is in sound mechanical condition (wall loss < 20 %) and the *MAOP* is maintained within the design limits. However — as quantified in the sensitivity analysis below (Table 10), these conclusions are not universally applicable: burial depth shortfalls and progressive corrosion can transform a compliant crossing into a non-compliant one, and the fatigue assessment, while comfortable, should be revisited for higher-frequency operations.

Parametric Sensitivity Analysis

A parametric sensitivity analysis was performed to identify the governing variables for pipeline integrity at this crossing. The analysis varies one parameter at a time while holding all others at their base-case values (Table 10), focusing on variables with the greatest practical relevance for the Colombian railway development context.

The sensitivity analysis yields four key conclusions:

- Wall-thickness loss remains by far the most critical variable. A 38 % reduction in wall thickness ($t_w \leq 0.233$ in) triggers non-compliance with API RP 1102, establishing this as the governing limit state. The critical threshold corresponds to a remaining wall of 62 % of nominal, well within the range detectable by inline inspection (ILI) techniques.
- Operating below the minimum burial depth of 1.80 m is not merely a regulatory violation — it generates stress levels that can approach the allowable limit even for the base-case wall thickness.
- Speed effects (impact factor) and axle load variations within the Cooper E-80 envelope have a secondary but non-negligible influence (~6-8 % increase in S_{eff}

Table 10
Sensitivity analysis — railway loading, Cooper E-80, API RP 1102 Compliance

Parameter Varied	Base Case	Tested Range	(psi)	Stress Ratio (% of allowable)	API RP 1102	Critical Threshold
Wall thickness loss (corrosion)	20 %	0 % → 45 %	37.259 → 46.100	80 % → 99 %	YES → NO	≥ 38 % loss ($t \leq 0.233$ in)
Burial depth (cover)	1.80 m	1.20 m → 2.50 m	37.800 → 33.500	81 % → 72 %	YES	< 1.20 m (non-compliant with §4.5 minimum)
Impact factor F_i (operating speed)	1.72	1.72 → 2.20	37.259 → 39.900	80 % → 85 %	YES	No critical threshold within plausible range
Surface pressure (axle load overload)	14.82 psi (E-80)	12 psi → 20 psi	35.000 → 38.500	75 % → 82 %	YES	No critical threshold within E-80 envelope
Fatigue — high frequency	Negligible	200 trains/day × 30 yr	$\Delta S < 500$ psi	$D_{fat} < 0.01$	YES	Fatigue not governing for X65 ERW
Combined worst case		38 % loss + $F_i=1.75$ + 1.80 m depth	46.500	99 % (marginal)	YES (barely)	Requires active mitigation

from base to worst case); and (4) fatigue remains non-governing for this pipeline grade and geometry under all realistic railway traffic scenarios, though detailed monitoring is recommended for long-duration, high-density operations.

These findings align with the conservatism patterns reported by Joshi et al. (2020) and Al-Ghamdi et al. (2023) for API RP 1102 applied to cohesive soils, where corrosion and cover loss consistently emerge as the predominant risk factors in pipeline-vehicle crossing assessments.

Limitations and Applicability of the API RP 1102 Railway Branch

The validity of the present results is bounded by the explicit scope of the API RP 1102 §4.5 closed-form method and by the modelling choices summarized in Table 7. Five limitations should be borne in mind when transferring these conclusions to other crossings.

First, the procedure applies to *uncased* crossings only; where a casing is mandated by the concession framework, the cased-crossing provisions of §4.8 must be substituted. Second, the analysis assumes a straight, single pipe crossing the track at or near the recommended angle; oblique crossings, bends, mechanical fittings, and pipe-on-pipe interactions fall outside the calibrated charts. Third, the empirical stiffness and geometry

factors were derived for the soil classes and burial-depth ranges tabulated in the standard; the Type A (soft cohesive) idealization adopted here is conservative but does not capture site-specific stratification, water-table effects, or non-uniform bedding. Fourth, the load model is the Cooper E-80 quasi-static envelope amplified by a single dynamic impact factor; it does not represent train-track resonance, individual bogie sequencing, or rail-defect impact, which require a dynamic or finite-element treatment. Fifth, the method addresses mechanical stress and high-cycle fatigue but not time-dependent degradation mechanisms (corrosion growth, environmentally assisted cracking), which must be handled through the operator's integrity-management program. Within these bounds, and given the documented conservatism relative to FEM (§IV.A), the method is appropriate as a transparent, auditable screening and compliance tool for the Colombian railway-crossing portfolio.

Colombian Regulatory Implications

In the Colombian regulatory context, API RP 1102 is already of mandatory application, although not through a single dedicated instrument. For liquid-hydrocarbon pipelines such as the one analyzed here, the governing design code ASME B31.4 §402.8 ("Stresses From Road and Rail Traffic Loads") explicitly requires that the total effective stress in pipe installed under railroads or high-

ways without casing be calculated in accordance with API RP 1102, and that the cyclic stress components be checked for fatigue (ASME, 2019). This mandate is reinforced at the national level: the hydrocarbon-sector framework (Decreto 1073 de 2015, Ministerio de Minas y Energía, 2015) and, most recently, Resolution MME 00574 de 2026 (Ministerio de Minas y Energía, 2026), the Reglamento de Transporte por Oleoductos, whose article on technical standards requires adherence to internationally recognized standards and expressly names API), and, for gas pipelines, the Colombian standard NTC 3728 (Instituto Colombiano de Normas Técnicas y Certificación [Icontec], 2011), which in its special-crossings clause (§5.5.1) directs special works to follow the requirements of API RP 1102, while its design-factor table (Table 2B) and design-load list (§3.2.2.1) separately distinguish railway crossings and external-load effects; this technical standard is complemented by the Reglamento Técnico de Gasoductos (Ministerio de Minas y Energía, 2024). Against this backdrop, the present findings carry three concrete implications.

First, although the reference to API RP 1102 is well established, the national instruments do not specify how the railway branch (§4.5) in particular is to be applied to high-density urban crossings, nor do they prescribe a uniform fatigue-assessment and passage-frequency requirement; these are presently resolved on a project-by-project basis through concession-specific specifications. Explicitly designating §4.5 as the reference method, with an associated fatigue check per §4.7, would close this specification gap and give both the pipeline operator (Cenit/Ecopetrol) and the railway concessionaire (under ANI) a common, auditable acceptance criterion — consistent with the fatigue requirement already mandated by ASME B31.4 §402.8. Second, because the governing criterion identified here is the girth-weld fatigue limit rather than the static stress, this regulatory specification is not a formality but a safety-relevant gap. Third, the co-responsibility for crossing integrity sits across two separately regulated sectors (energy, under the Ministerio de Minas y Energía and the Superintendencia de Industria y Comercio; transport, under ANI and Inviás); a formal inter-agency protocol assigning monitoring and re-evaluation duties — triggered by changes in MAOP, rolling stock, or burial depth — would close the principal coordination gap exposed by this analysis.

CONCLUSIONS

The analysis, conducted in full accordance with API RP 1102 §4.5 (railway crossings) for the Yumbo-Buenaventura 12-in API 5L X65 pipeline under Cooper E-80 design loading and GE ES44AC operational loading, yields the following conclusions:

1. Structural compliance under Cooper E-80 design loading. The pipeline, buried at the mandatory minimum depth of 1.80 m, satisfies all API RP 1102 acceptance criteria with a combined effective stress of 37.259 psi — 79.6 % of the allowable limit (= 46.800 psi) for single track and 81.4 % for double track, both confirming that the pipeline corridor is structurally compatible with heavy-haul freight railway operations under controlled conditions.
2. Fatigue criterion near-critical — compliance with limited margin. $\Delta S_{Hr} = 7\,609$ psi satisfies $\Delta S_{Hr} \leq SFG \times F = 8\,640$ psi (88.1 % utilized) and constitutes the tightest compliance margin; $\Delta S_{Lr} = 7\,494$ psi satisfies $\Delta S_{Lr} \leq SFL \times F = 16\,560$ psi (45 % utilized). Any combination of wall loss ≥ 15 %, axle loads exceeding Cooper E-80 by ≥ 10 %, or burial depth below 1.80 m would drive ΔS_{Hr} beyond the fatigue endurance limit, requiring a dedicated assessment per API 579-1/ASME FFS-1 Part 14.
3. Internal pressure remains the dominant stress mechanism. The operating pressure contribution ($S_{Hi} = 29.750$ psi) represents approximately 75 % of the dominant principal stress $S_I = 39.448$ psi. External railway live loads contribute < 4 % to total stress, underscoring that pressure control and corrosion management remain the primary drivers of long-term pipeline integrity at railway crossings.
4. Wall thickness loss is the dominant risk factor. Sensitivity analysis demonstrates that a 38 % reduction in wall thickness (from $t_{nom} = 0.375$ in to $t_w \leq 0.233$ in) drives $Seff$ to the allowable limit, establishing wall condition as the primary determinant of crossing integrity. This finding reinforces the mandatory requirement for ILI-based integrity verification before any railway construction or rehabilitation work over the pipeline.

Under the analyzed conditions — Cooper E-80 design loading, minimum 1.80 m burial depth, API 5L X65 pipeline with 20 % corrosion allowance, and

MAOP = 1400 psi — the pipeline exhibits safe, stable behavior fully compliant with API RP 1102. The results establish that Colombia's emerging railway network can coexist safely with existing buried hydrocarbon infrastructure, provided that the mandatory burial depth, integrity management protocols, and engineering oversight prescribed herein and in API RP 1102 are rigorously implemented.

RECOMMENDATIONS

Railway crossing design and management

Minimum burial depth — non-negotiable

A minimum burial depth of 1.80 m (pipe crown to finished grade, including ballast subgrade) shall be maintained throughout the full influence zone of the railway crossing. Any reduction below this value shall trigger immediate re-evaluation per API RP 1102 §4.5 and, if necessary, installation of reinforced concrete protective slabs or steel casing.

Pre-crossing integrity verification (API, 2019).

Prior to authorizing any railway construction or rehabilitation work over an existing pipeline, the mechanical integrity of the affected segment shall be confirmed through: direct visual inspection via excavation at all planned crossing points; review of In-Line Inspection (ILI) smart-pig data (MFL, UT, geometry tools) within the previous five years; and NDT verification if anomalies are suspected. The pipeline shall be free of corrosion metal loss $\geq 30\%$ of nominal wall thickness, dents $> 6\%$ of diameter, or any mechanical damage, before railway construction may proceed.

Crossing geometry

The railway shall cross the pipeline at an angle as close to 90° as practicable (minimum 70° per API RP 1102 §4.3.1) to minimize the length of pipeline exposed to railway live loads and to simplify the API RP 1102 stress calculation. Skewed crossings with angles $< 70^\circ$ require supplementary finite-element analysis.

Casing pipe consideration

While API RP 1102 and modern practice in many jurisdictions have moved away from mandatory casing for non-carrier pipe scenarios (due to the risk of annular corrosion under casing), casing pipes may be required by specific Colombian regulatory or concession framework

provisions. Where casing is installed, API RP 1102 §4.8 procedures for cased crossings shall be applied; where uncased crossings are permitted, the present methodology (§4.5, uncased) applies directly.

MAOP control and re-evaluation

Any increase in operating pressure above the MAOP used in the API RP 1102 analysis (1400 psi for this study) shall require a full re-evaluation of all stress components and compliance criteria before implementation.

Operational and monitoring

Integrated monitoring protocol

A joint monitoring protocol shall be established between the pipeline operator and the railway concessionaire, including regular topographic surveys of burial depth in the crossing zone; periodic above-ground corrosion survey (ACVG, DCVG, or CIPS) along the crossing influence zone; vibration monitoring during initial high-speed train operations; and coordinated emergency shutdown procedures.

Fatigue monitoring for high-density operation

For railway corridors with scheduled traffic exceeding 50 train passages per day on a sustained basis, cumulative fatigue damage shall be formally tracked using cycle counting and the Palmgren-Miner rule per API RP 1102 §4.7. Records of train type, axle load, speed, and passage frequency shall be maintained for the duration of operations.

Change management for heavier rolling stock

If rolling stock with axle loads exceeding the Cooper E-80 controlling axle (80 kips / 356 kN) is introduced on the corridor — as may occur with ultra-heavy haul mineral railways — the crossing analysis shall be repeated with updated load parameters before service commencement. Similarly, any change in track configuration (rail type, sleeper spacing, ballast depth) shall trigger a review of the load transmission model.

Protection during railway construction

During railway construction and rehabilitation works, heavy construction equipment (cranes, ballast regulators, tamping machines) may impose loads comparable to or exceeding Cooper E-80 at shallow burial depths.

An API RP 1102 assessment of construction equipment loads shall be conducted prior to construction commencement, with mechanical protection (concrete slabs, steel plates) installed if required.

Implications for Colombia's Railway Development Program

The results and methodology of this study are directly applicable to the engineering assessment requirements of Colombia's three principal active railway development projects:

- **Corredor Férreo del Pacífico (Buenaventura-La Tebaida-La Felisa).** Highest priority for pipeline-railway coexistence assessment, given the dense Cenit multiproduct network in Valle del Cauca. The Yumbo-Buenaventura pipeline analyzed in this study is a direct case study for this corridor.
- **Tren del Caribe (La Dorada-Chiriguaná rehabilitation).** Crossings with the ODC and Ocesa pipelines in the Magdalena Valley require systematic API RP 1102 §4.5 assessments, particularly for the Ocesa 24-in X70 pipeline segments where higher operating pressures reduce the stress margin.
- **Regiotram de Occidente (Bogotá-Facatativá light rail).** Lower axle loads (light rail) relative to Cooper E-80 result in more conservative stress margins; however, the high frequency of urban light-rail operations (up to 300+ passages/day) necessitates rigorous fatigue assessment per API RP 1102 §4.7.

The authors recommend that Colombia's pipeline and railway regulatory agencies — specifically the Ministerio de Minas y Energía, Invías, ANI, and the Superintendencia de Industria y Comercio — formally adopt API RP 1102 §4.5 as the mandatory technical standard for engineering assessment of all new railway crossings over buried steel pipelines, supplemented by the regional calibrations and sensitivity analysis framework demonstrated in this study. Its integration into Pipeline Integrity Management Systems (PIMS), in accordance with API 1160 and ASME B31.8S, would harmonize risk-management practices and promote the safe, sustainable development of Colombia's railway and energy infrastructure in parallel.

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ANNEX

The methodology evaluates the following principal stress components and acceptance criteria (§4.6 and §4.6 API RP 1102), as shown in Figure 1. The figure references the equations, figures, and acceptance criteria from API RP 1102, listed in order of appearance in this document. These equations are subsequently applied in the results section, with the corresponding citations repeated for completeness and traceability.

The factors related to the pipeline and the terrain such as depth, geometry, stiffness of the track or railway, type of road, impact factor, type of pavement and resistance limits, to proceed with the calculation of the stresses on the pipeline, are described below:

- B_g : Burial factor for circumferential stress per ground load.
- E_g : Digging factor for circumferential stress per ground load.
- G_{Hb} : Geometry factor for the cyclic circumferential stress of vehicle load on tracks.
- G_{Lb} : Geometry factor for the cyclic longitudinal stress from the loading of vehicles on tracks.
- K_{He} : Stiffness factor for the circumferential stress of the ground load.
- K_{Hb} : Stiffness factor for the cyclic circumferential stress of road vehicle load.
- K_{Hr} : Stiffness factor for the cyclic circumferential stress of railway cargo.
- K_{Lb} : Stiffness factor for the cyclic longitudinal stress of the road load.
- L : Road axle configuration factor.
- F_i : Impact factor (taken from API RP 1102 as 1.5).
- A : Road pavement type factor.
- RL : Longitudinal stress reduction factor due to fatigue.
- SFG : Fatigue strength limit of circumferential welding.
- SFL : Fatigue strength limit longitudinal welding.
- ΔS_{Hb} : Cyclic circumferential stress of the load of vehicles on roads, in psi or kPa.
- ΔSL : Cyclic longitudinal stress, in psi or kPa.
- ΔS_{Lb} : Cyclic longitudinal stress of road vehicle load, in psi or kPa.
- S_{Hr} : Internal pressure stress.
- S_{He} : Ground load stress.
- ΔSH : Stress by live loads.
- S_1, S_2, S_3 : Main efforts.
- S_{eff} : Total effective effort.
- w : Applied design surface pressure.

Figure 1

Flow diagram of procedure for uncased crossings of highways. Adapted from API RP 1102 (API, 2007)

