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Original
Análise do Ciclo de Vida de um Pneu de Passeio no Brasil: Seleção de Material da Banda de Rodagem e Aspectos de Gestão de Fim de Vida / Maluf Filho, W.M., Evangelista, P.A., Ganharul, G.K.Q., Pinheiro, H.D.C., Duran, G.C., Alves, M.A.L., De Andrade, G.S.. - ELETTRONICO. - 13/1:(2026), pp. 204-229. (XXXIII International Symposium on Automotive Engineering (SIMEA 2026) Sao Paulo (Brazil) 26-27/08/2026) [10.5151/2357-7592-pap30].

Availability:
This version is available at: 11583/3016347 since: 2026-10-06T08:28:27Z

Publisher:
Blucher Engineering Proceedings

Published
DOI:10.5151/2357-7592-pap30

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27 October 2026

Life Cycle Assessment of a Passenger Car Tire in Brazil: Tread Material Screening and End-of-Life Management Insights

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ABSTRACT

This study assesses the life cycle of a standard passenger car tire in the Brazilian context using Ansys Granta EduPack. A representative 195/65R15 tire was modeled considering constituent materials, manufacturing routes, a simplified 2000 km transport stage, a 5-year service life, and 75,000 km of use. Carbon and energy footprints were estimated for the main life-cycle stages. The results indicate that the use phase is the dominant contributor to tire carbon footprint under the adopted assumptions.

Based on vehicle dynamics, the tread was identified as the most relevant functional element for a preliminary material-selection study. Using an Ashby-based approach, elastomer candidates were screened and EVA was selected for comparative assessment due to its recyclability. However, the subsequent life-cycle analysis showed that replacing conventional tread rubber with EVA increased both carbon and energy footprints, despite improving end-of-life potential. An additional scenario assuming correct end-of-life destination for all tires reduced carbon footprint, although without energy-footprint gains.

Within the limits of the simplified model, the results suggest that end-of-life management is a more promising lever than direct EVA substitution for improving tire sustainability.

1) INTRODUCTION

The transport sector is among the most significant contributors to global greenhouse gas (GHG) emissions, with road transport alone responsible for roughly 70% of all transport-related CO_2-equivalent emissions worldwide [1]. Within this sector, passenger cars and light-duty vehicles concentrate the largest share of fuel-related emissions and have therefore become a primary focus of decarbonization strategies, both through powertrain electrification and through incremental efficiency gains in conventional components [2].

Among these components, tires play a disproportionately large role because they mediate every longitudinal and lateral force exchanged between the vehicle and the road and, through rolling resistance, directly govern a meaningful fraction of vehicle energy consumption [3]. Empirical evidence indicates that tire rolling resistance is responsible for approximately 20% to 30% of the fuel consumption of internal combustion vehicles and for an even higher share of the energy demand of battery electric

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vehicles, where it can reach roughly 25% of total tractive energy [4].

Consequently, even modest reductions in rolling resistance translate into measurable reductions in tailpipe CO_2 emissions and local pollutants such as CO and NO_x across the in-use phase of the vehicle [5].

Beyond their influence on energy consumption, tires also generate substantial environmental impacts through their material composition, manufacturing energy intensity, and post-consumer fate. Recent reviews report that global tire production is approaching 2.5 billion units per year, with more than one billion units reaching the end-of-life condition annually and representing close to 2% of total global solid waste by mass [6].

Tires are non-biodegradable composite products typically containing 40–65% natural and synthetic rubber, around 20% carbon black, reinforcing steel cords, textile fibers, vulcanization agents, and processing oils, a composition that makes both their production and their disposal environmentally demanding [7].

Furthermore, tire wear particles have been identified as the largest single contributor to primary microplastic emissions in the environment, with global annual releases estimated at approximately 5.9 million tons and additional concerns associated with the leaching of tire-specific additives such as 6PPD-quinone [8]. Such evidence reinforces the view that the environmental burden of tires extends well beyond their carbon footprint and justifies a comprehensive life-cycle perspective when evaluating design alternatives.

Life Cycle Assessment (LCA), as standardized by the ISO 14040 family of norms, has emerged as the canonical methodology to quantify these multi-stage environmental burdens through the four interrelated phases of goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation [9]. Systematic reviews of tire LCA studies consistently identify the use stage as the dominant contributor to climate change, acidification, and primary energy demand, while raw-material acquisition and manufacturing carry the heaviest burden on human toxicity and resource depletion indicators [10].

Comparative LCA results obtained for representative passenger car tires using Eco-indicator 99, Cumulative Energy Demand, and IPCC characterization factors confirm this pattern and additionally emphasize the sensitivity of conclusions to assumptions about service life, mileage, and end-of-life routing [11]. Software tools such as Ansys Granta EduPack support this type of analysis by integrating curated materials databases with eco-audit and material-selection capabilities, making structured early-stage assessment of design alternatives accessible to engineering teams [12].

Designing for lower life-cycle impact ultimately requires acting on the tire components that most directly govern in-use performance and wear, and the tread is the natural focus of such intervention because it both transmits the contact-patch forces that determine handling and absorbs the largest share of material loss during operation [13].

Tread compound design, however, is constrained by the well-known "magic triangle" of conflicting objectives connecting rolling resistance, wet grip, and abrasion resistance, in which improving one attribute typically penalizes at least one of the others [14].

Modern tread formulations rely heavily on reinforcing fillers, notably carbon black and precipitated silica, whose proportions and surface chemistry govern the dynamic mechanical response of the rubber and therefore its hysteretic losses and wear rate [15]. Recent research has explored hybrid carbon-black/silica systems, bio-based plasticizers, and rice-husk-derived green silica as routes to decouple these conflicting attributes while reducing fossil-resource intensity [16]. Within this design space, the systematic material-selection methodology proposed by Ashby, which translates functional requirements into performance indices and screens candidate materials on logarithmic property charts, provides a transparent framework for narrowing the candidate field before more detailed compound-level testing [17].

The Brazilian context introduces additional specificity to this discussion. Brazil hosts one of the ten largest tire-producing industrial bases in the world and operates a mature Extended Producer Responsibility scheme grounded in CONAMA Resolution No. 416/2009 and Normative Instruction No. 001/2010, under which manufacturers and importers must ensure environmentally adequate destination of one waste tire for every new tire placed in the replacement market [18]. Comparative analyses of Latin American end-of-life tire (ELT) management systems indicate that Brazil, together with Argentina and Mexico, has reached relatively high formal recovery rates, although significant volumes of ELTs still reach unlawful sites and create localized public-health risks such as the proliferation of disease vectors in stagnant water accumulated in stockpiled units [19].

In Brazil, coprocessing in cement kilns absorbs the largest share of recovered ELT mass, complemented by granulation, lamination, and an emerging contribution from pyrolysis, the latter offering the technical possibility of recovering pyrolysis oil, recovered carbon black, and steel for reincorporation into the tire value chain under circular-economy principles [20].

Given that the use phase dominates the carbon footprint and that the tread governs both wear and rolling resistance, the joint examination of tread-material screening and end-of-life management appears as a natural and timely line of inquiry for the Brazilian context, and constitutes the central objective of the present work.

2) LITERATURE REVIEW

2.1) STRUCTURE AND MATERIALS OF PASSENGER CAR TIRES

A modern passenger car tire is a composite engineering artifact in which several functionally specialized layers cooperate to deliver simultaneously load support, traction, comfort, and durability [21]. The tread is the outermost rubber layer that establishes direct contact with the road surface and is therefore responsible for grip, water drainage through grooves and sipes, and the bulk of abrasive wear during service [22]. Beneath the tread, the belt package, typically formed by two cross-plied steel-cord layers, stiffens the crown region, stabilizes the contact patch, and protects the carcass from external impacts [23].

The carcass plies act as the load-bearing skeleton of the tire and are composed of fabric cords of polyester, nylon, rayon, or aramid embedded in rubber, with their orientation defining the distinction between radial and bias-ply constructions [24].

The bead consists of high-strength steel cables encased in rubber that anchor the tire to the wheel rim and ensure airtight sealing under inflation pressure [25]. An inner liner of low-permeability halobutyl rubber retains the inflation gas and has progressively replaced the inner tube of earlier tire generations [26]. The natural rubber that is widely used in carcass and sidewall compounds is obtained almost exclusively from the latex of Hevea brasiliensis, a tropical species native to the Amazon basin and currently cultivated mostly in Southeast Asia, whose supply chain has been identified as a strategic sustainability concern for the global automotive sector [27].

2.2) LIFE CYCLE ASSESSMENT METHODOLOGY APPLIED TO TIRES

The Life Cycle Assessment (LCA) framework formalized by the ISO 14040 family of standards has become the reference methodology for quantifying environmental burdens of engineered products across raw-material acquisition, manufacturing, use, and end-of-life stages [28].

In the specific context of tires, the cradle-to-grave scope is the most common choice, although cradle-to-gate analyses focused on the manufacturing phase remain useful for benchmarking specific production routes and identifying internal hotspots [29]. The functional unit definition is a critical methodological choice and is typically expressed as a single tire of a given size operated over a defined mileage and service life, since this choice directly governs the allocation of in-use fuel consumption between the tire and the rest of the vehicle [30]. Life cycle inventories for tire LCA usually combine primary data from manufacturers with secondary data from curated databases such as Ecoinvent and the GREET model, and the resulting impact profiles can vary appreciably depending on the choice and vintage of the inventory source [31].

Earlier case studies that adopted process-based, cradle-to-grave inventories for a single passenger car tire reported total life-cycle greenhouse gas emissions of the order of one to two hundred kilograms of CO_2 equivalent per unit, with strong sensitivity to assumed annual mileage and fuel mix [32]. Eco-indicator 99 results obtained for a representative summer tire confirmed that the use phase is the principal driver of damage to human health and resources, while the production phase remains the dominant contributor to ecosystem-quality categories such as toxicity and acidification [33]. Independent LCA work conducted with silica-silane tread technology under ISO 14040 and 14044 protocols further documented measurable reductions in global warming potential associated with rolling-resistance improvements when filler systems are reformulated [34].

2.3) VEHICLE DYNAMICS AND THE TIRE-ROAD INTERFACE

From a vehicle-dynamics perspective, the tire is the unique mechanical element capable of generating the longitudinal and lateral forces that govern acceleration, braking, and cornering response, and its behavior is fundamentally non-linear with respect to load, slip, and inclination [35]. The empirical Magic Formula, originally proposed by Pacejka and now embedded in nearly every commercial vehicle-dynamics simulation environment, captures this non-linear response by fitting a small set of coefficients that describe the relationship between slip quantities and the resulting tire forces and moments [36].

The lateral force generated under cornering grows almost linearly with the slip angle for small values, reaches a peak typically located between three and six degrees, and then decays into a sliding regime in which the available friction has been exceeded [37]. The slope of this curve at the origin, designated as the cornering stiffness, is the single parameter that most directly characterizes the steady-state handling response of the vehicle and is itself a function of vertical load, inflation pressure, and tread compound stiffness [38].

The camber angle of the wheel introduces a secondary lateral-force contribution, whose stiffness is typically about one order of magnitude smaller than the cornering stiffness in conventional passenger cars and which becomes critical during body roll in cornering maneuvers [39]. Beyond steady-state response, the dynamic characteristics of the contact patch dictate ride comfort, noise, vibration, and harshness performance, and recent research employing flexible-ring models such as FTire has improved the resolution with which these phenomena can be simulated across diverse road textures [40].

2.4) ROLLING RESISTANCE, TREAD WEAR, AND THE PERFORMANCE TRIANGLE

Tread compound design is dominated by what the industry terms the magic triangle of performance, in which rolling resistance, wet grip, and abrasion resistance

constitute three mutually conflicting objectives that cannot be maximized simultaneously [41]. The fundamental physics underlying this conflict resides in the viscoelastic dissipation of the rubber, since the same hysteretic losses that provide microscopic adhesion to road asperities under wet conditions also generate the macroscopic energy losses that manifest as rolling resistance during steady-state operation [42].

Empirical reports indicate that current passenger-car treads exhibit material loss rates of approximately 0.06 to 0.09 millimeters per thousand kilometers under normal driving conditions, with marked sensitivity to compound stiffness, contact-patch temperature, and driving aggressiveness [43].

The progressive replacement of carbon black by precipitated silica in solution-styrene-butadiene-rubber compounds, in conjunction with bifunctional silane coupling agents, has enabled simultaneous reductions in rolling resistance and improvements in wet grip while preserving abrasion performance, and constitutes the most significant compound innovation of the last three decades [44].

More recent investigations have explored hybrid carbon-black and silica systems, demonstrating around ten percent increases in tensile strength and twenty percent improvements in elongation at break relative to single-filler reference compounds [45]. Parallel work on the styrene content of solution-styrene-butadiene-rubber has shown that higher styrene fractions promote silica dispersion, raise crosslink density, and translate into measurable improvements across all three vertices of the performance triangle [46].

The economic significance of these improvements is substantial, as a twenty percent reduction in rolling resistance has been estimated to yield approximately five percent fuel savings at the fleet level, equivalent to billions of liters of gasoline avoided annually under B-class green-tire labeling regimes [47].

2.5) ENVIRONMENTAL IMPACTS OF THE IN-USE PHASE

The dominance of the use phase in tire LCA results derives not only from the cumulative fuel consumption associated with rolling resistance but also from the release of particulate matter into the environment as the tread wears against the road [48]. Tire wear particles are now recognized as the largest single source of primary microplastics, with downstream transport into stormwater, sediments, and the marine environment well documented in recent monitoring campaigns [49]. The transformation product 6PPD-quinone, generated by ozonation of the antioxidant N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine used in virtually all commercial tire compounds, has been causally linked to acute mass mortality events of coho salmon in the Pacific Northwest at threshold concentrations below one microgram per liter [50]. Subsequent monitoring of urban watersheds entering Lake Ontario confirmed elevated wet-weather concentrations of 6PPD-quinone in streams with high road density, suggesting that landscape and traffic variables can be used to identify priority mitigation locations [51].

Toxicity studies extended to multiple freshwater invertebrate species have begun to populate species-sensitivity distributions necessary for ecological risk assessment of this contaminant beyond the original salmonid focus [52]. Airborne fractions of tire and road wear particles have also been characterized through purpose-built vehicle measurement platforms, confirming that finer particle classes contribute to the inhalable PM10 fraction and to non-exhaust emissions that grow in relative importance as tailpipe emissions decline [53]. In summary, the use phase imposes simultaneous burdens on climate change, on aquatic ecotoxicity, and on local air quality, all of which depend strongly on tread-compound formulation and on tire wear behavior.

2.6) END-OF-LIFE MANAGEMENT AND CIRCULAR ECONOMY PATHWAYS

End-of-life management of tires has progressively shifted from landfilling toward a portfolio of material- and energy-recovery options that align with circular-economy principles [54].

Retreading remains the most direct route for extending tire service life and has been reported to preserve approximately seventy percent of the materials and avoid up to seventy-five percent of the CO_2 emissions associated with manufacturing a new tire, although its market share for passenger car tires is far smaller than for commercial truck tires [55].

Material recovery routes based on mechanical shredding and granulation yield crumb rubber that finds extensive application in civil engineering, particularly as an additive to asphalt binders for road pavements where it improves rutting resistance, fatigue tolerance, and durability [56]. Hybrid blends of devulcanized and conventional crumb rubber have recently been demonstrated to enable asphalt formulations with recycled-rubber contents above forty percent while preserving rheological and pavement-performance metrics, expanding the absorption capacity for end-of-life tire feedstock [57].

Pyrolysis has emerged as the most actively studied thermochemical valorization route, since it simultaneously recovers steel cords, pyrolysis gas suitable for internal process heating, pyrolysis oil with properties intermediate between diesel and gasoline, and recovered carbon black with semi-reinforcing properties [58]. Comparative LCA studies of pyrolysis versus conventional end-of-life pathways indicate that, when the functional unit is fixed at one tonne of end-of-life tires, advanced pyrolysis can outperform coprocessing on several impact categories provided that downstream products are effectively reincorporated into the value chain [59].

Recovered carbon black produced from end-of-life tire pyrolysis carries an estimated cradle-to-gate emission factor of approximately two kilograms of CO_2 per kilogram, against ten kilograms for virgin furnace carbon black, which translates into a decarbonization potential of roughly eighty percent when one-to-one substitution is technically feasible [60]. Comparative work on EPDM sealing compounds further indicates that recovered carbon blacks derived from end-of-life tires possess higher iodine adsorption number and reinforcement efficiency than those derived from waste plastics, confirming the feedstock-dependence of recyclate quality [61]. Recent reviews of LCA in the tire recycling and pyrolysis industry highlight the importance of consistent process-flow modeling and transparent allocation rules to avoid burden shifting between life-cycle stages [62].

2.7) MATERIAL SELECTION METHODS FOR SUSTAINABLE DESIGN

The systematic translation of life-cycle insights into design decisions requires methods that connect functional requirements, environmental indicators, and the discrete material-property data available to engineers [63]. Ashby-type performance indices, derived analytically from the governing equations of a chosen functional case, allow candidate materials to be ranked on logarithmic property charts in which iso-performance lines isolate the most promising regions of the materials space [64]. Extensions of the original methodology to multi-objective optimization and to mixed mechanical loading regimes have broadened its applicability to industrial cases that exceed the simple bending or tension archetypes of textbook treatments [65].

Multi-criteria decision-making methods such as the Analytic Hierarchy Process, TOPSIS, and Best-Worst Method are frequently coupled with material indices to incorporate qualitative considerations such as recyclability, supply-chain risk, and regulatory compliance into the final selection [66].

Integrated frameworks that combine eco-design principles with life-cycle assessment during the early design stages have been advocated as the most effective route to avoid sub-optimization at the component level and to make trade-offs explicit before tooling investments are committed [67]. Pareto-optimal decision trees populated with Life Cycle Sustainability Assessment indicators have been proposed as a prospective method that shifts quantitative multi-criteria analysis upstream into the conceptual phase, enabling early comparison of material and process alternatives [68].

Recent applications of these methods to rubber compound selection for tire applications have produced quantitative substitutability rankings between natural rubber options under sustainability constraints, demonstrating the transferability of the approach to the tread-material screening problem addressed in the present work [69].

3) THE BRAZILIAN TIRE INDUSTRY

3.1) THE ANIP SYSTEM

The institutional architecture that governs the Brazilian tire industry is organized around an integrated set of bodies collectively referred to as the ANIP System, which articulates the technical, regulatory, environmental, and labor dimensions of the sector under a single coordinated framework [70].

Within this system, ANIP itself performs the institutional representation of national tire manufacturers, while Reciclanip is exclusively responsible for the management and final destination of end-of-life tires on behalf of the affiliated manufacturers.

Technical standardization across Latin America is conducted under ALAPA, which harmonizes specifications, dimensional codes, and load and speed ratings throughout the regional industry. Labor representation of tire and inner tube manufacturers is centralized in SINPEC, while EMDAPI is the operational entity in charge of the processing and commercialization of end-of-life tire materials. This functional segmentation ensures that environmental responsibility, technical regulation, product standardization, and industrial relations are addressed through dedicated and specialized institutional channels, while preserving consistency at the system level. *Figure 1* illustrates the composition of the ANIP System and the specific role assigned to each of its constituent organizations.

Figure 1 – Institutional structure of the ANIP System and the specialized roles of its constituent organizations (ANIP, Reciclanip, ALAPA, SINPEC, and EMDAPI) within the Brazilian tire industry [70].

3.2) THE ROLE AND INDUSTRIAL FOOTPRINT OF ANIP

The National Association of the Tire Industry, ANIP, has operated since 1960 as the principal institutional representative of the tire and inner tube sector in Brazil, articulating dialogue between manufacturers and the federal government and contributing to the formulation of public policies aimed at strengthening the entire tire ecosystem. Its mandate encompasses three strategic pillars, namely market access, technical and tax compliance, and the environment, which together frame the sectoral agenda for economic, social, and sustainable development. Under this institutional umbrella, eleven manufacturers currently operate nineteen industrial facilities distributed across seven Brazilian states, with production capacity dimensioned to serve the domestic market in full compliance with applicable governance, technical, and tax standards.

The geographical concentration of the productive base in the southeastern and southern regions of the country reflects historical proximity to the automotive assembly industry, while the presence of facilities in the Northeast and in the Amazon region attests to the national reach of the sector.

Figure 2 presents the geographical distribution of the nineteen factories operated by the eleven affiliated manufacturers across the seven Brazilian states that host tire production.

Figure 2 – Geographical distribution of the nineteen tire manufacturing facilities operated by the eleven ANIP-affiliated manufacturers across seven Brazilian states (AM, BA, SP, RJ, PR, SC, and RS) [70].

3.3) EMPLOYMENT IN THE BRAZILIAN TIRE INDUSTRY

The Brazilian tire industry constitutes a meaningful source of formal employment and qualified labor, sustaining approximately thirty-five thousand direct jobs with an average monthly remuneration of about one thousand U.S. dollars and a total annual payroll of around three hundred and sixty-nine million U.S. dollars.

The labor footprint extends well beyond direct manufacturing employment, with an estimated five hundred thousand indirect jobs generated along the broader supply chain, including tire retail, vehicle manufacturing, retreading services, natural rubber extraction, synthetic fiber production, organic chemical manufacturing, and steel wire fabrication.

This distribution highlights the position of the tire industry as a multiplier of industrial activity within the national economy, linking primary agricultural and extractive activities to advanced manufacturing and after-market services.

The capillarity of indirect employment across multiple supplier tiers also reinforces the strategic relevance of the sector for regional development and for the consolidation of skilled industrial labor in Brazil.

Figure 3 summarizes the principal employment indicators of the Brazilian tire industry, encompassing both direct manufacturing positions and indirect jobs along the supply chain.

Figure 3 – Employment indicators of the Brazilian tire industry, including direct jobs, average monthly salary, total annual payroll, and indirect jobs distributed across the supply chain [70].

3.4) NET REVENUE, TAX CONTRIBUTION, PRODUCTION, AND SALES

The economic significance of the Brazilian tire industry is reflected in its aggregate financial and productive indicators. In 2024, the sector recorded net revenue of approximately 4.9 billion U.S. dollars and a tax contribution of about 874 million U.S. dollars, the latter expressing the substantive fiscal role of the industry within the national economy. Installed production capacity reached 51 million tires in 2024, while average annual sales over the preceding seven-year period were approximately 43 million units, indicating a sustained operational utilization compatible with both domestic demand and export commitments. These figures position the sector as a structurally relevant component of the Brazilian industrial base, with stable production volumes and predictable fiscal returns to the public treasury. The convergence between installed capacity and historical sales also signals a mature market in which incremental capacity expansions are predicated on long-term demand projections rather than on short-term cyclical movements. *Figure 4* consolidates the principal economic and productive indicators of the Brazilian tire industry for the reference year of 2024.

Figure 4 – Net revenue, tax contribution, installed capacity, and average annual sales of the Brazilian tire industry, with reference values for 2024 and historical averages for the preceding seven-year period [70].

3.5) INVESTMENTS

The Brazilian tire industry has sustained a robust investment trajectory aligned with capacity modernization, product development, and environmental performance. Over the past five years, the sector has committed approximately 1.6 billion U.S. dollars to industrial investments, and an additional 971 million U.S. dollars is projected for deployment over the next five-year horizon. This capital allocation pattern reveals a long-term strategic orientation toward technological upgrading, productivity gains, and alignment with international sustainability standards. The continuity of investment between past and projected

horizons signals industrial confidence in the domestic market and a steady commitment to maintaining Brazil's competitive position within the global tire manufacturing landscape. *Figure 5* presents the consolidated investment indicators of the Brazilian tire industry, contrasting realized investments over the past five years with planned investments for the next five-year period.

Figure 5 – Consolidated investment indicators of the Brazilian tire industry, comparing realized investments over the past five years with planned investments for the next five-year period [70].

3.6) TECHNOLOGY AND INNOVATION

The technological and innovation infrastructure of the Brazilian tire industry comprises sixteen specialized laboratories and three testing tracks distributed across the national territory, supporting both fundamental and applied research on tire performance, durability, and safety. Innovation efforts are concentrated on three principal fronts.

The first is the development of smart tires capable of incorporating embedded sensing technologies for real-time monitoring of operational variables such as inflation pressure, contact-patch temperature, and tread depth, thereby enabling predictive maintenance and integration with advanced driver-assistance systems.

The second is the substitution of mineral and petroleum-based feedstocks by alternative natural resources, in line with global decarbonization commitments and with the broader transition toward circular and bio-based materials in tire compounding.

The third is the consolidation of the national testing infrastructure as a competitive asset for product validation under tropical operating conditions, which differ materially from the temperate-climate scenarios that dominate the European testing landscape.

Taken together, these initiatives position the Brazilian industry as an active participant in the global technological frontier of tire engineering, rather than as a mere recipient of innovations developed elsewhere.

3.7) THE TIRE ECOSYSTEM

A The production of a passenger car tire involves a complex ecosystem of upstream raw material suppliers and downstream industrial customers whose coordinated operation is essential to deliver the performance and safety attributes demanded by modern vehicles. On the upstream side, five principal input streams converge into the manufacturing process, namely chemicals, natural and synthetic rubber, carbon black, metal reinforcements, and textile cords. Each of these inputs influences specific aspects of tire performance, including elasticity, abrasion resistance, structural integrity, and thermal stability, which in turn directly affect vehicle behavior. On the downstream side, the finished product is channeled into three principal market destinations, namely original equipment supply to automakers and body manufacturers, the replacement aftermarket, and the export market. The quality requirements imposed by each of these channels reinforce the need for high-grade raw materials and rigorous process control throughout the value chain. *Figure 6* represents the structure of the Brazilian tire ecosystem, illustrating both the upstream supply of raw materials and the downstream allocation of finished tires across original equipment, replacement, and export markets.

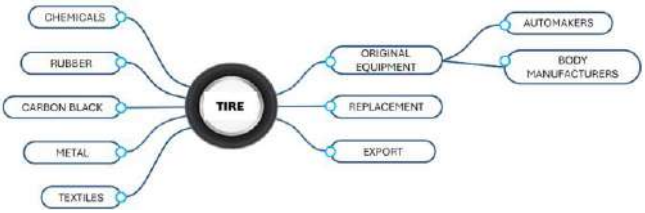


Figure 6 – Structure of the Brazilian tire ecosystem [70].

3.8) REVERSE LOGISTICS FOR END-OF-LIFE TIRES

The reverse logistics infrastructure for end-of-life tires in Brazil constitutes one of the most consolidated post-consumer waste management programs in the country and is currently the largest of its kind in Latin America and the third largest worldwide.

The program originated in 1999 with the National Program for the Collection and Disposal of Scrap Tires, implemented by ANIP, and was subsequently expanded into a nationwide operation. In 2007, the affiliated manufacturers founded Reciclanip as a dedicated organization exclusively responsible for the operational execution of reverse logistics, in compliance with the environmental targets established by the federal government and monitored through the Brazilian Institute of Environment and Renewable Natural Resources. Since 1999, cumulative investments of approximately 350 million U.S. dollars have supported the deployment of more than one thousand collection points across all twenty-seven Brazilian federative units, with full territorial coverage.

In 2024 alone, more than 394 thousand tons of end-of-life tires were properly disposed of, and the cumulative volume processed between 2011 and 2024 reached 5.6 million tons, with one hundred percent of the collected tires receiving environmentally adequate destination. These results document the operational maturity of the program and its alignment with the principles of Extended Producer Responsibility established by Brazilian environmental legislation. *Figure 7* summarizes the operational indicators of the reverse logistics program managed by Reciclanip,

including geographical coverage, cumulative investment, processed volumes, and disposal performance.

Figure 7 – Operational indicators of the Reciclanip reverse logistics program for end-of-life tires [70].

4) END-OF-LIFE TIRE MANAGEMENT IN BRAZIL: OFFICIAL RESULTS FOR 2024

4.1) REGULATORY FRAMEWORK

The Brazilian regulatory framework for the environmentally adequate destination of end-of-life tires is anchored in CONAMA Resolution No. 416, of September 30, 2009, which establishes that manufacturers and importers of new tires with a unitary weight exceeding two kilograms are jointly responsible for the collection and proper destination of end-of-life tires throughout the national territory.

The same resolution mandates the implementation of collection points in every municipality with a resident population above one hundred thousand inhabitants. Operational supervision of compliance is conducted by the Brazilian Institute of Environment and Renewable Natural Resources, IBAMA, through its Coordination of Waste and Emissions Control, which receives the mandatory annual declarations from manufacturers, importers, and destination companies. The declaration framework, initially established by IBAMA Normative Instruction No. 01 of 2010, was updated by Normative Instruction No. 09 of July 20, 2021, with the objective of improving procedural consistency and methodological transparency in the implementation of the resolution [71].

4.2) KEY DEFINITIONS

For the purposes of the regulatory framework, a tire is defined as a component of a wheel system constituted by elastomers, textile products, steel, and other materials that, when mounted on a vehicle wheel and pressurized with fluid, transmits traction through ground adhesion, elastically supports the vehicle load, and resists the pressure imposed by the ground reaction.

A new tire is one that has not been subjected to any use or reform and shows no signs of aging or deterioration, while a used tire is one that has undergone use or wear, including retreaded tires and unserviceable tires.

The category of end-of-life tire designates a used tire presenting irreparable structural damage that prevents both further service and reform. The environmentally adequate destination of end-of-life tires comprises technical procedures through which the tires are decharacterized from their initial form and their constituent elements are reused, recycled, or processed by techniques approved by the competent environmental authorities.

A collection point is defined as a location designated by manufacturers and importers for receiving and provisionally storing end-of-life tires [71].

4.3) METHODOLOGY FOR THE DETERMINATION OF THE DESTINATION TARGET

The destination target is calculated under a one-to-one rule, by which one end-of-life tire must receive adequate destination for each new tire commercialized in the replacement market. The conversion of the target to mass units incorporates a thirty percent discount associated with the wear factor of the new tire over its service life.

The replacement market itself is computed as the difference between the sum of domestic production and imports and the sum of exports and tires delivered to vehicle assemblers as original equipment, with each tire category classified under the Mercosur Common Nomenclature in accordance with GECEX Resolution No. 272 of November 19, 2021, and subsequent updates.

Manufacturers and importers file two complementary reports through IBAMA's online services, one detailing production, importation, exportation, and shipments to assemblers, and the other registering the location and storage capacity of declared collection points.

Destination companies, in turn, register the recipient manufacturer or importer, the quantity destined in kilograms, and the destination technology employed, with the system automatically reconciling the obligations and the executed destinations [71].

4.4) REPLACEMENT MARKET AND COMPLIANCE WITH THE NATIONAL DESTINATION TARGET

In 2024, the Brazilian replacement market for new tires reached 91,385,363 units, corresponding to 1,180,089.98 metric tons, computed from a domestic production of 65,490,968 units, imports of 54,033,265 units, shipments to assemblers of 19,138,254 units, and exports of 9,000,616 units.

The breakdown of the replacement market between manufacturers and importers is shown in *Figure 8*, which indicates that domestic manufacturers accounted for 56.43 percent of the market in 2024, while importers were responsible for the remaining 43.57 percent.

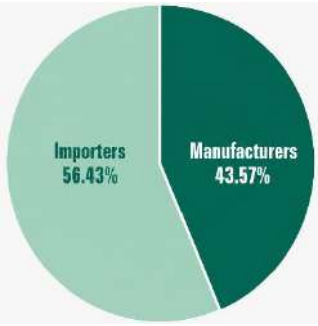


Figure 8 – Share of the Brazilian new tire replacement market between domestic manufacturers and importers in 2024 (units) [71].

The national destination target for 2024 was established at 826,062.98 metric tons, against an effectively destined balance of 784,111.58 metric tons, corresponding to an overall compliance rate of 94.92 percent. *Figure 9* presents the compliance ratio between destined and non-destined fractions of the national target for 2024, evidencing that approximately five percent of the obligation remained unfulfilled at the aggregate national level.

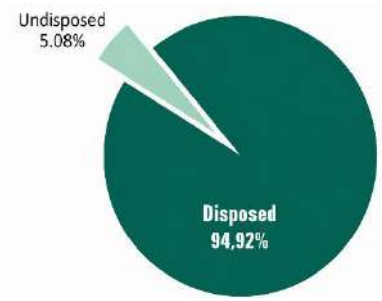


Figure 9 – Compliance with the national destination target for end-of-life tires in 2024, expressed as the percentage of destined and non-destined fractions [71].

Disaggregating the compliance by obligor category, domestic manufacturers reached 101.26 percent of their assigned target of 394,737.58 metric tons, with effective destination of 399,720.26 metric tons, whereas importers attained 89.12 percent of their target of 431,325.40 metric tons, with effective destination of 384,391.32 metric tons. The persistent gap between the two categories reflects a structural compliance differential that has characterized the Brazilian end-of-life tire management system across multiple reporting cycles.

4.5) DESTINATION TECHNOLOGIES AND GEOGRAPHICAL DISTRIBUTION

Four technologies are recognized by IBAMA as environmentally adequate destination routes for end-of-life tires. Coprocessing consists of the use of unserviceable tires in clinker kilns as partial substitutes for fossil fuels and as a source of metallic elements. Lamination corresponds to the manufacture of rubber artifacts from end-of-life tire material. Granulation is the industrial process of producing ground rubber at controlled particle sizes, with separation and recovery of the embedded steel. Pyrolysis is the thermal decomposition of the rubber matrix under absent or oxygen-limited conditions, generating oils, steel, and recovered carbon black as principal products.

In 2024, coprocessing remained the dominant route, absorbing 321,953.51 metric tons and accounting for 41.06 percent of the national destination, followed by granulation with 227,469.64 metric tons (29.01 percent), lamination with 209,222.54 metric tons (26.68 percent), and pyrolysis with 25,465.88 metric tons (3.25 percent).

The geographical distribution of destinations across Brazilian states confirms a strong concentration in the South and Southeast regions, with Paraná (15.16 percent), São Paulo (15.01 percent), Santa Catarina (12.49 percent), Goiás (11.63 percent), and Minas Gerais (10.63 percent) jointly accounting for nearly two thirds of the national total. At the regional level, the South region led with 33.19 percent of total destinations, followed by the Southeast with 30.04 percent, the Center-West with 25.42 percent, the Northeast with 9.49 percent, and the North with 1.86 percent.

4.6) HISTORICAL EVOLUTION OF THE REPLACEMENT MARKET

The historical trajectory of the Brazilian replacement market between 2009 and 2024 is shown in *Figure 10* in unit terms.

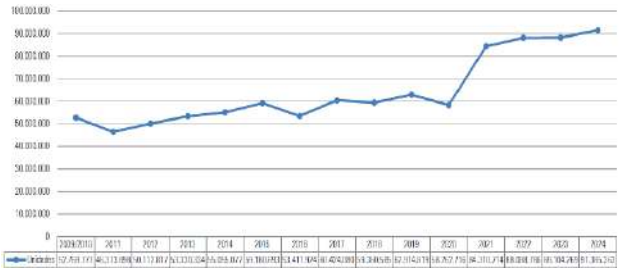


Figure 10 – Historical evolution of the Brazilian new tire replacement market between 2009 and 2024, expressed in units [71].

Figure 11 presents the same data in mass terms.

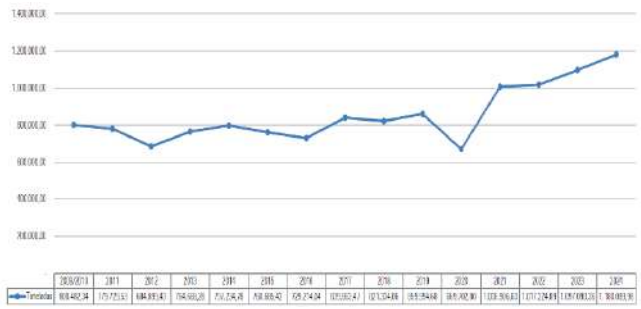


Figure 11 – Historical evolution of the Brazilian new tire replacement market between 2009 and 2024, expressed in metric tons [71].

The number of new tires placed in the replacement market grew from 52,769,777 units in the 2009/2010 cycle to 91,385,363 units in 2024, with a notable expansion observed between 2020 and 2021, when the volume rose from 58,262,716 to 84,310,714 units, reflecting the post-pandemic recovery of the Brazilian vehicle fleet activity. Between 2023 and 2024, the market expanded by approximately 3.28 million units, sustaining the upward trend.

In mass terms, the replacement market grew from 800,482.34 metric tons in the 2009/2010 cycle to 1,180,089.98 metric tons in 2024, surpassing the symbolic threshold of one million metric tons in 2021 and consolidating an upward trend that reflects both fleet growth and changes in the average tire size composition.

4.7) HISTORICAL COMPLIANCE WITH THE DESTINATION TARGET

The compliance performance of manufacturers and importers between 2009 and 2024 is shown in *Figure 12*, which evidences a recurrent gap between the two categories.

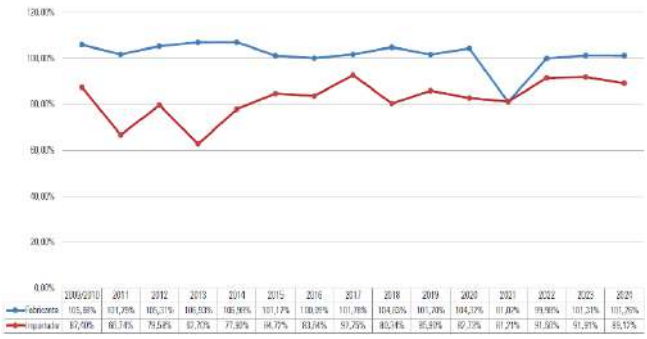


Figure 12 – Historical compliance with the national destination target for end-of-life tires by manufacturers and importers between 2009 and 2024 [71].

Manufacturers have consistently exceeded the one hundred percent compliance threshold across most reporting cycles, with the notable exception of 2021, when the rate fell to 81.02 percent, while importers have remained systematically below the target, oscillating between 62.70 percent and 92.75 percent across the series.

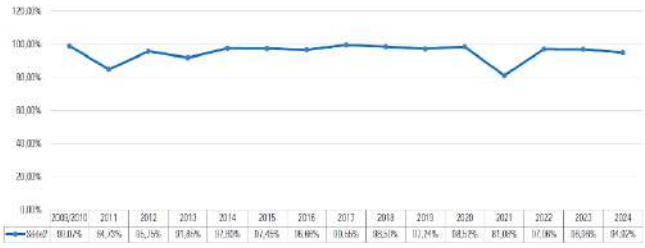


Figure 13 – Historical evolution of the aggregate national compliance rate with the destination target for end-of-life tires between 2009 and 2024 [71].

The aggregate national compliance rate, shown in *Figure 13*, has remained above 95 percent in most years, with the lowest values recorded in 2011 (84.73 percent) and 2021 (81.08 percent), and reached 94.92 percent in 2024.

Since 2013, IBAMA has conducted annual enforcement operations to identify cases of non-compliance with CONAMA Resolution No. 416/2009. The cumulative results of these operations comprise 727 companies investigated, 657 formal notifications issued, and 710 infraction notices filed, with aggregate financial penalties amounting to approximately 33.5 million Brazilian reais.

4.8) HISTORICAL EVOLUTION OF DESTINATION TECHNOLOGIES

The evolution of the destination technology mix between 2009 and 2024 is shown in *Figure 14* in percentage terms and in *Figure 15* in absolute mass terms.

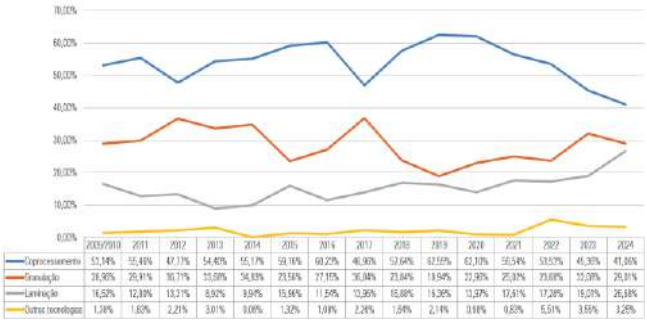


Figure 14 – Historical evolution of the destination technology mix for end-of-life tires in Brazil between 2009 and 2024, expressed as a percentage of the total destination [71].

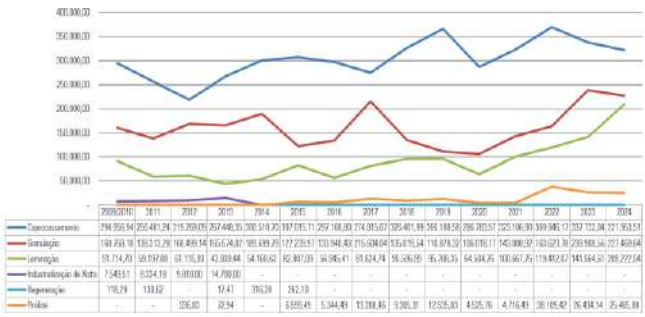


Figure 15 – Historical evolution of the destination technology mix for end-of-life tires in Brazil between 2009 and 2024, expressed in absolute metric tons [71].

Coprocessing in clinker kilns has remained the principal destination route throughout the series, although its share has progressively declined from a peak of 62.55 percent in 2019 to 41.06 percent in 2024, reflecting the diversification of the destination portfolio. Granulation has fluctuated around 25 to 35 percent, while lamination has grown markedly in recent years, rising from 9.94 percent in 2014 to 26.68 percent in 2024. Pyrolysis, although still representing a minor share, has shown sustained growth from negligible levels in the

early years of the series to 3.25 percent in 2024, with an intermediate peak of 5.51 percent in 2022.

In 2024, 37 cement companies declared coprocessing activities to IBAMA, consolidating this route as the principal industrial outlet for end-of-life tire material in Brazil.

The combined contribution of granulation and lamination, both of which generate intermediate rubber materials suitable for subsequent industrial applications, reached 55.69 percent of the national total, indicating a progressive shift toward material recovery alongside the traditional energy-and-material recovery via coprocessing.

4.9) COLLECTION POINTS INFRASTRUCTURE

The collection infrastructure declared by manufacturers and importers in 2024 comprised 1,197 collection points distributed across the national territory, of which 1,115 were located in municipalities with resident populations above one hundred thousand inhabitants. Forty-four municipalities meeting this population threshold remained without any declared collection point in 2024, indicating a persistent gap in the territorial coverage of the reverse logistics network.

4.10) CONCLUDING OBSERVATIONS FROM THE IBAMA REPORT

The 2024 results consolidate the Brazilian reverse logistics system for end-of-life tires as one of the most operationally mature mandatory take-back programs in the country, with national compliance approaching 95 percent and a diversified portfolio of environmentally adequate destination technologies. The data declared to IBAMA evidence the structural reliability of the system, while simultaneously revealing two persistent weaknesses, namely the systematic under-compliance of importers relative to domestic manufacturers, and the residual absence of collection points in a non-negligible number of large municipalities. The historical series, which now spans fifteen years of continuous reporting under CONAMA Resolution No. 416/2009, provides a robust empirical basis for the monitoring of the Brazilian extended producer responsibility framework and may serve as a methodological reference for analogous reverse logistics programs applied to other categories of post-consumer products.

5) PASSENGER CAR TIRES COMPONENTS

A passenger car tire is a complex composite component formed by multiple structural layers that operate cooperatively to deliver safety, comfort, and performance to the vehicle [72]. Each layer fulfills a specific mechanical or functional role and is manufactured from materials selected according to the intended service condition of the tire. A cross section of a passenger tire is presented in *Figure 16*.

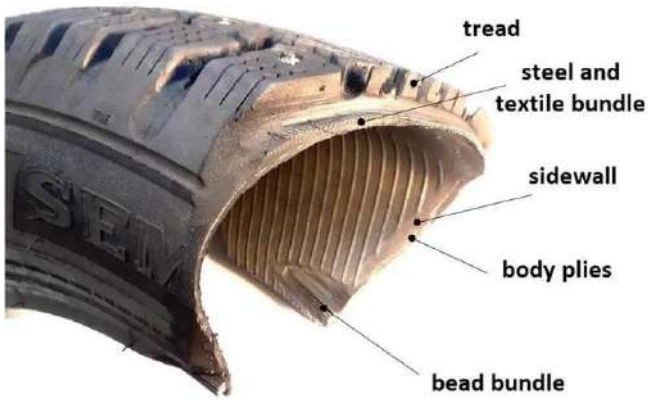


Figure 16 – Passenger car typical structure [73].

The innermost layer is the inner liner, manufactured from a halobutyl-based synthetic rubber compound specifically formulated to exhibit very low air permeability. This layer has progressively replaced the inner tube of earlier tire generations and is responsible for retaining the inflation pressure and preventing gas leakage through the tire structure [74].

Immediately above the inner liner are the carcass plies, formed by polyester, nylon, or steel cords embedded in a synthetic rubber matrix. These plies constitute the load-bearing skeleton of the tire and provide the combination of mechanical strength and flexibility required to support the vehicle weight without compromising ride comfort [75].

In the region adjacent to the wheel rim, the bead bundles ensure the structural anchoring of the tire to the wheel. These components are typically manufactured from high-carbon steel grades such as AISI 1070 or AISI 1080 and provide the radial stiffness required to prevent slippage between the tire and the rim during rotation under braking, traction, and cornering loads [76].

The sidewalls, located on the lateral surfaces of the tire, are composed of a flexible blend of natural and synthetic rubber and protect the carcass from external impacts, curb abrasion, and weathering, while simultaneously accommodating the cyclic deflection imposed by the vertical load [77].

Above the carcass, the steel belts consist of cross-plied steel-cord layers oriented at controlled angles relative to the circumferential direction. These belts increase the crown stiffness of the tire, stabilize the contact patch, and contribute to improved grip, dimensional stability, and tread wear life [78].

The tread, formed by an engineered blend of natural and synthetic rubber compounds, is the outermost layer that establishes direct contact with the road surface. Its geometry incorporates a tread pattern composed of grooves, sipes, and blocks designed to optimize water drainage, longitudinal traction, lateral grip, and noise behavior across diverse pavement and weather conditions. The specific composition

and number of constituent layers vary according to the tire category and its intended application [79].

Heavy-duty and commercial vehicle tires, for instance, employ stiffer compounds and additional reinforcement plies to withstand higher service loads and longer operating cycles, whereas passenger car tires prioritize ride comfort, low rolling noise, and rolling-resistance performance [80].

6) LIFE CYCLE ASSESSMENT OF A PASSENGER CAR TIRE

6.1) SCOPE, FUNCTIONAL UNIT, AND SIMPLIFYING ASSUMPTIONS

Any life cycle assessment requires prior specification of the simplifying assumptions that delimit the boundaries of the analysis, define the functional unit, and frame the interpretation of the results [81].

The present study addresses the life cycle of a conventional passenger car tire of medium dimensions, specifically a 195/65R15 unit operating under medium load capacity, which is taken as representative of the segment that dominates the Brazilian passenger vehicle fleet.

This simplification necessarily generalizes a broad and heterogeneous portfolio of commercially available products, but is considered methodologically adequate given the comparative and indicative nature of the analysis pursued in this work.

The assessment was conducted in the Ansys Granta EduPack environment, an educational software platform dedicated to teaching and applied work in materials science, design, and sustainability [82]. More refined investigations would naturally require commercial-grade tools coupled to specialized databases such as Ecoinvent or GaBi.

Nevertheless, for the scope and resolution targeted in the present analysis, the Granta EduPack environment provides a level of reliability and traceability that is consistent with the objectives of the study and aligned with the eco-audit methodology embedded in the tool.

6.2) MATERIAL COMPOSITION AND MANUFACTURING ROUTES

The first stage of the model consists in the specification of the constituent materials of the tire, of their associated manufacturing processes, and of the end-of-life routes assigned to each constituent [83].

The material composition adopted for the representative tire is presented in *Figure 17*, while the corresponding manufacturing processes and end-of-life routes are summarized in *Figure 18*.

Material, manufacture and end of life

Qty.	Component name	Material
1	Revestimento Interno (Borracha sintética - Reutilizado)	Polyisoprene rubber (unreinforced)
1	Revestimento Interno (Borracha sintética - Incinerado)	Polyisoprene rubber (unreinforced)
1	Lona da Carcaça (Poliéster)	Polyester (cast, flexible)
1	Lona da Carcaça (Borracha sintética - Reutilizada)	Polyisoprene rubber (unreinforced)
1	Lona da Carcaça (Borracha sintética - Incinerada)	Polyisoprene rubber (unreinforced)
1	Aros dos Talões (Aço AISI 1080)	Carbon steel, AISI 1080, normalized
1	Flancos (Borracha sintética - Reutilizada)	Polyisoprene rubber (unreinforced)
1	Flancos (Borracha sintética - Incinerada)	Polyisoprene rubber (unreinforced)
1	Flancos (Borracha natural - Reutilizada)	Natural rubber (15-42% carbon black)
1	Flancos (Borracha natural - Incinerada)	Natural rubber (15-42% carbon black)
1	Cintura Metálica (Aço AISI 1080)	Carbon steel, AISI 1080, normalized
1	Banda de Rodagem (Borracha sintética - Reutilizada)	Polyisoprene rubber (unreinforced)
1	Banda de Rodagem (Borracha sintética - Incinerada)	Polyisoprene rubber (unreinforced)
1	Banda de Rodagem (Borracha natural - Reutilizada)	Natural rubber (15-42% carbon black)
1	Banda de Rodagem (Borracha natural - Incinerada)	Natural rubber (15-42% carbon black)

Figure 17 – Material composition adopted for the representative medium-sized passenger car tire (195/65R15) modeled in Ansys Granta EduPack.

Material, manufacture and end of life

Qty.	Component name	Mass (kg)	Primary process	End of life
1	Revestimento Interno (Borracha sintética - Reutilizado)	0,112	Polymer molding	Downcycle
1	Revestimento Interno (Borracha sintética - Incinerado)	0,224	Polymer molding	Combust
1	Lona da Carcaça (Poliéster)	0,32	Polymer molding	Combust
1	Lona da Carcaça (Borracha sintética - Reutilizada)	0,112	Polymer molding	Downcycle
1	Lona da Carcaça (Borracha sintética - Incinerada)	0,224	Polymer molding	Combust
1	Aros dos Talões (Aço AISI 1080)	0,943	Wire drawing	Recycle
1	Flancos (Borracha sintética - Reutilizada)	0,359	Polymer molding	Downcycle
1	Flancos (Borracha sintética - Incinerada)	0,717	Polymer molding	Combust
1	Flancos (Borracha natural - Reutilizada)	0,306	Polymer molding	Downcycle
1	Flancos (Borracha natural - Incinerada)	0,612	Polymer molding	Combust
1	Cintura Metálica (Aço AISI 1080)	0,943	Extrusion, foil rolling	Recycle
1	Banda de Rodagem (Borracha sintética - Reutilizada)	0,538	Polymer molding	Downcycle
1	Banda de Rodagem (Borracha sintética - Incinerada)	1,076	Polymer molding	Combust
1	Banda de Rodagem (Borracha natural - Reutilizada)	0,459	Polymer molding	Downcycle
1	Banda de Rodagem (Borracha natural - Incinerada)	0,918	Polymer molding	Combust

Figure 18 – Manufacturing processes and end-of-life routes adopted for the constituent components of the representative medium-sized passenger car tire (195/65R15) modeled in Ansys Granta EduPack.

6.3) TRANSPORT STAGE

The second stage of the model addresses the transport phase, comprising both the inbound logistics of raw materials to the manufacturing plants and the outbound distribution of finished tires to the consumer market. A simplified scenario of 2,000 kilometers transported by a medium-sized truck was adopted as a first-order approximation. This simplification reflects the inherent difficulty of accurately characterizing transport distances at the national scale, given the continental dimensions of Brazil and the geographical dispersion between raw-material suppliers, manufacturing facilities, distribution centers, and end consumers.

Although the productive base and consumer demand are concentrated in the South and Southeast regions, the 2,000-kilometer assumption is retained throughout the analysis as a transparent and reproducible aggregate proxy.

The transport stage adopted in the model is depicted in *Figure 19*.

Transport

Name	Transport type	Distance (km)
Transporte médio dos pneus	32 tonne (4 axle) truck	2000

Figure 19 – Transport scenario adopted for the representative medium-sized passenger car tire (195/65R15) in the life cycle model.

6.4) USE PHASE

The third stage of the model defines the operational regime of the tire over its service life. A useful service life of 5 years and a cumulative mileage of 75,000 kilometers were adopted, in accordance with the upper-bound values typically recommended by tire manufacturers for passenger car applications.

The actual operational regime is recognized to be highly variable across users, vehicle types, road conditions, and maintenance practices, and the adopted values should therefore be interpreted as an upper reference scenario for the in-service performance of the modeled tire. The use phase as adopted in the model is illustrated in *Figure 20*.

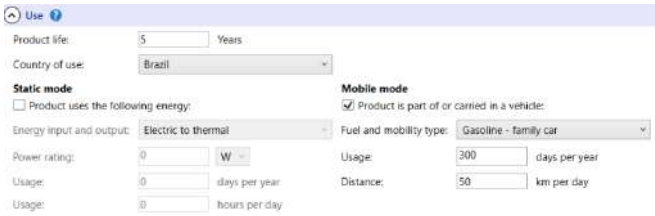
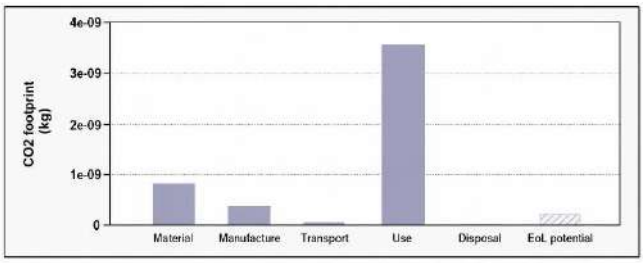


Figure 20 – Use phase regime adopted for the representative medium-sized passenger car tire (195/65R15) in the life cycle model, corresponding to a service life of 5 years and a cumulative mileage of 75,000 kilometers.

6.5) CARBON FOOTPRINT AND ENERGY FOOTPRINT RESULTS

Once the material composition, manufacturing routes, transport scenario, and use-phase regime have been specified, the model is closed by scaling the per-tire inventory to the annual production volume of the segment under analysis.

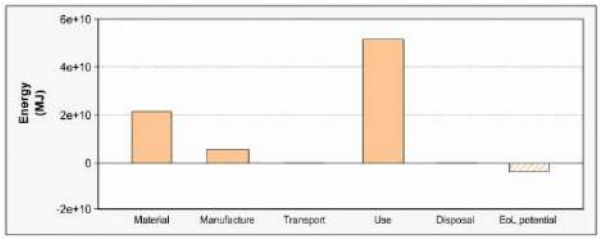
In accordance with the reference year adopted in this study, the per-unit inventory was multiplied by the approximately 27.5 million passenger annual passenger-car tire volume adopted for 2023, allowing the Ansys Granta EduPack environment to estimate the aggregate carbon footprint and energy footprint associated with each life cycle stage. *Figure 21* presents the carbon footprint of the representative passenger car tire disaggregated by life cycle stage.



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	9,51e+08

Figure 21 – Carbon footprint of the representative medium-sized passenger car tire (195/65R15) disaggregated by life cycle stage, scaled to the annual Brazilian production volume of 2023.

The same modeling framework was applied to the energy demand of the system, allowing the estimation of the cumulative energy footprint of the representative tire across its life cycle stages. The corresponding results are presented in *Figure 22.*



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	1,57e+10

Figure 22 – Energy footprint of the representative medium-sized passenger car tire (195/65R15) disaggregated by life cycle stage, scaled to the annual Brazilian production volume of 2023.

In order to facilitate the comparative reading of the results, the relative contribution of each life cycle stage to the total carbon and energy footprints is summarized in the column chart presented in Figure *23*.

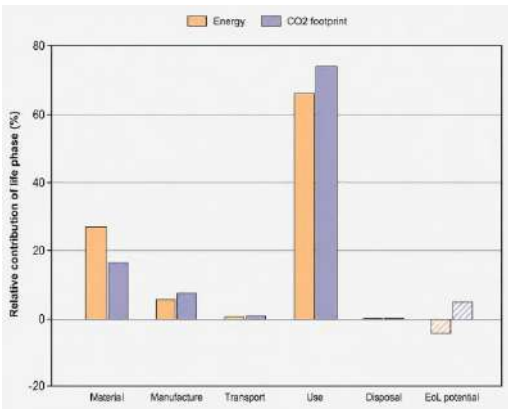


Figure 23 – Relative percentage contribution of each life cycle stage to the carbon and energy footprints of the representative medium-sized passenger car tire (195/65R15).

The aggregate numerical values are consolidated in *Table 1*.

Table 1 – Energy and carbon footprint of the representative medium-sized passenger car tire (195/65R15) by life cycle stage.

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	2,14e+10	27,2	8,16e+08	17,2
Manufacture	4,67e+09	5,9	3,67e+08	7,7
Transport	5e+08	0,6	3,6e+07	0,8
Use	5,18e+10	66,0	3,52e+09	74,1
Disposal	1,46e+08	0,2	1,02e+07	0,2
Total (for first life)	7,85e+10	100	4,75e+09	100
End of life potential	-2,93e+09		2,36e+08	

7) FUNDAMENTALS OF VEHICLE DYNAMICS

In the case of conventional passenger cars, all primary control and disturbance forces acting on the vehicle, with the exception of aerodynamic forces, are generated within the tire-road contact area. As stated by Gillespie [84], "the critical control forces that determine how a vehicle turns, brakes, and accelerates are developed in four contact patches no larger than the palm of a man's hand."

Within the framework of vehicle dynamics theory, the tire performs three fundamental functions, namely supporting the vertical load while damping road irregularities, generating longitudinal forces for acceleration and braking, and generating lateral forces for cornering. Although the tire is geometrically a simple viscoelastic toroid, it constitutes a complex non-linear system whose quantification through closed-form models is impractical; for the purposes of understanding its role in vehicle dynamics, it is sufficient to characterize its essential properties through empirical data.

7.1) COORDINATE SYSTEM

In order to standardize the description of operating conditions, forces, and moments experienced by a tire, the Society of Automotive Engineers (SAE) has defined the coordinate system shown in *Figure 24*.

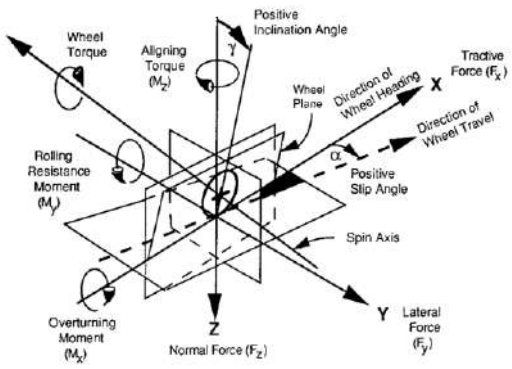


Figure 24 – SAE tire coordinate system [84].

From the SAE convention, the following definitions are adopted for the description of the tire and its associated reference frame. The wheel plane is the central plane of the tire perpendicular to the spin axis. The wheel center is the intersection of the spin axis with the wheel plane. The tire contact center is the intersection between the wheel plane and the projection of the spin axis onto the road plane. The tractive force Fx is the component of the force exerted on the tire by the road, lying in the road plane and parallel to the intersection between the wheel plane and the road plane; when oriented in the direction of vehicle motion, this component is referred to as the tractive force. The lateral force Fy is the component of the road-induced force lying in the road plane and normal to the intersection between the wheel plane and the road plane.

The normal force Fz is the component of the road-induced force perpendicular to the road plane and carries a negative magnitude under the SAE convention, while the vertical load is conventionally defined as the negative of Fz and is therefore expressed as a positive quantity. The overturning moment Mx acts about the axis parallel to the intersection between the wheel plane and the road plane. The rolling resistance moment My acts about the axis normal to that intersection. The aligning torque Mz acts about the axis normal to the road plane. The slip angle α is defined as the angle between the direction in which the wheel is pointed and the actual direction of travel, while the camber angle γ is the angle between the wheel plane and the vertical plane, with positive camber corresponding to the upper portion of the tire leaning outward relative to the vehicle.

7.2) MECHANICS OF FORCE GENERATION

The forces acting on a tire are not concentrated at a single point but rather result from normal and shear stresses distributed across the entire contact patch [84]. The pressure distribution beneath the tire is non-uniform along both the longitudinal and lateral directions, and under rolling conditions the pressure gradient tends to be higher on the leading edge of the contact patch, as illustrated in *Figure 25*.

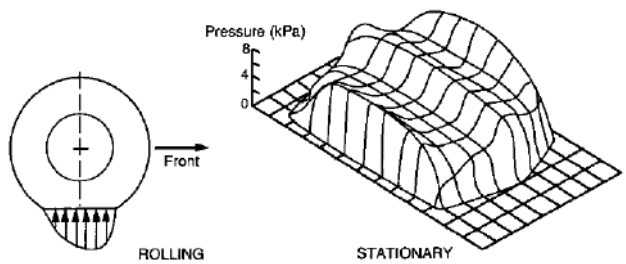


Figure 25 – Pressure distribution in tire contact patch [84].

Owing to the viscoelastic nature of the rubber compound, the deformation in the leading portion of the contact patch shifts the resultant of the vertical pressure slightly forward of the wheel center. As a consequence, the centroid of the vertical force no longer lies on the spin axis of the wheel, and a moment opposing the rolling motion is

generated, which constitutes the physical origin of the rolling resistance. As the tire rolls over the pavement, both tractive and lateral forces are developed through a shearing mechanism. Each element of the tread that enters the contact patch is subjected to a shear stress whose integration over the contact area yields the tractive and lateral forces developed by the tire.

The friction between the tire and the road surface is governed by two primary mechanisms, namely adhesion and hysteresis, as illustrated in *Figure 26*.

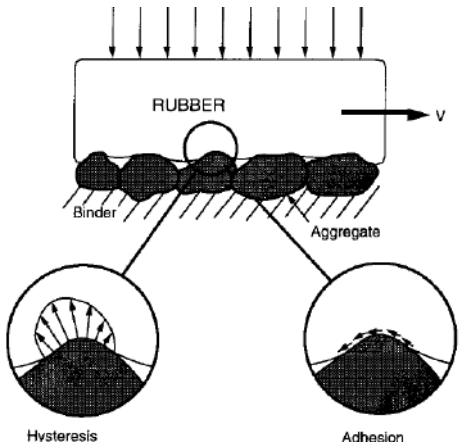


Figure 26 – Tire-road friction mechanisms: adhesion and hysteresis [84].

Hysteresis represents the energy dissipation that occurs within the rubber compound as it undergoes cyclic deformation in the contact patch, and is a bulk phenomenon that is essentially unaffected by the presence of water on the pavement [85].

Surface adhesion arises from intermolecular bonds established between the rubber compound and the asperities of the road surface, and is strongly influenced by the presence of a water film, since adhesion is consistently higher on dry pavements [86]. Both adhesion and hysteresis friction require a small amount of microscopic slip at the tire-road interface in order to operate, which means that tread abrasion is an intrinsic and unavoidable condition for the proper transmission of forces between the tire and the road [87].

7.3) CORNERING PROPERTIES

One of the most critical functions of the tire is the generation of the lateral forces required to control the heading of the vehicle, to produce the lateral acceleration imposed by cornering and lane-change maneuvers, and to resist external disturbances such as crosswind gusts [88]. These lateral forces are generated by lateral slip of the tire (slip angle α), by lateral inclination of the wheel plane (camber angle γ), or by a combination of both effects [89].

When a rolling tire is subjected to a lateral force, such as that imposed by a steering input, the tire begins to slip laterally relative to its plane [90]. A slip angle α is then established between the direction in which the tire is pointed and the actual direction in which it is traveling, as depicted in *Figure 27*.

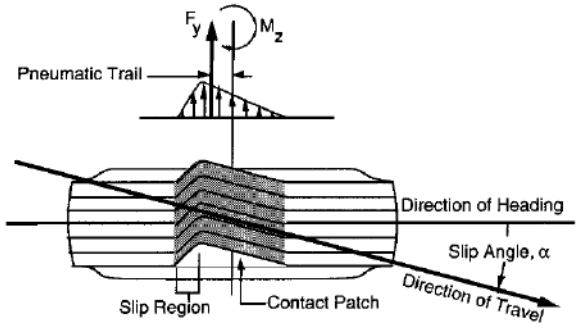


Figure 27 – Lateral deformation of a rolling tire subjected to a lateral force [84].

Immediately after the lateral force is applied, the tire begins to advance in a direction that differs from the orientation of the tread elements, while the portion of the tread in contact with the road remains momentarily aligned with its previous trajectory [91].

In this transient interval, the tread elements have not yet been displaced from their undeformed position and the tire cannot support any appreciable lateral force [92]. As the rolling continues, the tread elements in the contact patch progressively shear laterally relative to the centroid of the tire, and a growing lateral force Fy develops as a result of this distributed shear deformation [93].

Eventually, a condition may be reached in which the lateral force exceeds the available friction, leading to gross sliding of the contact patch [94]. This force-build-up mechanism is not instantaneous, but exhibits a delay relative to the development of the slip angle, owing to the time required for the tread to deflect laterally [95]. This transient is intrinsically linked to the rotation of the tire and typically requires between half a revolution and one full revolution for the lateral force to reach its steady-state value [96]. The longitudinal distance traveled during this transient phase is commonly referred to as the relaxation length [97]. The steady-state relationship between slip angle and lateral force is illustrated in *Figure 28*.

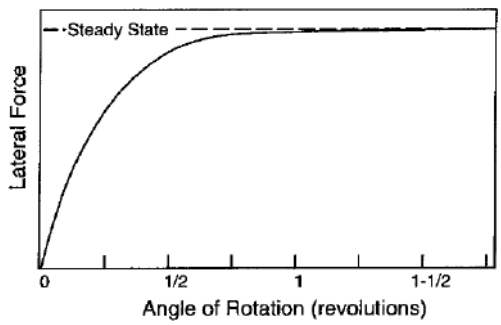


Figure 28 – Lateral force as a function of slip angle [84].

A second mechanism for the generation of lateral force in a tire arises from rolling in a non-vertical orientation, with the angle between the wheel plane and the plane normal to the pavement being denominated the camber angle γ [98]. The lateral force developed under this condition is referred to as the camber thrust [99].

By convention, camber is positive when the upper portion of the wheel leans outward relative to the vehicle, and as a consequence the direction associated with positive camber differs between the left and right sides of the vehicle, which makes the unique definition of a positive lateral force less straightforward [100].

For practical purposes, it is sufficient to recognize that the camber thrust is always oriented in the direction toward which the tire is inclined. The camber thrust is expressed according to Equation (1).

$$C_\gamma = \left.\frac{\partial F_y}{\partial \gamma}\right|_\gamma \quad (1)$$

Where C_γ is the camber stiffness, F_y is the lateral force, and γ is the camber angle. *Figure 29* presents the relationship between lateral force, camber angle, and normal load.

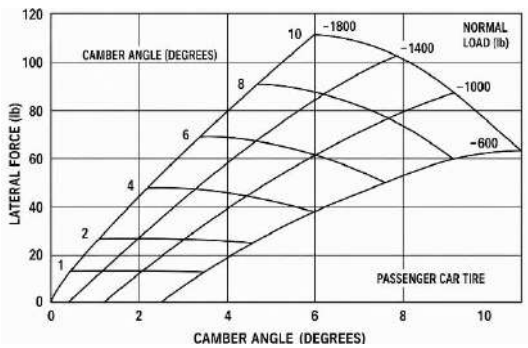


Figure 29 – Lateral force as a function of camber angle and normal load for a bias-ply tire [84].

It is also worth noting that the lateral force associated with inclination of the wheel plane does not arise exclusively from the cambering of the wheel itself. When a vertically oriented tire operates on a transversely inclined road surface, the horizontal component of the vertical load tends to push the wheel toward the lower side of the incline. The corresponding free-body diagram is shown in *Figure 30*.

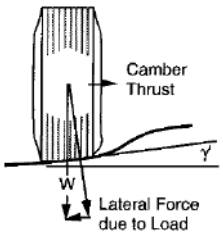


Figure 30 – Free-body diagram of a tire operating on a transversely inclined pavement [84].

The relationship between the lateral force per unit load and the road inclination angle is given by Equation (2).

$$\frac{F_y}{W} = \sin\gamma \cong \gamma \quad (2)$$

Where W is the vertical load acting on the tire and γ is the transverse inclination angle of the pavement. In response to this gravity-induced lateral force, the camber thrust acts to push the tire upward along the incline [101]. As a final remark, the camber stiffness is itself a function of the tread stiffness, with stiffer tread compounds yielding higher camber stiffness values and therefore greater sensitivity of the lateral force to camber inputs [102].

8) MATERIAL SELECTION FOR THE TREAD COMPOUND

8.1) IDENTIFICATION OF THE CRITICAL COMPONENT

The fundamentals of vehicle dynamics developed in the previous chapter support the conclusion that, among all the structural components that constitute a passenger car tire, the tread is the element that simultaneously experiences the highest wear rate and exerts the most direct influence on the service life and functional performance of the tire.

The recognition that the in-use phase dominates the aggregate environmental footprint, as documented in the life cycle assessment results, and the fact that the tread is the component that governs the mechanisms underlying that dominance, jointly justify its selection as the focal point of the material-selection exercise pursued in this chapter.

When analyzing an artifact as complex as a tire, it would be methodologically inappropriate to dismiss the contribution of other constituents such as the sidewalls, the carcass plies, or the bead bundles. However, established practice in material-selection studies prescribes the isolation of the component under analysis as a necessary condition for a tractable and reproducible screening. Once the eco-design exercise has been completed and a candidate material has been identified, a complementary analysis of the interactions between the new material and the full tire system becomes mandatory, but lies outside the scope of the present screening. Accordingly, the methodology proposed by Ashby [103] was adopted, and the corresponding selection framework is summarized in *Table 2*.

Table 2 – Material selection framework adopted for the tread compound of the passenger car tire, following the Ashby methodology [103].

Function	Tread for passenger car tires
Constraints	Recyclable; Resistant to water, heat, and wear; Must not undergo plastic deformation; Minimize mass
Objective	Minimize carbon footprint
Free variables	Material selection; Tread thickness

8.2) DERIVATION OF THE PERFORMANCE INDEX

The screening of candidate materials capable of replacing the conventional rubber compound of the tread requires the prior derivation of the performance index to be maximized. The following parameters are introduced for this purpose:

- L: tread width;
- t: tread thickness;
- R: outer radius of the tread (including the thickness);
- r: inner radius of the tread (excluding the thickness);
- σ_e: yield strength of the candidate material;
- P: contact pressure;
- ρ_{CO_2}: carbon footprint per unit mass of the candidate material;
- C: carbon footprint of the candidate material.

The derivation of the performance index M is conducted in stages. The mechanical constraint on the candidate material is established by requiring that the yield stress withstand the pressure imposed on the tread, which yields the Equation (3).

$$\sigma_e \geq \frac{P \cdot R}{t} \tag{3}$$

The carbon footprint associated with the tread is expressed as the product of the mass of the tread and its specific carbon footprint, leading to Equations (4), (5) and (6).

$$C = m \cdot \rho_{CO_2} \tag{4}$$

$$m = \rho \cdot V \tag{5}$$

$$V = \pi \cdot L \cdot (R^2 - r^2) \tag{6}$$

Considering that the tread thickness t is much smaller than the outer radius R, Equation (6) can be simplified to Equations (7) and (8).

$$V \approx 2 \cdot \pi \cdot L \cdot R \cdot t \tag{7}$$

$$m = \rho \cdot 2 \cdot \pi \cdot L \cdot R \cdot t \tag{8}$$

Substituting Equation (8) into Equation (3) and rearranging in terms of the carbon footprint yields Equations (9) and (10).

$$C = 2 \cdot \pi \cdot L \cdot R \cdot t \cdot \rho \cdot \rho_{CO_2} \tag{9}$$

$$C = (2 \cdot \pi \cdot L \cdot R^2 \cdot P) \cdot \left(\frac{\rho \cdot \rho_{CO_2}}{\sigma_e}\right) \tag{10}$$

Equation (10) is composed of the product of two terms. The first term contains only quantities that can be treated as constants in the present analysis, since the geometry corresponds to a fixed 195/65R15 tire, while the second term depends exclusively on the candidate material.

The minimization of the second term therefore corresponds to the minimization of the carbon footprint of the tread for a given geometric configuration.

In accordance with the Ashby methodology [103], the performance index to be maximized is defined as the inverse of the material-dependent term, which yields Equation (11).

$$M = \frac{\sigma_e}{\rho \cdot \rho_{CO_2}} \tag{11}$$

8.3) SCREENING OF CANDIDATE MATERIALS

The performance index M defined in Equation (11) was implemented in the Ansys Granta EduPack environment, which allows the candidate materials to be ranked on a logarithmic property chart.

In *Figure 31*, the diagonal solid line corresponds to a constant value of the performance index M, with materials located further toward the upper-left region of the chart exhibiting higher values of M and therefore lower carbon footprints for the same mechanical performance.

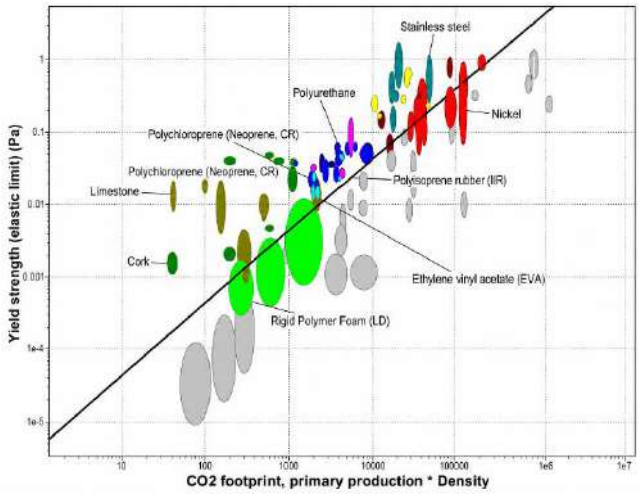


Figure 31 – Materials selection chart for the tread compound, with candidate materials ranked according to the performance index M defined in Equation (11).

The interpretation of the material selection chart reveals a broad set of materials that could in principle replace the vulcanized rubber currently employed in tire treads. The selection cannot, however, rely solely on the maximization

of the index M, since a literal application of that criterion would point to nickel as the best candidate, which is clearly incompatible with the functional requirements of a tread compound.

The performance index adopted in this work must therefore be interpreted as a screening-level proxy, intended to reduce the candidate material space under a combined mechanical and environmental criterion. It does not constitute a complete validation of tread-compound performance, nor does it replace dynamic-mechanical characterization, rolling-resistance measurement, wet-grip assessment, abrasion testing, or tire-level durability validation. In particular, the index does not explicitly capture the simultaneous trade-offs among rolling resistance, wet grip, and abrasion resistance that define the tire-performance triangle. Consequently, the selection of EVA at this stage should be understood as the identification of a recyclable elastomeric candidate for subsequent life-cycle comparison, rather than as evidence of its direct technical suitability for passenger-car tire tread application.

Restricting the candidate field to the elastomer family, the following alternatives emerge as the most promising options under the index M:

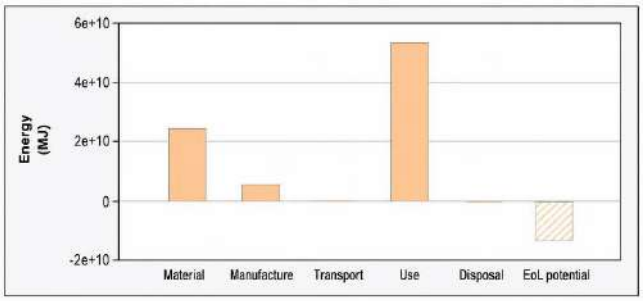
- Ethylene-vinyl acetate (EVA);
- Neoprene;
- Polyisoprene;
- Polyurethane.

Among these four candidates, EVA is the only one that exhibits intrinsic recyclability under the database adopted in this study. It is recognized that environmentally adequate destination routes other than recycling are available in the Brazilian context, as documented by IBAMA [71], and the absence of recyclability does not in itself disqualify a candidate material from the broader sustainability assessment. Nevertheless, for the purposes of the comparative analysis pursued in this chapter, EVA is selected as a candidate substitute for the conventional tread rubber, and its life-cycle performance is evaluated against the baseline scenario established.

8.4) LIFE CYCLE REASSESSMENT WITH THE EVA SUBSTITUTION

The life cycle model previously developed in Chapter 6 was rerun with the tread compound replaced by EVA, while all other components, manufacturing routes, transport scenarios, and use-phase parameters were kept unchanged.

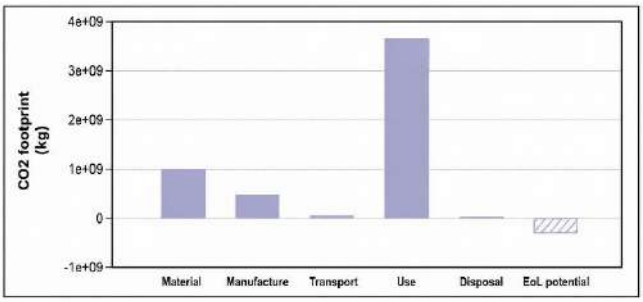
The corresponding energy footprint and carbon footprint results are presented in *Figure 32* and *Figure 33*, respectively.



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	1,69e+10

Figure 32 – Energy footprint of the representative passenger car tire after the substitution of the conventional tread rubber by EVA.

A comparison between the results presented in *Figure 32* and those previously reported for the baseline scenario indicates that the substitution of the conventional rubber by EVA increases the energy footprint of the tire, although an improvement is consistently observed in the end-of-life potential associated with the new material.



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 5 year product life):	1,04e+09

Figure 33 – Carbon footprint of the representative passenger car tire after the substitution of the conventional tread rubber by EVA.

The reassessment of the carbon footprint yields an unfavorable result for the EVA substitution. The comparison between *Figure 33* and the corresponding baseline result shows that the replacement of the conventional rubber by EVA increases the overall carbon footprint of the tire, even though the end-of-life potential remains more favorable for EVA than for the conventional rubber, in line with the trend observed for the energy footprint. The comparative results of the two scenarios are consolidated in *Table 3*.

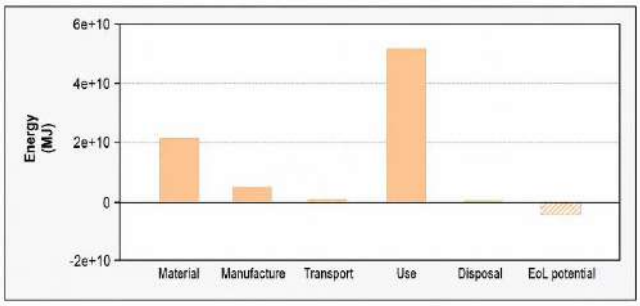
Table 3 – Comparative life cycle assessment results between the baseline tread compound and the EVA-based tread compound. Source: own elaboration based on Ansys Granta EduPack outputs.

Tread material	Energy Footprint (MJ/year)	Carbon Footprint (kg/year)
Rubber	$1.57e+10$	$9.51e+8$
EVA	$1.69e+10$	$1.04e+9$

8.5) ALTERNATIVE SCENARIO: CORRECT END-OF-LIFE DESTINATION FOR THE CONVENTIONAL COMPOUND

The unfavorable performance of the EVA substitution motivated a complementary scenario aimed at exploring the sensitivity of the life cycle results to the end-of-life management of the conventional tread compound.

In this scenario, the tread is maintained as a blend of natural and synthetic rubber, but all unserviceable tires are assumed to receive an environmentally adequate destination. The corresponding carbon footprint result is presented in *Figure 34*.



	Energy (MJ/year)
Equivalent annual environmental burden (averaged over 5 year product life):	1.57e+10

Figure 34 – Carbon footprint of the representative passenger car tire under the assumption of fully correct end-of-life destination for the conventional tread compound.

The inspection indicates that, although no improvement is obtained in the energy footprint relative to the baseline scenario, the assumption of full compliance with environmentally adequate end-of-life destination yields a measurable reduction in the carbon footprint of the tire.

9) CONCLUSIONS

The present work conducted a life cycle assessment of a representative medium-sized passenger car tire (195/65R15) within the Brazilian context, combined with a material-selection screening exercise based on the Ashby methodology and grounded in the fundamentals of vehicle dynamics. The analysis was framed by the consolidated regulatory and operational architecture of the Brazilian tire industry, which currently sustains one of the most mature mandatory take-back programs for end-of-life tires worldwide.

The life cycle assessment conducted in the Ansys Granta EduPack environment confirmed that, under the simplifying assumptions adopted in this study, the use phase is the dominant contributor to the carbon and energy footprints of the passenger car tire.

This finding is consistent with the systematic patterns reported in the international tire life cycle assessment literature and reinforces the strategic importance of the in-service stage as the principal target of any design or policy intervention aimed at reducing the aggregate environmental burden of the product.

The application of vehicle dynamics theory to the identification of the most relevant functional component of the tire indicated that the tread is the element that simultaneously experiences the highest wear rate and exerts the most direct influence on rolling resistance, lateral force generation, and overall service life.

The Ashby-based screening exercise, conducted with the derived performance index relating yield strength to density and to the specific carbon footprint of the candidate materials, identified ethylene-vinyl acetate (EVA) as the most promising recyclable elastomer alternative within the candidate field.

The life cycle reassessment conducted under the EVA substitution scenario, however, indicated that the direct replacement of the conventional tread rubber by EVA is not a viable route for reducing the environmental footprint of the passenger car tire within the scope of the present analysis.

Although the end-of-life potential of the tire improved consistently with the adoption of EVA, both the carbon footprint and the energy footprint increased relative to the baseline scenario, which neutralizes the recyclability advantage of the candidate material from a life cycle perspective. The complementary scenario, in which the conventional tread compound was maintained but all unserviceable tires were assumed to receive an environmentally adequate end-of-life destination, yielded a measurable reduction in the carbon footprint of the tire, although without an associated improvement in the energy footprint. This result indicates that, within the limits of the simplified model adopted in this study, the consolidation of the reverse logistics framework operated by Reciclanip under CONAMA Resolution No. 416/2009 constitutes a more effective lever for the reduction of the carbon footprint of the Brazilian passenger car tire fleet than the direct substitution of the tread material.

Two practical implications follow from these findings.

First, eco-design strategies focused exclusively on the substitution of the tread polymer matrix should be evaluated through a full life cycle perspective rather than through end-of-life potential alone, since the use-phase consequences of the new material may offset the recyclability gains.

Second, the marginal contribution of additional improvements in the Brazilian end-of-life management system, which has reached a national compliance rate of approximately 95 percent under the current regulatory framework, remains a relevant pathway for incremental gains in the aggregate carbon footprint of the sector, particularly through the closure of the residual gap associated with importer compliance and through the

diversification of the destination technology portfolio beyond coprocessing.

The limitations of the present study should be explicitly acknowledged. The life cycle model adopted simplifying assumptions with respect to material composition, transport scenario, and use-phase regime, and the Granta EduPack educational database, while methodologically transparent and traceable, does not reach the resolution of specialized commercial inventories such as Ecoinvent or GaBi. The screening of candidate materials was conducted under a single performance index relating mechanical strength to carbon footprint, and did not incorporate the multi-criteria conflicts that characterize the magic triangle of tire performance, namely the simultaneous trade-offs between rolling resistance, wet grip, and abrasion resistance. The assessment also did not include the environmental burden associated with tire wear particles and with the leaching of tire-specific additives, which the recent literature has identified as critical externalities of the in-use phase.

Future work should address these limitations along three principal directions.

First, the life cycle model should be refined through the incorporation of primary inventory data from the Brazilian manufacturing base and through the use of specialized life cycle assessment software coupled to internationally recognized inventory databases.

Second, the material-selection exercise should be extended to a multi-criteria framework that simultaneously accounts for rolling resistance, wet grip, abrasion resistance, recyclability, and supply-chain considerations, possibly through the integration of Ashby performance indices with established multi-criteria decision-making methods.

Third, the assessment should be extended to incorporate the in-use emissions of tire wear particles and associated tire-derived contaminants, which are not currently captured by the carbon and energy footprint indicators adopted in this work but are increasingly recognized as essential components of the aggregate environmental signature of the tire-road system.

Within the bounds of these acknowledged limitations, the present study contributes to the consolidation of a methodologically transparent and reproducible framework for the joint evaluation of tread material selection and end-of-life management in the Brazilian passenger car tire industry, and provides empirical support for the prioritization of end-of-life management as the most actionable lever for the improvement of the sustainability of the sector under the current technological and regulatory conditions.

REFERENCES

[1]. IPCC. 2022. "Chapter 10: Transport." Www.ipcc.ch. 2022. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/.

[2]. Šimaitis, Joris, Rick Lupton, Christopher Vagg, Isabela Butnar, Romain Sacchi, and Stephen Allen. 2025. "Battery Electric Vehicles Show the Lowest Carbon Footprints among Passenger Cars across 1.5–3.0 °c Energy Decarbonisation Pathways." *Communications Earth & Environment* 6 (1). https://doi.org/10.1038/s43247-025-02447-2.

[3]. Vikas Birajdar, Jamaleddin Mostafavi, Madhu Kandampadath, Mohammad Behroozi, and Javad Baqersad. 2024. "Influence of Tire Parameters on Contact Patch and Axle Force Generation against Short Obstacles Using DOE Approach." *Vehicles* 6 (4): 1690–1703. https://doi.org/10.3390/vehicles6040081.

[4]. Song, Jingeun. 2025. "Evaluation of Driving Resistance and Energy Consumption in Electric Vehicles under Various Ambient and Tire Temperatures Using Real-World Driving Data." *ETransportation* 25 (September): 100454. https://doi.org/10.1016/j.etran.2025.100454.

[5]. Hennequin, Thomas, Lotte van Vlimmeren, Silvia Mostoni, Francesca Rita Pomilla, Roberto Scotti, Claudia Stauch, Mitchell, Mark, and Rosalie van Zelm. 2024. "Environmental Impact Prediction of a New Tire Vulcanization Activator." *ACS Sustainable Chemistry & Engineering* 12 (16): 6102–10. https://doi.org/10.1021/acssuschemeng.3c06640.

[6]. Yaghi, Ahmad, Labeeb Ali, and Mohammednoor Altarawneh. 2025. "Recent Advances on Thermochemical Recycling of End-of-Life Tires and Their Coblending with Waste Plastic Fractions." *ACS Omega* 10 (25): 26233–49. https://doi.org/10.1021/acsomega.5c01592.

[7]. Stefanidis, Stylianos D., Eleni Pachatouridou, Eleni Heracleous, Angelos A. Lappas, and Iacovos A. Vasalos. 2025. "Chemical Recycling of End-of-Life Tires Using Catalytic Pyrolysis: Effects of Catalysts and Process Conditions toward the Production of a Highly Aromatic Pyrolysis Oil." *Industrial & Engineering Chemistry Research* 64 (40): 19342–58. https://doi.org/10.1021/acs.iecr.5c02163.

[8]. Li, Xinjie, Yingxia Li, Tianliang Zhao, Siyan Li, Jiangyan Yang, Yanbin Luo, Fanxiang Meng, Ning Liao, Yuxin Hu, and Xiangzhi Li. 2026. "Tire Wear Particles' Environmental Distribution and Potential Threats to Human Health." *Bulletin of Environmental Contamination and Toxicology* 116 (4). https://doi.org/10.1007/s00128-026-04224-z.

[9]. Pryshlakivsky, Jonathan, and Cory Searcy. 2013. "Fifteen Years of ISO 14040: A Review." *Journal of Cleaner Production* 57 (October): 115–23. https://doi.org/10.1016/j.jclepro.2013.05.038.

[10]. Dong, Yahong, Yating Zhao, Md. Uzzal Hossain, Yan He, and Peng Liu. 2021. "Life Cycle Assessment of Vehicle Tires: A Systematic Review." *Cleaner Environmental Systems* 2 (June): 100033. https://doi.org/10.1016/j.cesys.2021.100033.

[11]. Siwiec, Dominika, and Andrzej Pacana. 2024. "Materials and Products Development Based on a Novelty Approach to Quality and Life Cycle Assessment (QLCA)." *Materials* 17 (15): 3859. https://doi.org/10.3390/ma17153859.

[12]. Fredriksson, Claes, and Tatiana Vakhitova. 2020. "Educational Software for a Sustainable Future." IEEE Xplore. October 1, 2020. https://doi.org/10.1109/FIE44824.2020.9273909.

[13]. Fathi, Haniyeh, Zeinab El-Sayegh, Jing Ren, and Moustafa El-Gindy. 2024. "Analysis of Tire-Road Interaction: A Literature Review." *Machines* 12 (11): 812–12. https://doi.org/10.3390/machines12110812.

[14]. Rachman, Onny Aulia, and Chaoying Wan. 2025. "The Magic Triangle in Tire Technology: Advancements in Rolling Resistance, Wet Grip, and Durability." *Rubber Materials*, 507–30. https://doi.org/10.1016/b978-0-443-28989-7.00023-7.

[15]. Zou, Muhua, Wenke Gao, Zengcai Li, Binghua Liu, Bingxiang Li, Kai Liu, and Jinhui Liu. 2024. "Hybrid Carbon Black/Silica Reinforcing System for High-Performance Green Tread Rubber." *Polymers* 16 (19): 2762–62. https://doi.org/10.3390/polym16192762.

[16]. Elburg, Frances van, Fabian Grunert, Claudia Aurisicchio, Micol di Consiglio, Auke Talma, Pilar Bernal-Ortega, and Anke Blume. 2025. "Sustainable Rubber Solutions: A Study on Bio-Based Oil and Resin Blends." *Polymers* 17 (15): 2111. https://doi.org/10.3390/polym17152111.

[17]. Branowski, Bogdan, Marek Zabłocki, and Maciej Sydor. 2019. "The Material Indices Method in the Sustainable Engineering Design Process: A Review." *Sustainability* 11 (19): 5465. https://doi.org/10.3390/su11195465.

[18]. Padilla, León, Ángela Díaz, and Wendy Anzules. 2024. "Eco-Management of End-of-Life Tires: Advances and Challenges for the Ecuadorian Case." *Waste Management & Research the Journal for a Sustainable Circular Economy*, March. https://doi.org/10.1177/0734242x241237104.

[19]. Martínez, Juan Daniel. 2021. "An Overview of the End-of-Life Tires Status in Some Latin American Countries: Proposing Pyrolysis for a Circular Economy." *Renewable and Sustainable Energy Reviews* 144 (July): 111032. https://doi.org/10.1016/j.rser.2021.111032.

[20]. Dharanija Banala, Ylias Sabri, Namita Roy Choudhury, and Rajarathinam Parthasarathy. 2025. "Sustainable Valorisation of End-of-Life Tyres through Pyrolysis-Derived Recovered Carbon Black in Polymer Composites." *Polymers* 17 (20): 2771–71. https://doi.org/10.3390/polym17202771.

[21]. Kabutz, Thomas B., and P. Schalk Els. 2026. "Tyre Tread Estimation from 3D Contact Patch Measurements on the inside of a Deformed Tyre." *Journal of Terramechanics* 121 (January): 101102. https://doi.org/10.1016/j.jterra.2025.101102.

[22]. Tushar, Quddus, Joao Santos, Guomin Zhang, Muhammed A. Bhuiyan, and Filippo Giustozzi. 2022. "Recycling Waste Vehicle Tyres into Crumb Rubber and the Transition to Renewable Energy Sources: A Comprehensive Life Cycle Assessment." *Journal of Environmental Management* 323 (December): 116289. https://doi.org/10.1016/j.jenvman.2022.116289.

[23]. Kemal Cellat, Yusuf Güner, and Ali Erkin Kutlu. 2026. "Comparative Evaluation of Recovered Carbon Blacks from Tire and Plastic Wastes in EPDM Formulations for Automotive Sealing Applications." *Polymer Engineering and Science*, April. https://doi.org/10.1002/pen.70548.

[24]. Heisler, Heinz. 2002. "Tyres." *Advanced Vehicle Technology*, 270–310. https://doi.org/10.1016/b978-075065131-8/50009-9.

[25]. Mao, Chunyu, Yanhong Sun, Xiaodong Yang, and Shuwei Lv. 2022. "Design of Bionic Tire Tread Compounds with Pit Structures and the Improvement Mechanism of Wear and Wet Grip Resistance." *Journal of Applied Polymer Science* 139 (43). https://doi.org/10.1002/app.53066.

[26]. "Material Selection for a given Engineering Application." n.d. *Springer Series in Advanced Manufacturing*, 53–69. Accessed May 21, 2026. https://doi.org/10.1007/978-1-84628-819-7_5.

[27]. Hern Boon, Zhen, Yin Yin Teo, and Desmond Teck-Chye Ang. 2022. "Recent Development of Biodegradable Synthetic Rubbers and Bio-Based Rubbers Using Sustainable Materials from Biological Sources." *RSC Advances* 12 (52): 34028–52. https://doi.org/10.1039/D2RA06602E.

[28]. Tam, Vivian WY., Yijun Zhou, Chethana Illankoon, and Khoa N. Le. 2022. "A Critical Review on BIM and LCA Integration Using the ISO 14040 Framework." *Building and Environment* 213 (April): 108865. https://doi.org/10.1016/j.buildenv.2022.108865.

[29]. Shanbag, Amit, and Sampatrao Manjare. 2020. "Life Cycle Assessment of Tyre Manufacturing

Process." *Journal of Sustainable Development of Energy, Water and Environment Systems* 8 (1): 22–34. https://doi.org/10.13044/j.sdewes.d7.0260.

[30]. Piotrowska, Katarzyna, Weronika Kruszelnicka, Patrycja Bałdowska-Witos, Robert Kasner, Jacek Rudnicki, Andrzej Tomporowski, Józef Flizikowski, and Marek Opielak. 2019. "Assessment of the Environmental Impact of a Car Tire throughout Its Lifecycle Using the LCA Method." *Materials* 12 (24): 4177. https://doi.org/10.3390/ma12244177.

[31]. Liao, Kejun, Junyi Yu, Ruohan Huang, Wenjing Zhou, Yuwei Zhou, Junru Guo, Shengman Zhang, et al. 2026. "Co-Mitigating Tire Wear Particles and Their Leachates across the Life Cycle: A Critical Review." *Water Research* 301 (August): 125994. https://doi.org/10.1016/j.watres.2026.125994.

[32]. Li, Tianbo, and Qing Li. 2017. "The Carbon Footprint Analysis Of Tire Throughout The Life Cycle In China." *JP Journal of Heat and Mass Transfer* 14 (3): 421–43. https://doi.org/10.17654/hm014030421.

[33]. Pavlović, Angelina, Danijela Nikolić, Sasa Jovanovic, Goran Bošković, and Jasmina Skerlić. 2019. "Life Cycle Assessment Of The Car Tire With Eco Indicator 99 Methodology." *Mobility and Vehicle Mechanics* 45 (3): 13–23. https://doi.org/10.24874/mvm.2019.45.03.02.

[34]. Tunali, Merve, and Bernd Nowack. 2025. "Towards Including Soil Ecotoxicity of Microplastics and Tire Wear Particles into Life Cycle Assessment." *Ecotoxicology and Environmental Safety* 303 (August): 118856. https://doi.org/10.1016/j.ecoenv.2025.118856.

[35]. Joy, Jiby, and Zeinab El-Sayegh. 2026. "Non-Pneumatic Tire–Road Interaction: A Tractive Effort Analysis." *Transactions of the Canadian Society for Mechanical Engineering* 50 (January): 1–11. https://doi.org/10.1139/tcsme-2025-0243.

[36]. Pacejka, Hans B. 2012. "Semi-Empirical Tire Models." *Elsevier EBooks*, January, 149–209. https://doi.org/10.1016/b978-0-08-097016-5.00004-8.

[37]. Singh, Kanwar Bharat, and Srikanth Sivaramakrishnan. 2023. "Extended Pacejka Tire Model for Enhanced Vehicle Stability Control." ArXiv.org. May 28, 2023. https://doi.org/10.48550/arXiv.2305.18422.

[38]. Swami, Aakash, Chao Liu, Jan Kubenz, Günther Prokop, and Ashok Kumar Pandey. 2021. "Experimental Study on Tire Contact Patch Characteristics for Vehicle Handling with Enhanced Optical Measuring System." *SAE International Journal of Vehicle Dynamics, Stability, and NVH* 5 (3). https://doi.org/10.4271/10-05-03-0023.

[39]. Kageyama, I. 2002. "A Study on Tire Modeling for Camber Thrust and Camber Torque." *JSAE Review* 23 (3): 325–31. https://doi.org/10.1016/s0389-4304(02)00204-7.

[40]. Graham, W.R. 2024. "Impact of the Contact-Patch Gap on Sound Radiation from a Tyre." *Journal of Sound and Vibration* 573 (March): 118188. https://doi.org/10.1016/j.jsv.2023.118188.

[41]. Premarathna, W.A.A.S., Kumar Anupam, M. Moenielal, Thijs Wensveen, Cor Kasbergen, and Sandra M.J.G. Erkens. 2026. "A Novel Tire-Pavement Related Parameter for Improved Rolling Resistance Predictions." *International Journal of Mechanical Sciences* 320 (June): 111619. https://doi.org/10.1016/j.ijmecsci.2026.111619.

[42]. Araujo-Morera, Javier, Marianella Hernández Santana, Raquel Verdejo, and Miguel Angel López-Manchado. 2019. "Giving a Second Opportunity to Tire Waste: An Alternative Path for the Development of Sustainable Self-Healing Styrene–Butadiene Rubber Compounds Overcoming the Magic Triangle of Tires." *Polymers* 11 (12): 2122. https://doi.org/10.3390/polym11122122.

[43]. Löber, Manuel, Linda Bondorf, Tobias Grein, Sven Reiland, Steffen Wieser, Fabius Epple, Franz Philipps, and Tobias Schripp. 2024. "Investigations of Airborne Tire and Brake Wear Particles Using a Novel Vehicle Design." *Environmental Science and Pollution Research* 31 (40): 53521–31. https://doi.org/10.1007/s11356-024-34543-9.

[44]. Veiga, Viviane Dall'Agnol, Taline Marchesini Rossignol, Janaina da Silva Crespo, and Larissa Nardini Carli. 2017. "Tire Tread Compounds with Reduced Rolling Resistance and Improved Wet Grip." *Journal of Applied Polymer Science* 134 (39): 45334. https://doi.org/10.1002/app.45334.

[45]. Bhushan Nandkumar Hajare, Subramanian Radhakrishnan, Bazli Hilmi, Mimi Syahira, and Raa Khimi Shuib. 2025. "Synergistic Hybrid Reinforcement Effects of Carbon Black, Silica, and Multiwalled Carbon Nanotubes in Self-Healing Natural Rubber Composites." *Polymers and Polymer Composites* 34 (January). https://doi.org/10.1177/09673911261448786.

[46]. Qin, Xuan, Ning Zhang, Bingyong Han, Bo Wang, Lixin Mao, and Lei Zhang. 2018. "Novel Design of Eco-Friendly Super Elastomer Materials with Optimized Hard Segments Micro-Structure: Toward Next-Generation High-Performance Tires" 6 (July). https://doi.org/10.3389/fchem.2018.00240.

[47]. Mattsson, Karin, Juliana Aristéia, Tim Wilkinson, Ida Järlskog, Elisabet Ekstrand, Yvonne Andersson Sköld, Mats Gustafsson, and Martin Hassellöv. 2023. "Tyre and Road Wear Particles from Source to Sea." *Microplastics and Nanoplastics* 3 (1). https://doi.org/10.1186/s43591-023-00060-8.

[48]. Järlskog, Ida, David Jaramillo-Vogel, Juanita Rausch, Mats Gustafsson, Ann-Margret Strömvall, and Yvonne Andersson-Sköld. 2022. "Concentrations of Tire Wear Microplastics and Other Traffic-Derived Non-Exhaust Particles in the Road Environment." *Environment International* 170 (December): 107618. https://doi.org/10.1016/j.envint.2022.107618.

[49]. Tian, Zhenyu, Haoqi Zhao, Katherine T. Peter, Melissa Gonzalez, Jill Wetzel, Christopher Wu, Ximin Hu, et al. 2021. "A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon." *Science* 371 (6525): 185–89. https://doi.org/10.1126/science.abd6951.

[50]. Tom, Milanta, Tapas Ranjan Mohanty, Sabu Thomas, Bastien Seantier, Yves Grohens, S. Ramakrishnan, and P.K. Mohamed. 2025. "Investigating the Synergism and Partial Replacement of Carbon Black by Cellulose Nanofibers in Natural Rubber-Based Tyre Tread Composites." *Polymer* 325 (April): 128302. https://doi.org/10.1016/j.polymer.2025.128302.

[51]. Helm, Paul A., Melanie Raby, Sonya Kleywegt, Ryan J. Sorichetti, Grace Arabian, Derek Smith, E. Todd Howell, and John Thibeau. 2024. "Assessment of Tire-Additive Transformation Product 6PPD-Quinone in Urban-Impacted Watersheds." *ACS ES&T Water* 4 (4): 1422–32. https://doi.org/10.1021/acsestwater.3c00589.

[52]. Prosser, R.S, J. Salole, and S Hang. 2023. "Toxicity of 6PPD-Quinone to Four Freshwater Invertebrate Species." *Environmental Pollution* 337 (November): 122512–12. https://doi.org/10.1016/j.envpol.2023.122512.

[53]. Kim, Minseong, Min Pak, Se Hyun Lee, Jimin Hur, Woosuk Chung, Minseung Hyun, Sangmin Oh, et al. 2026. "Three-Dimensional Distribution of Roadside Airborne/Tire-Wear Particles and Implications for Pedestrian Exposure." *Journal of Hazardous Materials* 512 (May): 142426–26. https://doi.org/10.1016/j.jhazmat.2026.142426.

[54]. Santiago Gomes, Thiago, Genecy Rezende Neto, Ana Claudia Nioac de Salles, Leila Lea Yuan Visconte, and Elen Beatriz Acordi Vasques Pacheco. 2019. "End-of-Life Tire Destination from a Life Cycle Assessment Perspective." *New Frontiers on Life Cycle Assessment - Theory and Application*, June. https://doi.org/10.5772/intechopen.82702.

[55]. "Retread Tires | Cost-Effective Driving with Retreading | Nokian Tyres / Nokian Tyres." Nokian Tyres. 2026. https://www.nokiantyres.com/heavy/treads/retread-tires/.

[56]. Bressi, Sara, Nicholas Fiorentini, Jiandong Huang, and Massimo Losa. 2019. "Crumb Rubber Modifier in Road Asphalt Pavements: State of the Art and Statistics." *Coatings* 9 (6): 384. https://doi.org/10.3390/coatings9060384.

[57]. Wang, Zhengkun, Ruihuan Wang, Heng Zhang, Bo Zhang, Yinghua Fan, Wenwen Yu, Qiang Zheng, and Fengbo Zhu. 2025. "Hybrid Devulcanized/Vulcanized Crumb Rubber Strategy for High-Performance Asphalt with over 40% Recycled Tire Rubber Content." *Polymers* 17 (22): 2987–87. https://doi.org/10.3390/polym17222987.

[58]. Costa, Sebastião M. R., David Fowler, Germano A. Carreira, Inês Portugal, and Carlos M. Silva. 2022. "Production and Upgrading of Recovered Carbon Black from the Pyrolysis of End-of-Life Tires." *Materials* 15 (6): 2030. https://doi.org/10.3390/ma15062030.

[59]. Maga, Daniel, Venkat Aryan, and Jan Blömer. 2023. "A Comparative Life Cycle Assessment of Tyre Recycling Using Pyrolysis Compared to Conventional End-of-Life Pathways." *Resources, Conservation and Recycling* 199 (December): 107255. https://doi.org/10.1016/j.resconrec.2023.107255.

[60]. Bogdahn, Sebastian, Christian Malek, Edwin Koch, and Danka Katrakova-Kruger. 2025. "Production and Characterization of Recovered Carbon Black (RCB) by Waste Tire Pyrolysis as a Potential Carbon Black (CB) Substitute." *Advanced Materials & Sustainable Manufacturing*: 10007–7. https://doi.org/10.70322/amsm.2025.10007.

[61]. Fadipe, Olusola Olayemi, Kehinde Adenike Oyewole, Abiola Usman Adebanjo, Ayotunde Taiwo Ajiferuke, and Olakunle Olukayode. 2025. "Evaluating the Reusability of Carbon Black Recovered from Waste Tyres: An Elemental and Microstructural Analysis." *Results in Surfaces and Interfaces* 18 (February): 100472. https://doi.org/10.1016/j.rsurfi.2025.100472.

[62]. Sergei Kononov. 2019. "Weibold Academy: Life Cycle Assessment in the Tire Recycling and Pyrolysis Industry | Weibold – Tire Recycling & Pyrolysis Consulting." Weibold.com. December 31, 2019. https://weibold.com/life-cycle-assessment-in-the-tire-recycling-and-pyrolysis-industry.

[63]. Huang, Haihong, Zhifeng Liu, Lei Zhang, and John W. Sutherland. 2009. "Materials Selection for Environmentally Conscious Design via a Proposed Life Cycle Environmental Performance Index." *The International Journal of Advanced Manufacturing Technology* 44 (11-12): 1073–82. https://doi.org/10.1007/s00170-009-1935-9.

[64]. D'Errico, Fabrizio. 2015. "The Material Selection Strategy." *SpringerBriefs in Materials*, 1–32. https://doi.org/10.1007/978-3-319-13030-9_1.

[65]. Bouaziz, Olivier, and Jean-Philippe Masse. 2012. "Extension of Ashby's Performance Indexes in Mixed Tension-Bending Solicitations." *Advanced Engineering Materials* 14 (7): 497–98. https://doi.org/10.1002/adem.201200050.

[66]. Xu, Tao, Wei Liu, and Zicheng Zhu. 2023. "Multi-Criteria Decision-Making Methods Applied To Achieve Sustainable Design: A Systematic Review." *Proceedings of the Design Society* 3 (June): 2725–34. https://doi.org/10.1017/pds.2023.273.

[67]. Wei, Amos, Si Ying Chung, Yee Shee Tan, Sarene Koh, Wen Feng Lu, and Jonathan Sze. 2023. "Enhancing the Environmental Sustainability of Product through Ecodesign: A Systematic Review." *Journal of Engineering Design*, October, 1–30. https://doi.org/10.1080/09544828.2023.2261094.

[68]. Buchert, Tom, Sabrina Neugebauer, Sebastian Schenker, Kai Lindow, and Rainer Stark. 2015. "Multi-Criteria Decision Making as a Tool for Sustainable Product Development – Benefits and Obstacles." *Procedia CIRP* 26: 70–75. https://doi.org/10.1016/j.procir.2014.07.110.

[69]. Ayar, Murat, Alper Dalkiran, Utku Kale, András Nagy, and Tahir Hikmet Karakoc. 2021. "Investigation of the Substitutability of Rubber Compounds with Environmentally Friendly Materials." *Sustainability* 13 (9): 5251. https://doi.org/10.3390/su13095251.

[70]. ANIP — National Association of the Tire Industry, *Overview of the Brazilian Tire Industry*, Institutional Folder, São Paulo, Brazil, April 2026. Available: https://www.anip.org.br/anip-em-numeros/dados-gerais/.

[71]. "Pneumáticos Inservíveis." 2026. Ibama. 2026. https://www.gov.br/ibama/pt-br/assuntos/emissoes-e-residuos/residuos/pneumaticos-inserviveis#destinacao-adequada.

[72]. Fang, Tiange, Lei Sheng, Qiang Zeng, Guang Yang, Jinsheng Zhang, Wendi Wei, Jianfei Peng, et al. 2026. "Real-World Key-Process Emission Factors Optimized Environmental Impact from Passenger Car Tires' PM2.5 and Typical Chemicals throughout Lifecycle." *Journal of Hazardous Materials* 503 (February): 141202. https://doi.org/10.1016/j.jhazmat.2026.141202.

[73]. Lapkovskis, Vjaceslavs, Viktors Mironovs, Andrei Kasperovich, Vadim Myadelets, and Dmitri Goljandin. 2020. "Crumb Rubber as a Secondary Raw Material from Waste Rubber: A Short Review of End-Of-Life Mechanical Processing Methods." *Recycling* 5 (4): 32. https://doi.org/10.3390/recycling5040032.

[74]. Zappa, Emanuele, Luca Parenzan, Edoardo Montini, Stefano Melzi, Andrea Gregorini, and Andrea Natta. 2026. "Measurement of a Tyre's Inner Liner Point Dynamics with Pose Estimation." *Measurement* 270 (April): 120932. https://doi.org/10.1016/j.measurement.2026.120932.

[75]. Kawasaki, K., Umezawa, Y. and Sugawara, T. Heavy Duty Radial Tyres with Metallic Carcass Ply." 1992. *Composites* 23 (6): 466. https://doi.org/10.1016/0010-4361(92)90054-x.

[76]. Pneumatic tyre having carcass ply end portions anchored in each bead bundle. (1992). *Composites*, *23*(6), 466. https://doi.org/10.1016/0010-4361(92)90057-2.

[77]. Li, Xu, Jiapeng Han, Xuezhen Dai, Zhuowen Zheng, and Yanhui Niu. 2024. "Monitoring Overloaded Trucks with Infrared Thermal Imaging of Tire Sidewall." *Heliyon* 10 (14): e34358. https://doi.org/10.1016/j.heliyon.2024.e34358.

[78]. Graham, W.R. 2025. "Modelling High-Frequency Tyre Belt Vibrations." *Journal of Sound and Vibration* 619 (December): 119393. https://doi.org/10.1016/j.jsv.2025.119393.

[79]. Huang, Yihao, Ziyuan Zhang, Chengzhe Zheng, and Youping Wu. 2026. "Factors Affecting Abrasion Resistance of Aircraft Tire Tread Material." *Polymer* 354 (March): 129935. https://doi.org/10.1016/j.polymer.2026.129935.

[80]. Goswami, Mohit, Sujit Sharma, Soumya Roychowdhury, Stéphane P.A Bordas, and Santanu Chattopadhyay. 2023. "Fracture of V-Notched Natural Rubber Composites Used in Heavy-Duty Tire Tread." *Engineering Failure Analysis* 150 (May): 107358–58. https://doi.org/10.1016/j.engfailanal.2023.107358.

[81]. Briones-Hidrovo, Andrei, Sebastião M.R. Costa, Cristiana Maganinho, Clara M.C. Silva, João Rocha, Ana Cláudia Dias, Inês Portugal, and Carlos M. Silva. 2025. "Recovering Carbon Black from End-of-Life Tires: A Consequential Life Cycle Assessment." *Environmental Impact Assessment*

Review 115 (August): 108044. https://doi.org/10.1016/j.eiar.2025.108044.

[82]. Raque Canetl Cañete, Alberto Picardo, Paloma Trueba, Yadir Torres, and Estela Peralta. 2024. "A New Multi-Criteria Decision-Making Approach for the Design and Selection of Materials and Manufacturing Processes of Toys for Children with Autism." *Materials Today Communications*, July, 109709–9. https://doi.org/10.1016/j.mtcomm.2024.109709.

[83]. Gupta, Vipul, Gopalakrishnan Narayanamurthy, and Padmanav Acharya. 2018. "Can Lean Lead to Green? Assessment of Radial Tyre Manufacturing Processes Using System Dynamics Modelling." *Computers & Operations Research* 89 (January): 284–306. https://doi.org/10.1016/j.cor.2017.03.015.

[84]. Gillespie, Thomas D. 1994. *Fundamentals of Vehicle Dynamics*. Society Of Automotive Engineers.

[85]. Schallamach, A. 1960. "The Role of Hysteresis in Tire Wear and Laboratory Abrasion." *Rubber Chemistry and Technology* 33 (3): 857–67. https://doi.org/10.5254/1.3542203.

[86]. Little, Dallas N, David H Allen, and Amit Bhasin. 2017. "Chemical and Mechanical Processes Influencing Adhesion and Moisture Damage in Hot Mix Asphalt Pavements." *Springer EBooks*, September, 123–86. https://doi.org/10.1007/978-3-319-58443-0_4.

[87]. Al-Assi, Mohammad, and Emad Kassem. 2017. "Evaluation of Adhesion and Hysteresis Friction of Rubber–Pavement System." *Applied Sciences* 7 (10): 1029. https://doi.org/10.3390/app7101029.

[88]. Zhang, Xiaolong, Jinghan Huang, FengGeng Zou, Yangyang Liu, Yujie Wu, and Jie Meng. 2026. "Novel Lateral Force Estimation Method of Distributed Intelligent Tires System Based on Kolmogorov-Arnold Enhanced Gated Skip Connection Networks." *Sensors and Actuators A: Physical*, May, 117990. https://doi.org/10.1016/j.sna.2026.117990.

[89]. Badar, Tabish, Juha Backman, and Arto Visala. 2022. "Modeling of Tire Lateral Forces in Non-Linear 6-DOF Simulations for Off-Road Vehicles." *IFAC-PapersOnLine* 55 (32): 12–17. https://doi.org/10.1016/j.ifacol.2022.11.107.

[90]. Jazar, Reza N. 2019. "Tire Dynamics." *Advanced Vehicle Dynamics*, 1–113. https://doi.org/10.1007/978-3-030-13062-6_1.

[91]. Clark, Samuel K, and United States. National Bureau Of Standards. Office Of Vehicle Systems Research. 1971. *Mechanics of Pneumatic Tires,*. Washington, For Sale By The Supt. Of Docs., U.S. Govt. Print. Off.

[92]. Soica, Adrian, and Carmen Gheorghe. 2025. "Tire–Road Interaction: A Comprehensive Review of Friction Mechanisms, Influencing Factors, and Future Challenges." *Machines* 13 (11): 1005. https://doi.org/10.3390/machines13111005.

[93]. Filip Feldesi. 2019. *Three-Dimensional Contact Patch Strain Measurement inside Rolling Off-Road Tyres*.

[94]. Bo N.J. Persson. 2013. *Sliding Friction*. Springer Science & Business Media.

[95]. Trzesniowski, Michael. 2023. Suspension System. Springer Nature.

[96]. Sogand Abbaspoor-Zanjani, Carlo Antonini, Teresa Gatti, and Mengjiao Wang. 2026. "Anti-Slip Material-Based Strategies and Approaches." *Advanced Materials Technologies*, February. https://doi.org/10.1002/admt.202501936.

[97]. Turpin, Darrell R., and Douglas F. Evans. 1995. "High-Fidelity Road/Tire Interaction Models for Real Time Simulation." *SAE Technical Paper Series* 1 (February). https://doi.org/10.4271/950170.

[98]. Nanthakumar, A.J.D., Debopriyo Baisya, and Saksham Shrivastava. 2021. "Development of Mathematical Model for Real Time Estimation and Comparison of Individual Lateral Tire Force Generation." *Materials Today: Proceedings* 45: 6755–66. https://doi.org/10.1016/j.matpr.2020.12.665.

[99]. Park, Seong-Jun, and Jeong-Hyun Sohn. 2012. "Effects of Camber Angle Control of Front Suspension on Vehicle Dynamic Behaviors." *Journal of Mechanical Science and Technology* 26 (2): 307–13. https://doi.org/10.1007/s12206-011-1206-1.

[100]. Kavitha, C., S. Abinav Shankar, K. Karthika, B. Ashok, and S. Denis Ashok. 2019. "Active Camber and Toe Control Strategy for the Double Wishbone Suspension System." *Journal of King Saud University - Engineering Sciences* 31 (4): 375–84. https://doi.org/10.1016/j.jksues.2018.01.003.

[101]. Elsevier. 2005. *Tire and Vehicle Dynamics*. *Elsevier.com*. https://www.elsevier.com/books/tire-and-vehicle-dynamics/pacejka/978-0-7506-6918-4.

[102]. Xu, Nan, Hassan Askari, and Amir Khajepour. 2022. *Intelligent Tire Systems*. Springer Nature.

[103]. Ashby, Michael F, and Alexander Wanner. 2013. *Materials Selection in Mechanical Design : Das*

Original] Mit Übersetzungshilfen. Berlin: Springer Spektrum.

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