

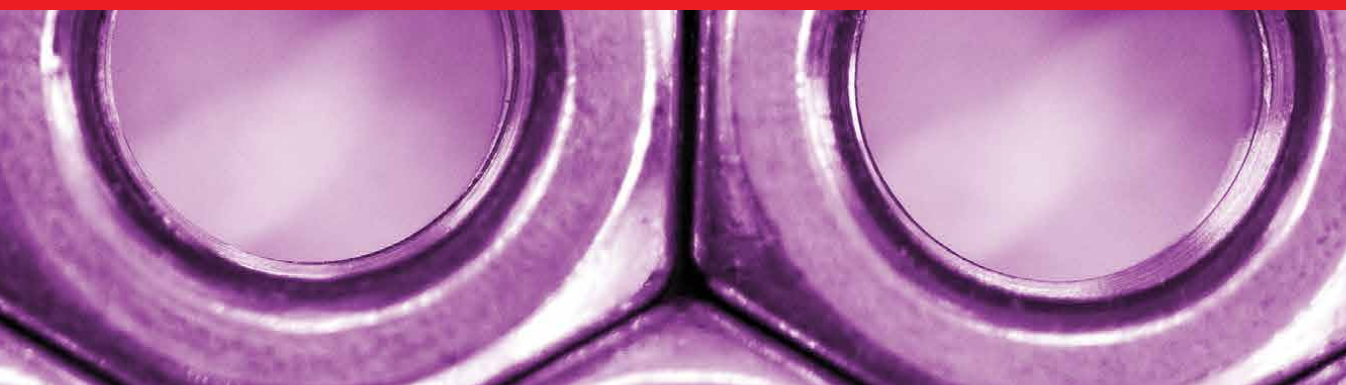


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**Railway Transport
and Engineering**
A Comprehensive Guide

Edited by Masoud Mohebbi



Railway Transport and Engineering - A Comprehensive Guide

Edited by Masoud Mohebbi

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Edited by Masoud Mohebbi

Contributors

Ahmet Bař, George Tumanishvili, Giorgi Tumanishvili, Habib Hadj-Mabrouk, Haitao Li, Huan Huang, Masoud Mohebbi, Rasul Mohebbi, Rustam Rakhimov, Samar Al Sayegh Petkovřek, Tengiz Nadiradze, Xiao Hu, Yougang Sun

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IntechOpen Book Series
Civil Engineering
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Aims and Scope of the Series

Civil engineering is a traditional field of engineering from which most other branches of engineering have evolved. It comprises traditional sub-areas like transportation, structures, construction, geotechnics, water resources, and building materials. It also encompasses sustainability, risk, environment, and other concepts at its core. Historically, developments in civil engineering included traditional aspects of architecture and urban planning as well as practical applications from the construction industry. Most recently, many elements evolved from other fields of knowledge and topics like simulation, optimization, and decision science have been researched and applied to increase and evolve concepts and applications in this field. Civil engineering has evolved in the last years due to the demands of society in terms of the quality of its products, modern applications, official requirements, and cost and schedule restrictions. This series addresses real-life problems and applications of civil engineering and presents recent, cutting-edge research as well as traditional knowledge along with real-world examples of developments in the field.

Meet the Series Editor



Professor Assed N. Haddad is a Civil Engineer with a degree from the Federal University of Rio de Janeiro (UFRJ) earned in 1986, as well as a Juris Doctor degree from the Fluminense University Center earned in 1993, and a Master's degree in Civil Engineering from the Fluminense Federal University (UFF) obtained in 1992. He completed his Ph.D. in Production Engineering from COPPE / Federal University of Rio de Janeiro in 1996. Professor Haddad's academic pursuits have taken him to postdoctoral stays at the University of Florida, USA in 2006; at the Universitat Politècnica de Catalunya, Spain in 2010; and at the University of New South Wales Sydney, Australia in 2019. Currently, he serves as a Full Professor at the Federal University of Rio de Janeiro. He has held visiting professorships at various institutions including the University of Florida, Universitat Politècnica de Catalunya, Universitat Rovira i Virgili, and Western Sydney University. His research expertise encompasses Civil, Environmental, and Production Engineering, with a primary focus on the following topics: Construction Engineering and Management, Risk Management, and Life Cycle Assessment. He has been the recipient of research grants from the State of Rio de Janeiro, Brazil: CNE FAPERJ from 2019 to 2022 and from 2023 to 2025. Additionally, his research grants obtained from the Brazilian Government CNP since 2012 last to this date. Professor Haddad has been involved in several academic endeavors, being the Guest Editor of the International Journal of Construction Management; MDPI's Sustainability, Energies, and Infrastructures; Associate Editor at Frontiers in Built Environment / Sustainable Design and Construction; Guest Editor at Frontiers in Built Environment / Construction Management; and Academic Editor of the Journal of Engineering, Civil Engineering Section of Hindawi. He is currently a Professor of the Environmental Engineering Program at UFRJ and the Civil Engineering Program at UFF.

Meet the Volume Editor



Dr. Masoud Mohebbi is a renowned expert in railway engineering with a Ph.D. from the Iran University of Science and Technology. His research focuses on aerodynamics, particularly the wind effects on high-speed trains, and has significantly contributed to optimizing windbreaks for railway applications. Dr. Mohebbi has received numerous awards, including the prestigious Top Academic Graduate Award from the Iran National Elites Foundation and several Top Researcher prizes from the Ministry of Roads and Urban Development. As a technical expert at the Construction & Development of Transportation Infrastructure Company (CDTIC), he has played a key role in regional and high-speed railway projects. He has published extensively in leading journals and serves as a reviewer for several international engineering publications.

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Preface

The railway transport and engineering field has witnessed rapid advances in technology, sustainability, and infrastructure development, yet integrating these innovations presents unique challenges. This book, *Railway Transport and Engineering – A Comprehensive Guide*, aims to explore the critical aspects of modern railway systems, from cutting-edge thermal management techniques to the development of futuristic transport modes like maglev.

The contributions of various scholars and engineers highlight both the technical challenges and opportunities that lie ahead for the global railway industry. As urbanization expands, efficient and environmentally friendly transportation systems will play a pivotal role in shaping the future of cities and economies. Topics covered in this volume include the application of lightweight aggregates in seismic zones, innovations in friction path and wheel wear, and the role of wildlife corridors in railway planning. In particular, the impact of high-speed rail as a catalyst for increasing regional connectivity and sustainability is discussed in great detail.

Each chapter explores both theoretical and practical considerations, offering valuable insights for academics, engineers, and policymakers alike. This compilation reflects the diversity of perspectives needed to address the complexities of modern rail transport, from material sciences and environmental concerns to cutting-edge transportation planning.

I want to express my gratitude to all the contributors for their expertise, as well as the editorial and production teams for their tireless efforts in bringing this work to fruition. Their collaboration has been essential in creating a comprehensive resource that I hope will inspire future research and development in the railway engineering sector.

Masoud Mohebbi
School of Railway Engineering,
Iran University of Science and Technology,
Tehran, Iran

Chapter 1

Advanced Thermal Management in Railway Systems

Rasul Mohebbi and Masoud Mohebbi

Abstract

Thermal management is pivotal for the efficient operation and longevity of railway systems. In modern railway engineering, particularly within electric and hybrid trains, effective thermal regulation is vital to ensure component reliability and safety. This chapter delves into advanced thermal management strategies in railway systems, with a primary focus on battery thermal management, innovative cooling systems, and the utilization of nanofluids. Key topics include the principles of forced convection heat transfer, emphasizing the superior thermal conductivity of nanofluids, which significantly enhances heat transfer performance. The application of the lattice Boltzmann method (LBM) for simulating fluid flows and heat transfer in complex geometries is thoroughly examined, providing critical insights for optimizing cooling strategies. Additionally, the thermophysical properties of nanofluids and their profound impact on battery thermal management systems (BTMS) are explored, demonstrating how these advanced cooling mediums prevent overheating, maintain optimal performance, and extend battery life. Through a comprehensive review of contemporary studies and numerical simulations, this chapter underscores the imperative of advanced thermal management systems in modern railway applications, presenting groundbreaking solutions to enhance system efficiency and safety.

Keywords: battery thermal management system, cooling systems, nanofluids, LBM, high-speed train

1. Introduction

Enhancing forced convection heat transfer in a train's radiator is crucial for maintaining optimal engine temperatures and overall system efficiency. In recent years, the use of nanofluids, which involve the dispersion of nano-sized particles (such as metals and metal oxides) in a base fluid, has gained prominence. These nanofluids exhibit higher thermal conductivity than traditional fluids, significantly improving heat transfer capabilities. This makes them particularly effective for applications like train radiators, where efficient thermal management is essential for cooling engine components and ensuring reliable operation [1–3].

Forced convection heat transfer in various geometries has been the subject of extensive research. For instance, Wang and Chen [4] investigated this phenomenon within a wavy-wall channel. Sheikholeslami and Bhatti [5] explored the forced

convection heat transfer of nanofluids in a porous semi-annulus using the control volume-based finite element method (CVFEM), and found that the Nusselt number increases with the CuO volume fraction, Reynolds number, and Darcy number. Aghanajafi et al. [6] conducted a numerical analysis on laminar forced convection in a triangular duct with a Reynolds number of 100, showing that the average convective heat transfer coefficient increases with both the heat flux ratio and the volume fraction of nanoparticles.

The lattice Boltzmann method (LBM), derived from kinetic theory, is an effective method for simulating fluid flows and heat transfer issues. One of the primary advantages of LBM is that its equations are hyperbolic, allowing for local, explicit, and efficient solutions on parallel computers. Nevertheless, LBM encounters difficulties when applied to high Reynolds number flows [7–10]. Alamyane and Mohamad [11] used the LBM to numerically simulate forced convection in a channel with extended surfaces. Their study revealed that placing blocks on the channel walls enhances heat transfer. Jafari et al. [12] applied LBM to examine the impact of pulsating flow on forced convection in a corrugated channel at different Reynolds numbers. Their results showed that oscillating velocity significantly affects heat transfer and flow field configurations in the corrugated channel.

Mohebbi and Rezvani utilized LBM to investigate the consequences of windbreak geometry on two-dimensional airflow past a high-speed train. Their study concluded that the windbreak's performance significantly depends on its height and edge angle [13]. In previous work, the authors assessed the impact of porous shelters alongside a high-speed track on the vehicle's aerodynamic behavior using the lattice Boltzmann method, demonstrating that LBM codes with smaller lattices can provide reasonable accuracy results [14]. Other works by Mohebbi et al. regarding the aerodynamics of trains using LBM further support the efficacy of this method in accurately simulating complex fluid flow and heat transfer scenarios in railway applications [15–17].

Ma et al. [18] studied the laminar forced convection heat transfer of nanofluid through a bent channel by LBM. They analyzed various parameters, including Reynolds number, vertical passage ratio, and nanoparticle solid volume fractions, focusing on streamlines, isotherms, and local Nusselt number. They found that the effect of nanofluid concentration on heat transfer enhancement was more significant at higher Reynolds numbers.

The thermal and flow characteristics of nanofluids around three heated obstacles in a channel with sudden expansion and contraction were studied by Mohebbi and Ma [19]. The analysis included nine heat sources and 47 different arrangements of obstacle positions to determine the effect of their relative positions. They found the thermal performance of each heat source was influenced by both its own position and the positions of the other two heated obstacles.

Improving heat transfer in heating systems enhances efficiency, decreases fuel usage, and results in economic savings. Enhancing system efficiency is a pivotal technical challenge across various industries. As a result, industrial professionals are seeking more efficient heating and cooling processes to optimize energy storage systems [20]. In recent decades, researchers have explored numerous methods to boost the thermal efficiency of energy systems through enhanced heat transfer techniques.

Climate change is a multifaceted issue influenced by numerous factors, including emissions from transportation [21]. Electric and hybrid vehicles are set to play a pivotal role in reducing carbon emissions from the transportation sector. Electric vehicles (EVs) rely solely on high-voltage batteries as their energy source, which is essential for ensuring vehicle efficiency and functionality. Heat transfer and fluid flow principles are

crucial considerations in the management of battery thermal dynamics [22–24]. Air cooling is widely adopted in vehicle and electronic industries as a cost-effective and straightforward cooling method [25–27]. Its popularity stems from its simplicity and affordability. However, air cooling may limit heat dissipation from batteries due to the lower heat transfer coefficient of gas compared to liquid. Various simulation and experimental studies have explored the effectiveness of air and water cooling.

Liquid cooling, specifically using nanoparticles, has garnered attention due to its superior heat capacity compared to air cooling. Soleymani et al. [28] examined an air-cooled BTMS with a liquid-cooled system incorporating nanoparticles. They evaluated the effects of CuO and Al₂O₃ nanoparticles at different concentrations and fluid velocities, and they used a unique transient analysis approach to enhance the thermal performance of lithium-ion batteries. Based on their findings, incorporating a 5% volume concentration of nanofluids can significantly improve the cooling efficiency of the system compared to pure liquid, especially at lower fluid velocities. Specifically, Al₂O₃ nanoparticles reduced temperatures by 7.89%, while CuO nanoparticles achieved a 4.73% temperature reduction at the same concentration.

Integration of thermoelectric cooling systems in railway systems is another innovative approach for precise temperature control of critical components. Thermoelectric coolers (TECs) can convert heat into electricity, providing dual benefits of cooling and energy generation. This technology can be particularly advantageous for maintaining optimal thermal conditions in railway components, enhancing overall system efficiency and reliability [29].

The use of phase change materials (PCMs) for thermal energy storage in railway systems has also shown promising results. PCMs can absorb and release large amounts of latent heat, providing effective temperature regulation. This can be especially beneficial for managing the thermal loads in railway systems, ensuring stable operation under varying thermal conditions [30].

Hybrid cooling systems, which combine air and liquid cooling methods, offer enhanced thermal management by utilizing the strengths of both cooling methods. These systems can be optimized to provide efficient cooling for railway applications, balancing the advantages of air and liquid cooling to achieve superior performance [31].

Nanotechnology plays a crucial role in developing advanced thermal management materials and systems, focusing on enhanced thermal conductivity and heat transfer efficiency. The incorporation of nanomaterials in cooling systems can lead to significant improvements in heat dissipation and overall thermal management performance [32].

The impact of advanced thermal management solutions on railway system reliability is profound [33].

By integrating state-of-the-art thermal management technologies, the railway industry can achieve improved performance, sustainability, and resilience in the face of growing operational demands. Enhanced heat dissipation, optimized energy consumption, and increased safety are key benefits that underscore the importance of advanced thermal management in modern railway systems.

2. LBM

For simulating nanofluid flow through a channel or cavity by LBM, there are different methods. Here a thermal lattice Boltzmann (LB) model with two distribution functions describe f for the flow field and g for the temperature field. For a D₂Q₉ model (see **Figure 1**) the velocity vectors e_i is [34].

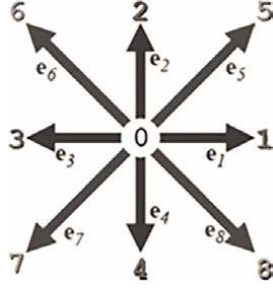


Figure 1.
D2Q9 particles direction.

$$e_i = \begin{cases} (0, 0) & (i = 0) \\ (\cos[(i-1)\pi/2], \sin[(i-1)\pi/2]) \cdot c & (i = 1, \dots, 4) \\ \sqrt{2}(\cos[(i-5)\pi/2 + \pi/4], \sin[(i-5)\pi/2 + \pi/4]) \cdot c & (i = 5, \dots, 8) \end{cases} \quad (1)$$

The distribution functions f and g are computed by applying the BGK (Bhatnagar-Gross-Krook) approximation:

$$f_i(x + e_i \Delta t, t + \Delta t) = f_i(x, t) + \frac{\Delta t}{\tau_v} [f_i^{eq}(x, t) - f_i(x, t)] \quad (2)$$

$$g_i(x + e_i \Delta t, t + \Delta t) = g_i(x, t) + \frac{\Delta t}{\tau_c} [g_i^{eq}(x, t) - g_i(x, t)] \quad (3)$$

In the lattice Boltzmann method for the temperature field, with Δt representing the lattice time (typically set to 1), the equilibrium distribution functions are denoted as f_{eq} and g_{eq} . The relaxation times τ_v and τ_c are:

$$\tau_v = 0.5 + v \frac{\delta t}{c_s^2} \quad (4)$$

$$\tau_c = 0.5 + \alpha \frac{\delta t}{c_s^2} \quad (5)$$

$$f_i^{eq} = w_i \rho \left[1 + \frac{e_i u}{c_s^2} + \frac{1}{2} \frac{(e_i u)^2}{c_s^4} - \frac{1}{2} \frac{u^2}{c_s^2} \right] \quad (6)$$

$$g_i^{eq} = w_i T \left[1 + \frac{c_i u}{c_s^2} \right] \quad (7)$$

where ρ represents the lattice fluid density, T denotes the lattice fluid temperature. The macroscopic variables are:

$$\text{Flow density : } \rho = \sum_i f_i \quad (8)$$

$$\text{Momentum : } \rho u = \sum_i e_i f_i \quad (9)$$

$$\text{Temperature : } T = \sum_i g_i \quad (10)$$

3. Nanofluid thermophysical properties

The properties of the nanofluid, such as thermal conductivity, heat capacitance, density, and thermal expansion, are solely dependent on the volume fraction of the nanoparticles. This has been demonstrated and utilized in numerous previous studies. The nanofluid's density is [35–38]:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_s \quad (11)$$

where ϕ is solid volume fraction of the nanoparticles. The effective heat capacity of the nanofluid is:

$$(\rho c_p)_{nf} = (1 - \phi)(\rho c_p)_f + \phi(\rho c_p)_s \quad (12)$$

where c_p represents the specific heat at constant pressure. The dynamic viscosity of the nanofluid is:

$$\frac{\mu_{nf}}{\mu_f} = (1 + 2.5\phi + 6.5\phi^2) \quad (13)$$

where μ_{nf} is the dynamic viscosity. The nanofluid thermal diffusivity is:

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} \quad (14)$$

Prandtl number is:

$$\text{Pr}_{nf} = \frac{(\mu c_p)_{nf}}{k_{nf}} \quad (15)$$

4. Battery thermal model analysis

As battery technology advances and power demands for EVs rise, interest in liquid cooling is increasing. Thermal diffusion fields within a battery cell were determined by discretizing the energy equations. The conservation equations for thermal and electrical properties in BTMS are presented in Eq. (16):

$$\frac{\partial \rho_b C_{p,b} T}{\partial t} = -\nabla \cdot (k_b \nabla T_b) = \sigma_+ |\nabla \phi_+|^2 + \sigma_- |\nabla \phi_-|^2 + \dot{q}_{ECh} + \dot{q}_{short} \quad (16)$$

The current flux at the positive and negative electrodes, determined by:

$$\nabla \cdot (\sigma_+ \nabla \phi_+) = -(j_{ECh} - j_{short}) \quad (17)$$

$$\nabla \cdot (\sigma_- \nabla \phi_-) = (j_{ECh} - j_{short}) \quad (18)$$

$$j_{ECh} = \frac{Q_{nominal}}{Q_{ref} Vol_b} Y[U - V] \quad (19)$$

$$DoD = \frac{Vol_b}{3600 Q_{nominal}} \int_0^t j dt \quad (20)$$

5. Thermal management in railway systems

Modern trains, especially those powered by batteries, require sophisticated thermal management systems to optimize performance and prolong battery life. Battery thermal management helps maintain batteries within their optimal temperature ranges, thereby enhancing efficiency and reliability. The integration of nanofluids as advanced cooling mediums has revolutionized this field by offering superior thermal conductivity and heat transfer capabilities compared to conventional fluids.

The importance of Thermal Management in Railway Systems is vital to:

Prevent Overheating and Thermal Runaway: Overheating can lead to thermal runaway, a dangerous situation where the battery's temperature increases uncontrollably, potentially causing fires or explosions. Effective cooling systems mitigate this risk by dissipating excess heat efficiently.

Maintain Optimal Performance and Efficiency: Batteries perform best within specific temperature ranges. Deviations from these ranges can reduce the battery's efficiency and power output. A well-designed thermal management system ensures that the battery operates within these optimal ranges, maximizing performance.

Prolong Battery Life: Continuous exposure to high temperatures can degrade battery materials and reduce their lifespan. By keeping the battery cool, thermal management systems help prolong the battery's life, reduce the frequency of replacements, and lower overall maintenance costs.

Ensure the Safety of Passengers and the Overall Railway System: Safety is paramount in railway operations. Effective thermal management systems prevent overheating and related hazards, ensuring the safety of passengers and protecting the integrity of the railway infrastructure.

Implementing advanced thermal management systems involves integrating these cooling technologies into the design and operation of railway systems:

Design Considerations: Incorporating cooling channels, heat exchangers, and thermal interfaces optimized for nanofluid circulation can significantly enhance heat dissipation. Engineers must consider factors such as flow rates, nanoparticle concentration, and fluid dynamics to maximize cooling efficiency.

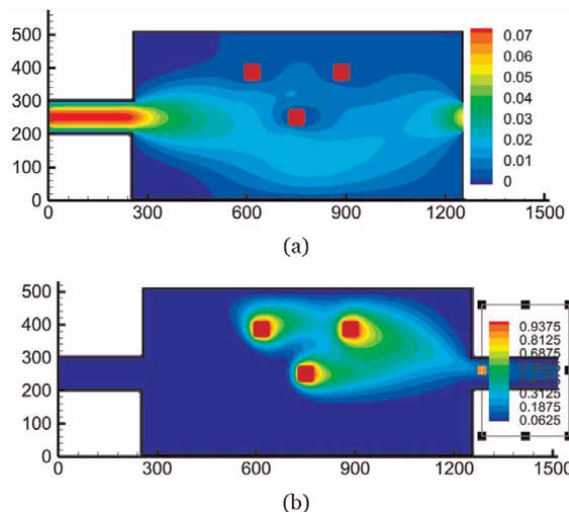


Figure 2. Velocity (a) and temperature (b) profiles for water and MWCNT/Fe₃O₄ water hybrid nanofluid at Re = 100 and φ = 0.004.

Monitoring and Control: Advanced sensors and control systems can monitor battery temperatures in real-time, adjusting cooling rates as needed to maintain optimal conditions. This dynamic control is essential for responding to varying operational demands and environmental conditions.

Maintenance and Upkeep: Regular maintenance of the thermal management system ensures continued performance. This includes checking fluid levels, inspecting cooling channels for blockages, and ensuring that nanoparticles remain evenly dispersed within the coolant.

Forced convection in a passage with sudden expansion and contraction which includes heat sources has garnered significant attention from researchers due to its engineering applications such as cooling electronic components and nuclear reactors. Mohebbi and Yuan [19] studied the nanofluid flow and thermal behavior around three heated obstacles in a channel featuring sudden expansion and contraction. **Figure 2** shows the velocity and temperature profiles for water and MWCNT/Fe3O4 water

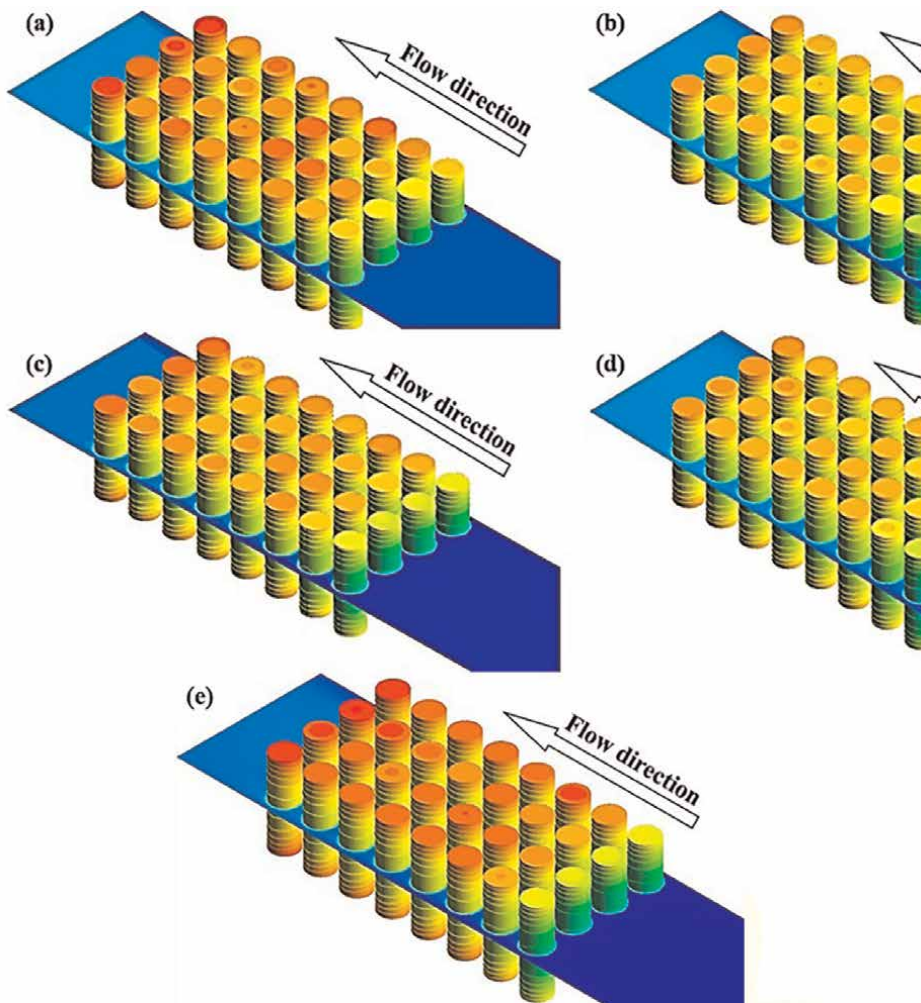


Figure 3. Temperature contours of water at two different concentrations of Al_2O_3 and CuO at 0.05 m/s velocity (a) CuO -2%, (b) CuO -5%, (c) Al_2O_3 -2%, (d) Al_2O_3 -5%, (e) Water at a 2C discharge rate.

hybrid nanofluid at $Re = 100$ and $\phi = 0.004$. Based this study the thermal efficiency of each heat source depends on its position and the positions of the other heat sources. When all three heat sources are arranged in the first row, they achieve better heat transfer performance compared to other configurations. However, a heat source located behind another tends to have a lower average Nusselt number. This results can be usefull in a battery thermal management cooling system.

Figure 3 shows temperature contours for 2 and 5% concentrations of both nanoparticles at a flow velocity of 0.05 m/s which studied by Soleymani et al. [28]. The contours indicate that the lowest temperature occurs at the inlet. Batteries located at the end of the pack experience the highest temperatures, though the temperature difference between the nanofluid inlet and outlet is minimal. Additionally, temperature reduction is more pronounced in the center of each battery cell compared to the upper and lower sections.

Innovative heat exchanger designs that maximize surface area and improve fluid dynamics can significantly enhance heat transfer efficiency. Techniques such as 3D printing and additive manufacturing allow for the creation of complex geometries that were previously impossible to produce. These advanced designs can be tailored specifically for railway applications, offering superior cooling performance. Urban transit systems, including subways and light rail, face unique thermal management challenges due to their frequent stops and starts, which generate significant heat. Implementing advanced cooling systems using nanofluids can improve their efficiency, ensuring passenger comfort and system reliability. Case studies have demonstrated that retrofitting existing cooling systems with nanofluid technology can lead to noticeable improvements in thermal performance, with temperature reductions of up to 10% observed in pilot implementations.

6. Conclusions

Effective thermal management is pivotal for ensuring the operational efficiency and longevity of modern railway systems, particularly for electric and hybrid trains. This chapter has examined advanced methodologies and technologies in thermal management, emphasizing battery thermal regulation, cutting-edge cooling systems, and the innovative use of nanofluids. The integration of nanofluids into thermal management systems has emerged as a transformative advancement due to their exceptional thermal conductivity and heat transfer performance compared to conventional fluids.

Research indicates that nanofluids significantly enhance forced convection heat transfer across various geometries, making them particularly advantageous for applications such as train radiators and battery cooling systems. The superior heat transfer characteristics of nanofluids translate into improved thermal management and operational efficiency in these critical components. The lattice Boltzmann method (LBM) has proven to be a valuable numerical technique for simulating nanofluid dynamics and heat transfer processes. Its ability to provide detailed, high-resolution insights into complex fluid flows and heat exchange phenomena enables the optimization of thermal management strategies in railway systems.

In the context of battery thermal management, nanofluids have demonstrated considerable potential in maintaining optimal battery temperatures, mitigating overheating risks, and extending battery lifespan. By ensuring that batteries operate within their specified thermal ranges, advanced thermal management systems

enhance both their performance and reliability. The successful application of nanofluids in these systems underscores the need for careful design, real-time monitoring, and ongoing maintenance to uphold performance standards and safety.

The evolution of battery technology and increasing power demands highlight the growing importance of sophisticated thermal management solutions. The adoption of advanced cooling technologies, particularly through the deployment of nanofluids, represents a critical advancement in optimizing the performance and safety of modern railway systems. As the railway industry continues to advance, the role of cutting-edge thermal management systems will become increasingly essential in ensuring the efficient, reliable, and safe operation of railway infrastructure.

Author details


Rasul Mohebbi^{1*} and Masoud Mohebbi²

1 School of Engineering, Damghan University, Damghan, Iran

2 Iran University of Science and Technology, Tehran, Iran

*Address all correspondence to: rasul_mohebbi@du.ac.ir

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Chapter 2

Features of Interaction of the New and Worn Wheel and Rail Profiles

*George Tumanishvili, Tengiz Nadiradze, Rustam Rakhimov
and Giorgi Tumanishvili*

Abstract

An increase in the friction path and sliding velocity contributes to an increase in thermal loading and wear of heavily loaded rubbing surfaces of wheels and rails. One of the reasons contributing to the development of these phenomena is the change in the shape of the rubbing profiles of wheels and rails due to wear. Conditions of power and thermal loading and increased wear rate of profiles of the wheels and rails are considered, and friction paths and sliding velocities are calculated at movement of new and worn wheels of the wheelset in the straight and curved sections of a rail track. It was revealed that wear of the profiles significantly increases friction path, sliding (friction) velocity, and frequency of lateral oscillations (zigzag movement) of the wheelset in the straight sections of the path along the rolling surface and in curved sections—the friction path of the inner wheel. Therefore, change of the wheel profile due to wear negatively affects the frequency of the wheelset lateral oscillations, friction path, sliding velocity, and wear rate that should be taken into account when determining wear norms of the wheels and rails.

Keywords: wheel, rail, wheel profile, friction path, sliding velocity, wear

1. Introduction

An increase in the speed and axial load of wheelsets leads to an increase in the power and thermal loads of the interacting surfaces of the wheels and rails, resistance to rotation of the wheels, and their damage. When the wheelset moves in a straight segment, it makes periodic lateral movements (lateral vibrations), which is due to the conical shape of the wheel rolling surface. This leads to increased wear of the wheel rolling surface and its angle of inclination, an increase in the frequencies of transverse vibrations, friction path, sliding velocity, and wear intensity. In addition, changes in the profiles of the interacting surfaces of wheels and rails due to wear affect the dynamic characteristics of railway transport both, on straight and curved sections of the track, on the stability of the movement of the rolling stock and the comfort of passengers. It can also contribute to wheel derailment, increased wear rate, etc. Therefore, the identification of parameters and the determination of their influence on tribological properties of interacting wheels and rails is a fundamental task of the railway industry [1–3]. However, insufficient knowledge of the processes occurring in

the contact zone of wheels and rails, in particular thermal, adhesive, fatigue, and other phenomena, makes it difficult to prevent the noted undesirable phenomena.

Wheel and rail wear rates are seen as one of the fundamental problems of rail transport. Different parts of interacting surfaces of wheels and rails have different functions, different creep, and therefore they should have different properties. The friction coefficient of the steering surfaces of the wheels and rails should be as low as possible—not more than 0.1. Excessively high friction on rolling surfaces lead to their increased shear stresses, plastic deformations, adhesion phenomena, and fatigue damage; low friction can lead to poor traction and braking, as well as heavy wear during traction and braking.

The wheel slipping causes an increase in thermal and power loads on contact surface layers, the vibrations, characteristic noise, and the most dangerous type of wear—scuffing [4]. **Figure 1** shows the standard geometric parameters of interacting surfaces of the wheels and rails (a), and a schematic view of various radii inside of the contact zone (b) [5], which causes an increase in the relative sliding velocity with an increase of the ratio R_2/R_1 .

Friction path and sliding velocity depend on difference of radii of contacting circles, angle of inclination of the tangent to the flange transitional curve, and coordinates of the wheel and rail contact points.

The nature of movement of a wheelset along a rail track, traffic safety, energy consumption for traction, and environmental pollution are largely determined by both

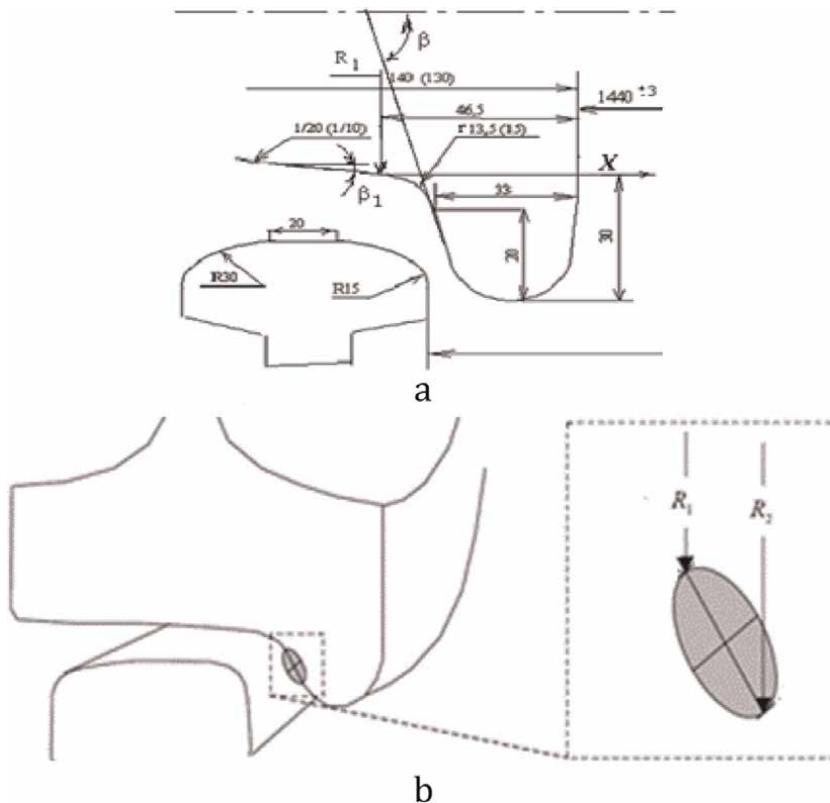


Figure 1. Standard geometric parameters of interacting surfaces of the wheels and rails (a), and a schematic view of various radii inside the contact zone of the wheel flange (b).

the tribological properties of the interacting surfaces of wheels and rails and the design and condition of the wheelsets and rails. At the same time, in straight and curved sections, the nature of movement of wheelsets along the rail track, their power and thermal load, and damageability differ significantly.

Attempts to increase the wear resistance of wheels and rails by choosing the initial roughness of their materials, by increasing hardness (about 400 HB) and other measures are known [6–8].

For a given axial load, at other conditions being equal, the wear of the wheel profile mainly depends on the sliding velocity and friction path. These parameters can change in straight sections, during lateral movements of the wheelset, and in curves, when the deflected from the radial position axis of the wheelset returns back to the radial position, contributing to the rail corrugation.

The research results show that to date there are no reasonable recommendations for improving tribological properties of the wheels and rails. The most effective method of improving tribological properties of the wheels and rails is considered to be lubrication of steering surfaces and modification of rolling surfaces. However, the specific conditions for applying lubricants and friction modifiers to rubbing surfaces, the direct environmental impact, as well as the constant change in the profiles of wheels and rails negatively affect the effectiveness of these measures. Apparently, a necessary condition for improving the tribological properties of the wheel and rail profiles is to increase the stability of the third body with due properties and reduce the thermal and power loads of the contact zone.

The destruction of the third body leads to direct contact of rubbing surfaces and a sharp deterioration in their tribological properties. With a given axial load and other equal conditions, the sliding velocity and friction path can have the greatest impact on the loading of the contact zone. The work considers the effect of the wheel profile wear on the sliding velocity and friction path, which increase the loading and damage to the rubbing surfaces of the working profiles of wheels and rails.

In straight and curved sections, the operating conditions of the wheel and rail differ significantly. In the straight sections, the contact zone is preferably located in the middle part of the rolling surface of the wheel, and the movement of the wheelset in the track occurs with the periodic contact of the wheel flange and the rail head.

In the curves, the contact surface of the first wheelset is displaced to the flange of the outer wheel and hence to the lateral surface of the rail head. In this process of movement, the contact surfaces are under the influence of a changing set of both, relative sliding and vertical and horizontal loads. Due to wear and movement of the contact point during displacements of the wheelset in the track, the initial conical shape of the rolling surface and the angle of inclination of the wheel flange are short-term. Constant changes of the wheel and rail profiles lead to an increase of power and thermal loads of the contact zone, seizure in places of destruction of the third body, increase of the friction coefficient, its instability and intensity of wear, decrease of the angle of inclination of the flange and lateral surface of the rail, and increase of probability of the wheel rolling on the rail.

In search of reducing the wheel damage, a large number of studies have been performed, and there are many recommendations: clarification of the initial profile of the wheel and rail; increased hardness of interacting surfaces; selection of materials; application of “conformal profiles” of rolling surfaces, etc. However, they do not always have reliable theoretical or experimental justifications and are not effective enough.

2. Features of movement of the wheelset on straight sections of the track

At movement of a wheelset in the straight segments, because of conical form of the wheel tread surface, it performs periodic lateral displacements (or “hunting” oscillations) that affect friction path, friction velocity, and wear rate (**Figure 2**).

The cyclic interaction of wheels and rails in the conditions of rolling with sliding, as well as the noted types of their damage, which have a different nature and are established visually without clear signs of their manifestation, are typical, limiting the efficiency of the wheels and rails. It should also be noted that the processes preceding the rise of adhesive wear and fatigue phenomena, in particular the processes of formation and destruction of the third body, have not been sufficiently studied, and some of the parameters that contribute to increasing the intensity of various types of damage have not been revealed.

The standard geometric parameters of the interacting surfaces of wheels and rails, in particular the radius of the base of the flange and the rounding of the corner of the rail, are different, which in some conditions excludes direct contact of the corner of the rail and the base of the wheel flange. However, the geometric parameters of the wheel and rail profiles are short-lived, wear out during operation, and lead to conformal contact. Worn wheels and rails under certain conditions are characterized by conformal contact, increased power and thermal loads of the contact zone and friction work, and, accordingly, increased wear intensity and instability of friction forces.

A typical feature of interaction of the wheel flange surface and lateral surface of the rail head is a comparatively small magnitude of the coefficient of friction (no more than 0.1). But this depends on the operating conditions of the wheel flange with the lateral surface of the rail head, and in severe operating conditions, the friction coefficient becomes unpredictable and can increase sharply, leading to catastrophic wear and rolling of the wheel on the rail.

The dependences of the radius of the wheel R on the coordinate of the contact point x on the transition curve, the angle of inclination β of the tangent passing through this point (**Figure 1a**), and the sliding path L per one revolution of the wheel, respectively, have the form:

$$\beta = \arctg \frac{x}{\sqrt{r^2 - x^2}}; \quad R = R_1 + k = R_1 + r - \sqrt{r^2 - x^2}; \quad L = 2R \arccos \frac{R_1}{R}; \quad h = IL, \quad (1)$$

where r is the radius of curvature of the flange base, x -coordinate of the point of contact of the flange base along the x -axis, R_1 —radius of the wheel at the beginning of the transitional curve; k —wheel radius increment; I —wear rate; L —friction path; h —wear value.

As can be seen from **Figure 3**, the thermal load of the rolling surfaces is relatively low. At operation of the wheel in traction and braking modes, at rotation around vertical axis, and at slipping, the values of sliding velocity and friction path increase. The flange root

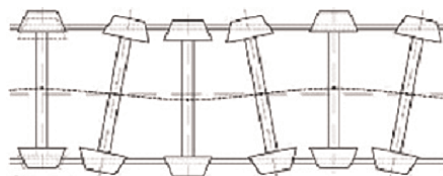


Figure 2.
Zigzag movement of a wheelset on a straight line.

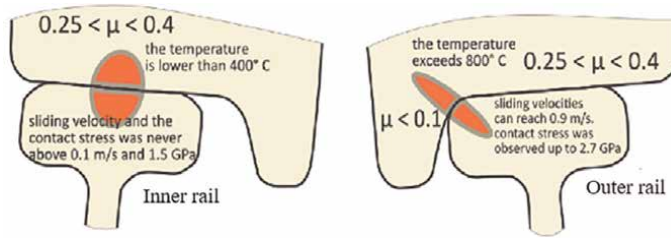


Figure 3.
 Power and thermal loads of the wheel and rail contact zones.

and the rail corner in the contact zone have sufficiently high tangential stresses, temperature, and creep level. They serve the role of both rolling surfaces and steering surfaces, and the value of the friction coefficient 0.1 for both cases is unacceptable. The flange root and the rail corner are involved in traction, braking and turning the wheel, which requires mutually exclusive properties: a relatively high value of the friction coefficient for traction and braking and a low value of the friction coefficient for steering.

Figure 4 schematically shows the conditions of loading and damage to the rubbing surfaces of wheels and rails when moving in straight and curved sections and the

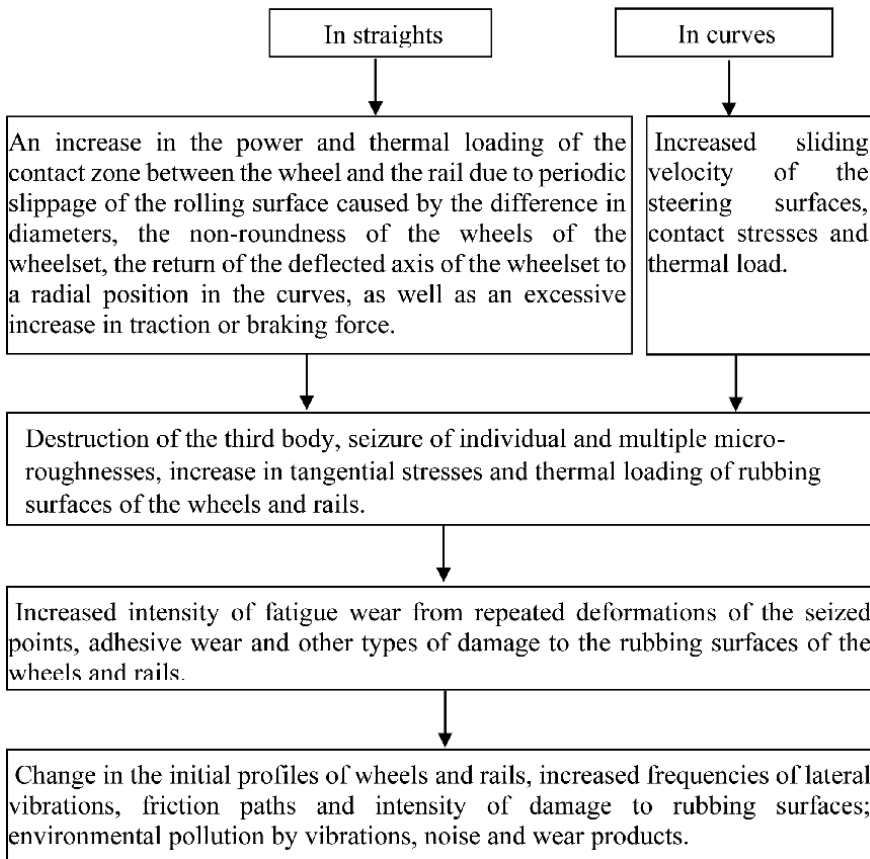


Figure 4.
 Loading and damage conditions of rubbing surfaces of wheels and rails when moving in straight and curved sections.

consequences of changing the initial profiles of wheels and rails, in particular: increased frequencies of lateral vibrations, friction paths and intensity of damage to rubbing surfaces, as well as environmental pollution with vibrations, noise, and wear products.

3. Power and thermal loads and damageability of wheels and rails

Figure 3 shows power and thermal loads of the wheel and rail contact zones (of tread and steering surfaces).

As can be seen from the figure, the root of the wheel flange and rail corner are the most loaded parts of their profiles where the greatest friction work is done. **Table 1** shows the contact stresses, temperatures, and friction coefficients in the contact zone of the tread surface as well as the surfaces of the wheel flange root and rail corner.

This causes a difficult-to-predict, destructive effect of surface layers, and many studies are devoted to its prevention [9, 10].

The actual contact area is much smaller than the nominal contact area (**Figure 5**) [8]. In the process of friction, with direct contact of surfaces, on actual contact zones, significant stresses arise, corresponding to deformation and heat release, leading to destruction of the third body and to seizure of directly interacting irregularities.

In the process of friction, separation of the seized places causes a sharp increase in tangential stresses and deformations.

Considering the heat distribution in irregularities as a boundary value problem describing heat transfer in the cylinder, the results of solving the problem for various surrounding materials—for water and lubricating oil—will have the form shown in **Figure 6**.

As it is seen from the figure, intensity of the temperature reduction toward the base of the micro-asperity is higher for water than for oil lubricant. The raised heat capacity and thermal conductivity of water contributes to better cooling conditions of

Parameter	Contact stress GPa	Required coefficient of friction	Temperature
Tread surface	1.5	0.2 -0.4	400 °C
Surfaces of the wheel flange root and rail corner	3	≤ 0.1	800°C

Table 1. Contact stresses, temperatures, and friction coefficients in the contact zone of the tread surface.

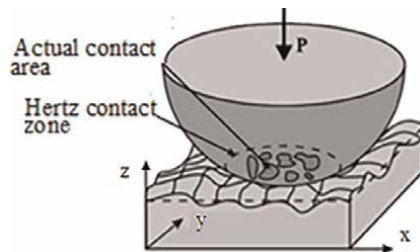


Figure 5. Zones of actual contact and corresponding surface deformations.

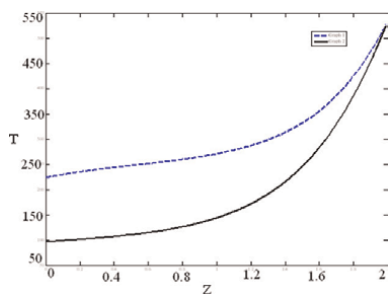


Figure 6. Dependence of the temperature on the distance from the micro-asperity base for various ambient: — water - - - oil lubricant.

the micro-asperity, and at increased distance from the heat source, the temperature for water is lower than for oil lubricant.

On the wheels and rails, in addition to the steering and tread surfaces, there are also surfaces of the flange root and the rail corner, which simultaneously play the roles of the steering and tread surfaces, though the requirements for these surfaces are different. Existing profiles of wheels and rails can be divided into rolling surfaces (participating in “free” rolling, traction, and braking) and steering surfaces (wheel flange and lateral surface of the rail, taking part in steering mainly in curves and preventing the wheelset from derailment). The root of the flange can roll along the corner of the rail, participate in traction, braking, and steering. But traction (braking) and steering require mutually exclusive properties: a relatively high value of the coefficient of friction during traction and braking and, as low as possible coefficient of friction during steering. And the “ideal” value of the coefficient of friction ($\mu \geq 0.1$) in the contact area of the wheel flange and rail corner is not acceptable for both cases. By gradually shifting the points of interaction of the wheel and rail from the rolling surface to the root of the flange and the rail corner and then to the flange and the lateral surface of the rail, the relative sliding velocity, friction path, the likelihood of fatigue damage, scuffing, vibration, noise, and wear intensity of the rubbing surfaces increase. In addition, the close proximity of the rolling and steering surfaces facilitates mixing of lubricants and friction modifiers. Therefore, the rolling and steering surfaces must be separated and modified with friction modifiers having corresponding properties.

Processes accompanying the interaction of profiles, especially with an increase in creep (with an increase in traction or when the interacting places move toward the flange of the wheel and the lateral surface of the rail), increase the likelihood of destruction of the third body and interacting surfaces. However, an increase in the relative sliding of the wheels causes an increase in thermal and power loads in the contact of surface layers, generating vibrations, characteristic noise, and the most dangerous type of wear—scuffing. Therefore, maintaining a third body between interacting surfaces is critical. The above problems are relevant for any railways, and their solution requires special experimental and theoretical studies. It is known that the working conditions of wheelsets in curved segments are very difficult, especially of the first wheelset. This issue has become especially acute in recent years with an increase in train speed, and a lot of work has appeared on increasing the resistance of wheel flanges to operational impacts.

Figure 7 shows wheels and rails interacting surfaces (tread and steering surfaces) and rail corner and root of the wheel flange (a) and friction work values (b) [11].

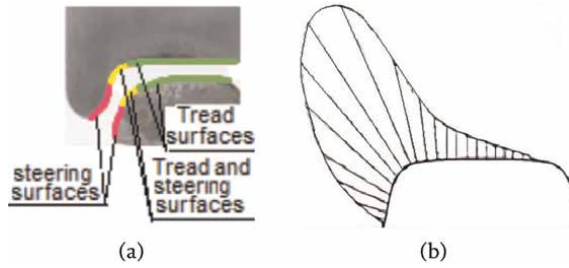


Figure 7. Tread and steering surfaces, rail corner, and root of the wheel flange (a) and friction work values (b).

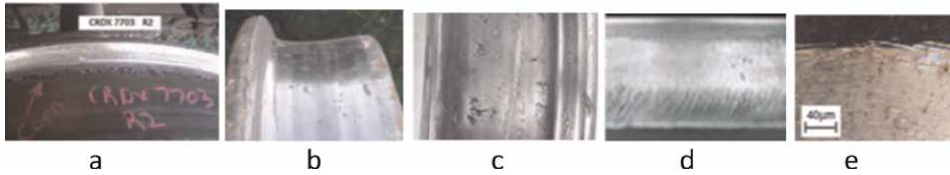


Figure 8. Damages of interacting surfaces of wheels and rails.

As seen in **Figure 7**, the greatest friction work falls on the root of the wheel flange and the rail corner, which contributes to the greatest resistance to wheel rotation, energy consumption to overcome this resistance, and damage to the wheels and rails.

Figure 8 shows damages of interacting surfaces of wheels and rails.

Figure 8a shows traces of fatigue damage to the rolling surface and adhesive wear of the steering surface, **Figure 8b**—grooved rolling surface, **Figure 8c**—traces of the wheel rolling surface melting, and **Figure 8d** and **e** show traces of fatigue damage to the rolling surface and delamination of the rail steering surface. These types of damage are formed simultaneously, and the dominant type depends on the working conditions.

4. Evaluation of the wheels and rails tribological parameters

Currently, there are no reliable and recognized methods for predicting the tribological parameters of rubbing surfaces of machines, including wheels and rails. To do this, they usually use methods used in mechanical engineering. The Amonton–Coulomb formula for determining the coefficient of friction $f = F_T/F_N$ is currently the most popular; to estimate the volume of worn material, Archard’s formula (1952) $W = KPS/H$ is used. It is assumed that the friction power under limiting conditions is constant and can be determined by the formulas $fPV = \text{const.}$, $P^m V^n = \text{const.}$, and the contact stress is determined by the Hertz formula (1892) $\sigma_H = 0.418(q \cdot E_{red}/\rho_{red})$, where f is the sliding friction coefficient; F_N and F_T —normal and tangential forces; W —volume of wear products; K —empirical coefficient, usually called the wear coefficient; P —normal contact load; S —friction path; H —hardness of surface layers of the material of rubbing parts; V —sliding velocity; m , n —exponents; σ_H —normal contact stress; q = linear load; E_{red} —reduced modulus of elasticity; ρ_{red} —reduced radius of curvature. However, these formulas are characterized by limited parameters and do not always give a satisfactory result.

As can be seen from the above formulas, tribological parameters largely depend on the sliding velocity, friction path, and contact load.

5. Wheelset movement in a straight segment

It is known that when the wheelset moves in a straight segment, due to the conical shape of the rolling surface of the wheel, it performs periodic zigzag movements (lateral oscillations), which affects the friction path, sliding velocity, and wear intensity. Therefore, we determine the friction path of the wheels and the average sliding velocity.

Consider new standard wheelset with the diameter of the rolling circumference $D = 957$ mm (radius $R = D/2 = 478.5$ mm) and a slope of the profile $n = \tan \alpha = \frac{1}{20} = 0.05$ and the same wheelset worn-out by 7 mm with the profile slope $n = 0.34$. For solution of the problem, we will use the graphs of periodic lateral displacements and the axle yaw of the free wheelset (without bogie) with the data: amplitude—for new wheelset $y_0 = 0.295^{\text{II}} = 7.5$ mm, for worn-out one $y_0 = 0.885^{\text{II}} = 22.5$ mm; wave length—for new wheelset $\lambda = 53\lambda = 1615.44$ cm, for worn-out one $\lambda = 20^{\text{I}} = 609.6$ cm (**Figure 9**) [12].

As seen from **Figure 9**, the amplitude and frequency of lateral oscillations and, accordingly, the friction path of a new and worn wheels are different. Let us determine numerical values of the friction paths for new and worn wheels.

Maximum value of the new wheelset axle yaw may be found by the formula [12]:

$$Q_{max}^0 = \sin^{-1}\left(\frac{2y_0}{R + ny_0}\right) = \sin^{-1}\left(\frac{2 \times 7.5}{478.5 + 0.05 \times 7.5}\right) = 1.7950; \quad (2)$$

At rotation of the wheelset axle by this angle, the contact points of its each wheel will slide on the rail by the distance

$$T_1/4 = \frac{d}{2} Q_{max} = \frac{d}{2} Q_{max}^0 \frac{\pi}{180^0} = \frac{10}{2} \times 1.7950 \frac{3.14}{180^0} = 0.1566 \text{ mm}. \quad (3)$$

where $d = 10$ mm is the diameter of the contact spot.

Consequently, friction path of the wheels during one cycle

$$T_c = T_1/4 \times 4 = 0.1566 \times 4 = 0.6264 \text{ mm} \quad (4)$$

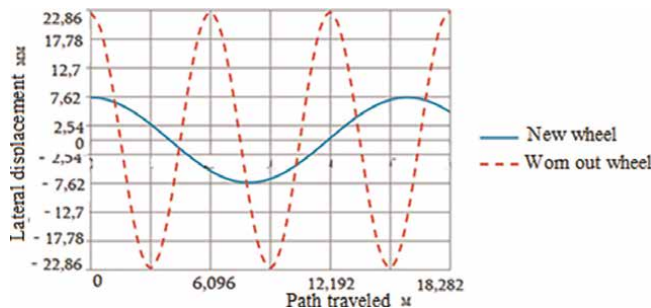


Figure 9.
 Lateral oscillatory movement of new and worn wheels.

and for distance of 1 km will be

$$T_{1km} = T_c \frac{1km}{\lambda} = 0.6264 \text{ mm} \frac{1000 \text{ m}}{16.1544 \text{ m}} = 38.77 \text{ mm.} \quad (5)$$

For the worn-out by 7 mm wheelset, with radius of the rolling circumference $R = 478.5 - 7 = 471.5 \text{ mm}$ and parameters $n = 0.34; y_0 = 0.885^{II} = 22.5 \text{ mm}$, using successively formulas (1), (2), (3)), and (4), we obtain $T_{1km} = 308.4 \text{ mm}$.

The frequency f and period P of the zigzag oscillations, as well as friction velocity U depend on the train speed V . Numerical values of these parameters at $V = 100 \text{ km/h} = 27.77 \text{ m/s}$ are calculated by the formulas $f = \frac{V}{\lambda}; P = \frac{1}{f}$ and $U = \frac{T_c}{P}$.

Table 2 shows the results of calculation of the friction path per 1 km, the frequency of zigzag oscillations, and the sliding velocity at the speed $V = 100 \text{ km/h}$.

As can be seen from **Table 2**, the friction path, frequency of the zigzag movement and sliding velocity and, accordingly, the wear rate, vibration, and noise of worn wheels are much greater than that of new ones.

Let us consider the sliding distance of the wheel flange during rolling, rolling with sliding, and sliding of the wheel tread. When the tread surface slides without rolling, the sliding path of the flange is maximum and equal to the arc cd (**Figure 10a**). At rolling of the wheel tread with sliding (**Figure 10b**), length of the arc of contact cd is decreased, and at rolling of the wheel without sliding of the wheel tread (**Figure 10f**) length of the arc of contact is minimal.

Therefore, sliding distance and hence sliding velocity depend on the ratio of the sliding velocity and rolling velocity of the wheel tread surface.

Parameter	Designation	The wheel condition	Value
Friction path per 1 km	T1km	New	38.74 mm
		Worn	308.4 mm
Frequency of the zigzag motion at $V = 100 \text{ km/h}$	f	New	1.72 Hz
		Worn	4.55 Hz
Friction (sliding) velocity at $V = 100 \text{ km/h}$	U	New	1.077 mm/s
		Worn	8.553 mm/s

Table 2. Results of calculation of the friction path per 1 km, the frequency of zigzag movement, and the sliding velocity at a speed of 100 km/h.

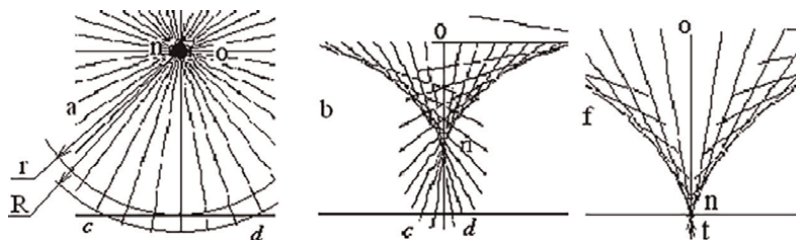


Figure 10. Arc of contact of the wheel flange and lateral surface of the rail head at various ratios of the sliding velocity and rolling velocity: (a) sliding without rolling; (b) rolling with sliding; (f) rolling without sliding.

6. Peculiarities of a wheelset movement in curves

At movement of the wheelset along a curved section of the track, in order to maintain the radial position of the wheelset, the wheels must travel different distances due to the difference in the radii of curvature of the outer and inner rails. But the lateral displacement of the wheelset with the initial tilt of the rolling surface of the wheels 1:20 (which is constantly changing due to wear) does not always compensate for the difference in the paths traveled by the outer and inner wheels and does not provide the radial position of the wheelset axle. The root of the flange or the flange of the outer wheel pressing against the lateral surface of the rail prevents the wheel from rolling onto the rail, leading to additional resistance to wheel rotation. In this case, the axle of the wheelset is twisted, bended, and deviated from the radial position, creating a two-point or conformal contact, increasing the angle of attack, and creating a danger of the wheel going off the rail. In the extreme case, when the axle of the wheelset is extremely deviated from the radial position, in order to continue movement, one of the wheels must slide along the rail (outer wheel in the direction of movement or

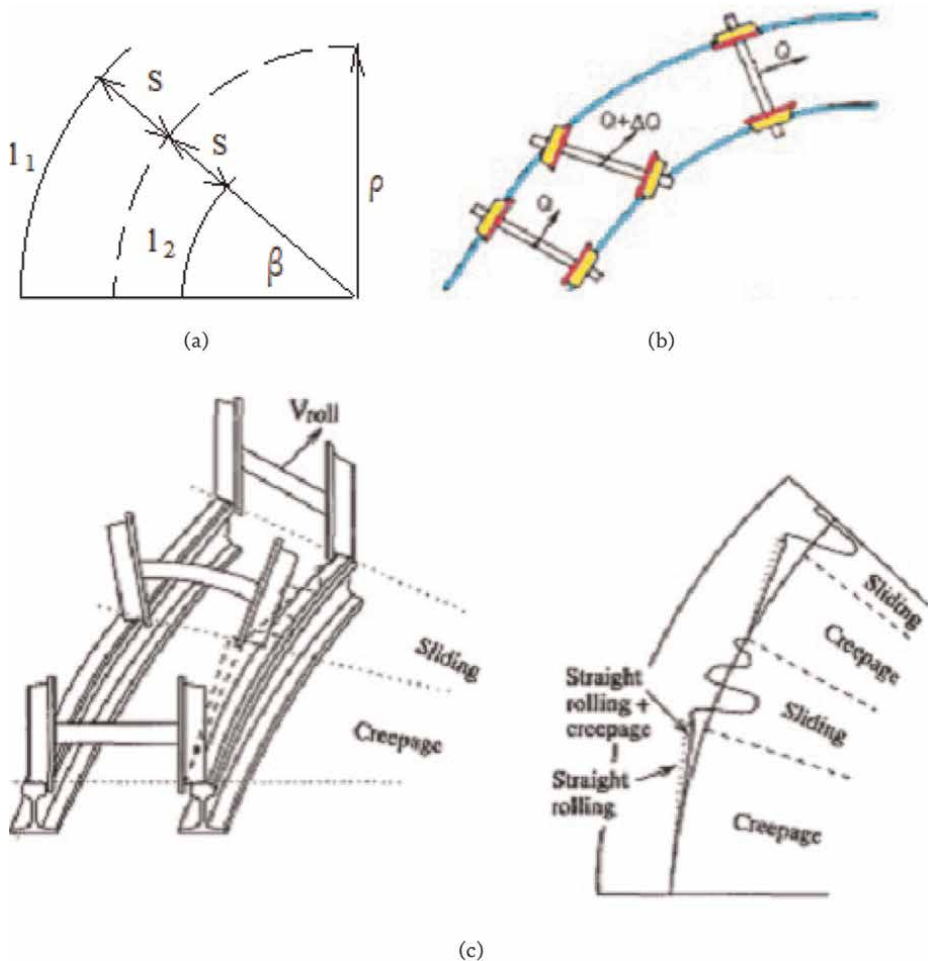


Figure 11.
 (a) Curved section of a track; (b) movement of a wheelset in curves; (c) slippage of the inner wheel [13].

inner wheel in the opposite direction) in order to return in the radial position, or the wheelset will roll onto the rail head and come off it. **Figure 11** shows: (a) a curved section of track; (b, c) movement of a wheelset in curves.

Intermittent slippage of one of the wheelset wheels (**Figure 11c**) is accompanied by torsional vibrations of the wheelset shaft and longitudinal vibrations of the carriage (which are identified as flange noises [14–16]) and the corresponding wear of the rails—the so-called corrugation that occurs mainly on the lower rail in the curves [17–20]. Despite numerous attempts, there is no reliable solution to the problem of rail corrugation, except for expensive grinding technology.

Figure 12 illustrates typical rail profile changes that arise in curves [21, 22]: (a, b) severe lateral wear and (c) severe rail corrugation. Such wear causes a great change of the rail profile and, therefore, strongly affects the running behavior of railway vehicles, such as motion stability, riding comfort, and derailment safety.

Determine numerical values of the friction parameters of a new (unworn) wheels of a wheelset moving in a curve with radius ρ (**Figure 11a**).

The outer wheel displaced laterally by $y = 10$ mm, rolling along the arc $l_1 = 1$ km = 1000 m and its flange sliding on the lateral surface of the rail, will make $n_1 = l_1 / 2 \pi R_1 = l_1 / 2\pi(R + ny) = 1000 / 2 \times 3.14(478.5 + 0.05 \times 10) = 332.265$ revolutions.

The flange points at one revolution describe an extended cycloid with a full loop below the rolling line (**Figure 13**), whose length presents the friction path. The maximum friction path will have the points K located at the greatest distance R_k from the wheel center (**Figure 14**).

The value of this radius will be $R_k = R_1 + h_k$, where $R_1 = 478.5 + 0.05 \times 10 = 479$ mm, and $h_k = 30 - 13 - ny = 30 - 13 - 0.05 \times 10 = 16.5$ mm, or.

$$R_k = 479 + 16.5 = 495.5 \text{ mm}$$

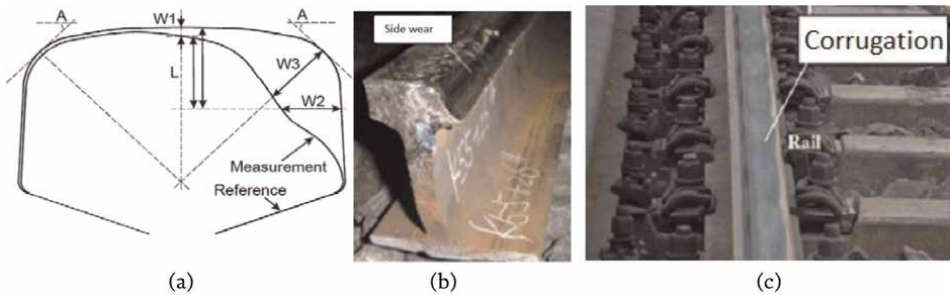


Figure 12. Wear magnitudes of different parts of the wheel working surface: W_1 —vertical wear; W_2 —horizontal wear; W_3 — 45° wear, severe lateral wear (a, b); severe rail corrugation (c).

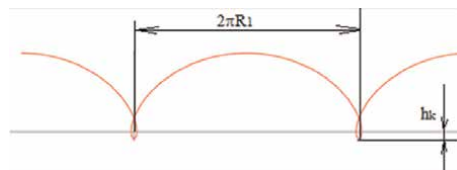


Figure 13. Extended cycloid.

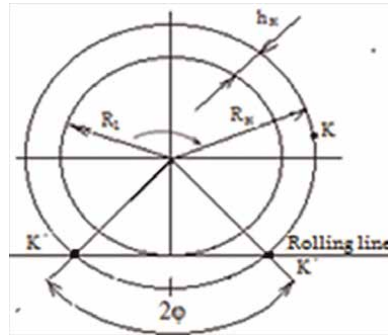


Figure 14.
 Wheel rolling on the rail.

Here 30 mm is the height of the flange and 13 mm—the height at which the peripheral part of the flange is rounded.

The length of the loop below the rolling line can be replaced by $2hk$ with sufficient accuracy. Then the friction path for the outer wheel per revolution will be.

$$F_1 = 2h_k = 2 \times 16.5 = 33 \text{ mm},$$

and at rolling along the arc $l_1 = 1 \text{ km}$, the friction path will be.

$$F = F_1 n_1 = 33 \times 332.265 = 10,965 \text{ mm} = 10.965 \text{ m}.$$

The wheel friction velocity depends on the train speed. To determine it, we divide the friction path of the wheel for its one revolution F_1 , by the time t required for rotation of the wheel by the angle 2φ (**Figure 14**), where

$$\varphi = \cos^{-1} \frac{R_1}{R_k} = \cos^{-1} \frac{479}{495.5} = 14.8270. \quad (6)$$

Consequently, $2\varphi = 2 \times 14.8270 = 29.650$, which is $29.650/3600 = 0.08236$ revolutions.

For the train speed $v = 50 \text{ km/h} = 50 \cdot n_1 = 50 \cdot 332.265 = 16613.25 \text{ rph} = 4.615 \text{ rps}$, the time t will be

$$t = 2\varphi/v = 0.08236/4.615 = 0.0178 \text{ c} \quad (7)$$

and sliding velocity

$$V_{sl} = F_1/t = 33/0.0178 = 1854 \text{ mm/s} = 1854 \text{ m/s}. \quad (8)$$

Consider now the inner wheel. Its effective radius of the wheel rolling circle.

$$R_2 = R - ny = 478.5 - 0.05 \times 10 = 478 \text{ mm}, \quad (9)$$

Determine the height of the wheelset cone ρ_w from the proportion (**Figure 15**):

$$\frac{R_1}{R_2} = \frac{\rho_w + S}{\rho_w - S} = \frac{R + ny}{R - ny}, \text{ from where } \rho_w = \frac{SR}{ny} = \frac{790 \times 478.5}{0.05 \times 10} = 756030 \text{ mm} = 756.03 \text{ m}. \quad (10)$$

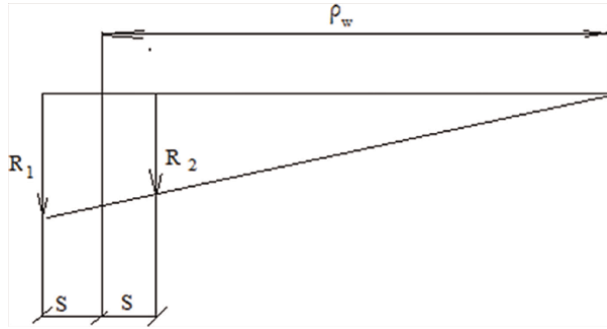


Figure 15.
Cone of the wheelset.

The inner wheel will not slide on the rail if the radius of curvature of the rail is $\rho = \rho_w$. If $\rho < \rho_w$, then the wheel will have a negative slip in the opposite to movement direction, and if $\rho > \rho_w$, then a positive slip in the direction of movement. Consider the last two cases.

1. ($\rho < \rho_w$); Suppose $\rho = 420$ m. In this case, the arc length l_2 (**Figure 11a**) will be

$l_2 = (\rho - S) \beta$, where $\beta = 1/(\rho + S) = 1000/(420 + 0.79) = 2.376$ rad. and substituting we get.

$$l_2 = (420 - 0.79) \cdot 2.376 = 996.244 \text{ m.}$$

The inner wheel will roll over the distance

$$l_2^1 = 2\pi R_2 n_1 = 2 \times 3.14 \times 0.478 \times 332.265 = 997.912 \text{ m,} \quad (11)$$

which is greater than l_2 . The total friction path will be

$$S_F = l_2 - l_2^1 = 996.244 - 997.912 = -1.668 \text{ m,} \quad (12)$$

that is, sliding occurs in the direction opposite to the movement.

2. ($\rho > \rho_w$); Suppose $\rho = 1020$ m. Determine the angle $\beta = 1/(\rho + S) = 1000/(1020 + 0.79) = 0.9796$ rad. The arc length $l_2 = (\rho - S)\beta = (1020 - 0.79) \cdot 0.9796 = 998.448$ m. The total friction path in this case will be

$$S_F = l_2 - l_2^1 = 998.448 - 997.912 = 0.537 \text{ m,} \quad (13)$$

that is, the wheel will slide in the direction of movement.

Determine the sliding velocity of the inner wheel. When rolling, the inner wheel periodically slides along the rail for the time t required to return the twisted axle of the wheelset to its original position. This time is equal to the quarter of the free oscillation period of the single-mass torsional oscillatory system “wheelset axle - inner wheel.”

$$t = \frac{T}{4} = \frac{1}{4} 2\pi \sqrt{\frac{I}{C}} = \frac{1}{4} 2 \times 3.14 \sqrt{\frac{54.96}{4.29 \times 10^6}} = 0.0056 \text{ s,} \quad (14)$$

where $I = 54.96 \text{ kgm}^2$ —moment of inertia of the internal wheel (mass $m = 398 \text{ kg}$) relative to the axis of rotation; $C = 4.29 \times 10^6 \text{ Nm}$ —torsional stiffness of the wheelset axis (diameter $d = 173 \text{ mm}$).

The maximum angle by which the axle of the wheelset will rotate each time will be

$$\gamma_{\max} = \frac{fQR_22S}{I_pG} = \frac{0.4 \times 10^5 \times 478 \times 2 \times 790}{87.94 \times 10^6 \times 77 \times 10^3} = 0.00446 \text{ rad} = 0.2556^\circ, \quad (15)$$

where $f = 0.4$ —friction coefficient between rail and wheel rolling surface; $Q = 10 \text{ t} = 105 \text{ N}$ —vertical load on the wheel; $I_p = 87.94 \times 10^4 \text{ mm}^4$ —polar moment of inertia of the wheelset axle cross section; $G = 77 \text{ GPa} = 77 \times 10^3 \text{ mPa} = 77 \times 10^3 \text{ N/mm}^2$ —shear modulus of the wheel axle material.

The inner wheel twisted by the angle γ_{\max} will slide during return to the initial position along the arc

$$l = R_2 \times \gamma_{\max} = 478 \times 0.00446 = 2.13 \text{ mm}, \quad (16)$$

representing elemental component of the total friction path. Consequently, sliding velocity of the inner wheel will be

$$V_{sl} = l/t = 2.13/0.0056 = 380.36 \text{ mm/s} = 0.3804 \text{ m/s}. \quad (17)$$

The friction parameters of the worn wheels are calculated similarly considering their parameters $y = 25 \text{ mm}$ and $n = 0.34$.

Table 3 shows numerical values of the friction parameters of a new (unworn) and worn wheels of a wheelset moving in a curved section of the track.

The most dangerous type of damage to the wheels of a wheelset moving along a curved section of the track is wear of the wheel flanges. As can be seen from **Table 3**, the friction path and sliding velocity of the flange of a new and worn wheels differ little from each other. The sliding velocities of a new and worn rolling and flange surfaces also differ little from each other; however, the friction path for a worn rolling

Parameter	Designation	Location of the rubbing element	The wheel condition	Height of the wheelset cone ρ_w	Radius of curvature of the track ρ	Value
Friction path per 1 km	F	On the flange of the outer wheel	New	-----	-----	10.965 m
			Worn	-----	-----	9.615 m
	S_F	On the rolling surface of the inner wheel	New	756.03 m	420 m ($\rho < \rho_w$) 1020 m ($\rho > \rho_w$)	-1.668 m 0.537 m
			Worn	43.82 m	1020 m ($\rho > \rho_w$)	33.86 m
Friction (sliding) velocity at $V = 50 \text{ km/h}$	Vsl	On the flange of the outer wheel	New	-----	-----	1.854 m/s
			Worn	-----	-----	1.729 m/s
		On the rolling surface of the inner wheel	New	-----	-----	0.380 m/s
			Worn	-----	-----	0.357 m/s

Table 3. Friction parameters of a new (unworn) and worn wheels of a wheelset moving in a curved section of the track.

surface of the wheel is much higher than that for a new one, and, therefore, its wear at the same wear rate will also prevail.

Due to the complexity and interdisciplinary of the interaction processes between wheels and rails, further research is planned in the direction of creating conditions for the generation of stable solid third bodies with the necessary tribological properties on rolling and directional surfaces, devices for their application to friction surfaces, and the development of wheel pairs with a reduced load of the contact zone rubbing surfaces.

7. Conclusions

At a given load of wheels and rails, contact stresses, and thermal loads of the zone of their friction contact, damage to the third body and the wear rate of rubbing surfaces mainly depend on the sliding velocity and friction path. The calculations have shown that at pure rolling of a worn wheelset in straight sections, the friction path, the frequency of zigzag movement, and the sliding velocity of rolling surfaces are much higher than those for new wheels.

At pure rolling of new (unworn) and worn wheelsets in curved sections, the friction paths of the wheel flanges are close, the friction path of the rolling surface of a worn wheel exceeds that of a new one about 20 times, and the sliding velocities of worn and new wheels are almost the same.

Also shown a change in the friction path of the wheel flange from pure rolling to pure sliding of the rolling surface, and that the rail corrugation is formed by periodic slippage of the inner wheel on the rail. The amplitude and frequency of lateral movement and, accordingly, the friction path of a new and worn wheels are different. During pure rolling of new (unworn) and worn by 7 mm wheelsets on curved sections, the friction paths of the wheel flanges are close, and the friction path of the tread surface of the worn wheel exceeds the friction path of the new wheel approximately 20 times, and the sliding speeds of worn and new wheels are almost the same. It also shows the change in the friction path of the wheel flange when the movement of the rolling surface changes from pure rolling to pure sliding.

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Conflict of interest

The authors declare no conflict of interest.

Author details


George Tumanishvili^{1*}, Tengiz Nadiradze¹, Rustam Rakhimov² and Giorgi Tumanishvili¹

¹ Department of Machine Dynamics, R. Dvali Institute of Machine Mechanics, Tbilisi, Georgia

² Faculty of Railway Transport Engineering, Tashkent State Transport University, Tashkent, Uzbekistan

*Address all correspondence to: ge.tumanishvili@gmail.com

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Chapter 3

Development and Challenges of Maglev Transportation

Huan Huang, Haitao Li, Yougang Sun and Xiao Hu

Abstract

Magnetic levitation (Maglev) transportation and Evacuated Tube Transportation (ETT) represent cutting-edge advancements in high-speed travel. Maglev trains utilize powerful magnets to levitate above the tracks, eliminating friction and allowing for extremely high speeds, and typically have a wide speed range. Since the 1960s, Germany has developed Maglev transportation technology to a mature stage for engineering application, providing new options for the further development of high-speed ground transportation. This technology is already in use in countries like Japan and China, offering efficient, fast, and smooth travel experiences. This chapter examines the development and application of Maglev and ETT. We divide the existing magnetic levitation systems into two categories: active electromagnetic suspension (EMS) and passive Maglev, which includes superconducting electrodynamic suspension (EDS) and pinning Maglev. It begins by analyzing the experience of existing commercial lines for medium- and low-speed EMS transportation, followed by a discussion of the advancements in high-speed EMS transportation. Then, this chapter explores the current status of passive Maglev transportation systems, with a focus on superconducting EDS and superconducting pinning Maglev technologies. Lastly, it reviews the research progress on ETT-Maglev systems and considers potential projects, highlighting the future possibilities of this cutting-edge technology.

Keywords: electromagnetic suspension, electrodynamic suspension, superconducting pinning suspension, medium and low-speed, high-speed, evacuate tube, hyperloop

1. Introduction

Maglev trains utilize linear motors for traction and power supply, balancing electromagnetic forces between the train and track to counteract gravity, thereby avoiding wear from wheel-rail and catenary contact. They boast high operational speeds, strong climbing capabilities, small turning radii, environmental friendliness, strong track adaptability, and reliability, representing a new generation of “green, smart, safe, and fast” transportation. Maglev trains are categorized based on their suspension principles into two types: active and passive suspensions, as shown in **Figure 1** [1]. Active suspension uses the electromagnetic attractive force, which is

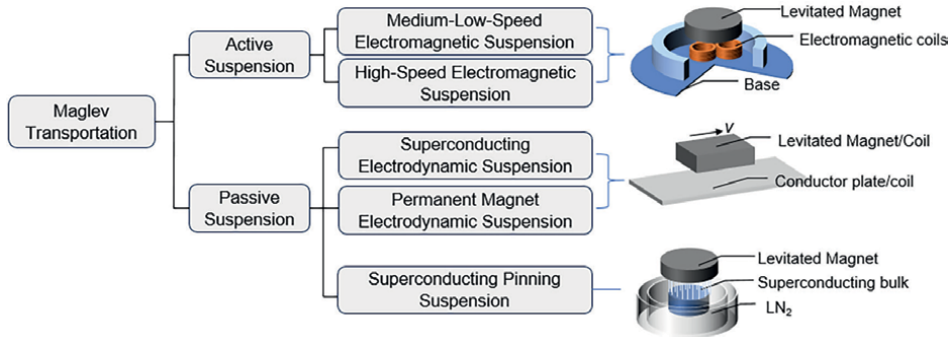


Figure 1.
Maglev transportation classification.

called Electromagnetic Suspension (EMS), originating in Germany, and uses onboard electromagnets interacting with magnetic tracks to levitate the train above the tracks, allowing for static suspension. This type of system is inherently unstable and requires additional control systems to maintain levitation. The linear motors are distinguished into short-stator Maglevs for medium to low speeds, and long-stator Maglevs for high speeds; the latter typically feature independent guidance magnets which are absent in slower systems. Repulsive Maglev systems, on the other hand, achieve self-stabilizing levitation and include superconducting electrodynamic suspension (EDS), permanent magnet EDS, and superconducting pinning suspension. This technology uses the relative motion between onboard magnets and track coils to induce currents, creating levitation forces that increase with speed.

Throughout the development and research of Maglev transportation systems, significant practical experience and many challenges have been identified that need resolution. This chapter provides an overview of these developments. Moreover, combining Maglev technology with evacuated tube technology enables the use of non-contact Maglev techniques for levitation and guidance. This integration creates a low vacuum environment within the tubes, reducing air resistance and utilizing powerful linear motors, thereby making possible ultra-high-speed rail travel exceeding transonic speeds.

2. Development status of active electromagnetic suspension

In 1937, Holmes at the University of Virginia managed to stably levitate objects using electromagnets, permanent magnets, and sensors. In 1934, German engineer Hermann Kemper patented the concept of a high-speed Maglev train. Advances in control theory and technology in the early twentieth century furthered this development.

2.1 Medium and low-speed EMS transportation

Japan Airlines (JAL) has been actively involved in the research of medium and low-speed conventional Maglev trains known as HSST (High-Speed Surface Transport) since 1972 [2]. In 1978, the HSST-01 achieved a test speed of 307.8 km/h on the Higashi-Ōgishima test line, using rocket propulsion. This milestone demonstrated

the potential of Maglev technology for high-speed applications. In 1987, JAL introduced the HSST-04 model and showcased it at the Saitama International Exposition. However, the focus soon shifted toward developing EMS vehicles for urban transit. These urban Maglev vehicles are characterized by moderate speeds but strong climbing capabilities, ensuring safety and comfort for passengers.

To achieve this goal, JAL developed two vehicle models: HSST-100S and HSST-100 L. The acronym HSST stands for High-Speed Surface Transport, with HSST-100S referring to a short vehicle designed for speeds up to 100 km/h and HSST-100 L referring to a long vehicle designed for the same speed. In the terminology used by the International Maglev and Direct Drive Conference, these systems are typically classified as Urban Maglev. Existing medium and low-speed Maglev lines have essentially evolved from this technological foundation.

2.1.1 Commercial applications of medium and low-speed EMS train

The world's first commercial short-stator low-speed Maglev was Birmingham's, operational until its replacement in 2003. In March 2005, Japan launched the Linimo Maglev train in Nagoya, Aichi Prefecture, based on the HSST-100 L model, marking the first commercial application of medium-low-speed Maglev technology. The Linimo Line, or Aichi High-Speed Transit Tobu Kyuryo Line, as shown in **Figure 2** [3], was introduced for the World Expo in Aichi Prefecture, spanning 8.9 kilometers from Fujigaoka Station to Yakusa Station. Operating at speeds up to 100 km/h, the line demonstrated the practicality of Maglev technology in urban settings, offering benefits like reduced travel times, increased comfort, and lower environmental impact. The Linimo's quiet operation, smooth ride, and ability to handle significant elevation changes highlighted the advantages of Maglev systems in urban transit. Continuous improvements have focused on enhancing passenger experience and operational efficiency.

The Incheon Airport Maglev Line as shown in **Figure 3** [4], inaugurated in 2016, is South Korea's first commercial Maglev system. Spanning 6.1 kilometers, it connects Incheon International Airport with Yongyu Station, with several intermediate stops. Operating at speeds up to 110 km/h, this line offers a quiet, efficient, and environmentally friendly transportation solution, demonstrating the feasibility of medium-speed Maglev technology in urban settings. Advanced control systems ensure operational reliability, while ongoing research focuses on reducing construction and maintenance costs.



Figure 2.
Linimo line [3].



Figure 3.
Incheon Airport Maglev line [4].

The Changsha Maglev Express, operational since May 2016, links Changsha Huanghua International Airport to Changsha South Railway Station over 18.55 kilometers, as shown in **Figure 4** [5]. Operating at a maximum speed of 100 km/h, it features three stations, with plans for two more. This line is notable for being China's first domestically designed, manufactured, and managed medium-speed Maglev system. It has provided significant insights into the design and operation of Maglev transit solutions, addressing challenges such as track precision and system stability. Ongoing research aims to improve energy efficiency and reduce operational costs, enhancing overall system sustainability.

Beijing Maglev Line S1 began operations in December 2017, as shown in **Figure 5** [6]. Running 10.2 kilometers from Shichang to Pingguoyuan, with eight elevated stations, it operates at speeds up to 100 km/h. This line has improved urban mobility in Beijing, offering a smooth and efficient transit option. Key challenges, such as integrating Maglev technology with existing urban infrastructure, have been addressed through advanced engineering solutions. Continuous monitoring and control systems ensure operational reliability, while future developments aim to further enhance system performance and passenger comfort.

Several completed Maglev systems have proven their effectiveness in different regions. The Shanghai Maglev, operational since 2004, connects Shanghai Pudong Airport to the city center at speeds up to 431 km/h. In Japan, the Linimo line in Aichi Prefecture serves as an urban Maglev, offering a quieter and smoother ride than



Figure 4.
Changsha Maglev express [5].



Figure 5.
Beijing Maglev line S1 [6].

traditional rail systems. These examples highlight the potential of Maglev technology to enhance urban mobility by reducing travel time and improving passenger comfort.

The Guangdong Qingyuan Maglev Tourist Line began trial operations in February 2024, marking Guangdong's first medium-low-speed Maglev line. Spanning 8.1 kilometers, it connects Yinzhan railway station on the Guangzhou-Qingyuan intercity railway with Qingyuan Chimelong Theme Park, operating at a maximum speed of 120 km/h. Utilizing advanced technology for quiet, low-vibration travel, it aims to enhance the tourist experience and regional connectivity. In Hunan Province, the Changsha-Zhuzhou-Xiangtan Metropolitan Area (CZT) is a hub for China's Maglev industry, with planned lines like the Changning and Changliu Maglev Lines to create an efficient regional transportation network.

2.1.2 Development trends of medium and low-speed EMS transportation

Medium and low-speed Maglev trains have already been explored and practiced in engineering, and will further develop toward high efficiency, energy saving, intelligence, safety, and comfort in the future. This is specifically reflected in the following aspects [7, 8].

2.1.2.1 Improved operating speed

Currently, the maximum operating speed of medium and low-speed Maglev vehicles is around 100 km/h, as shown in **Figure 6**. Traditional urban rail transit, like subways and light rails, typically averages 30–40 km/h. The speed overlap between

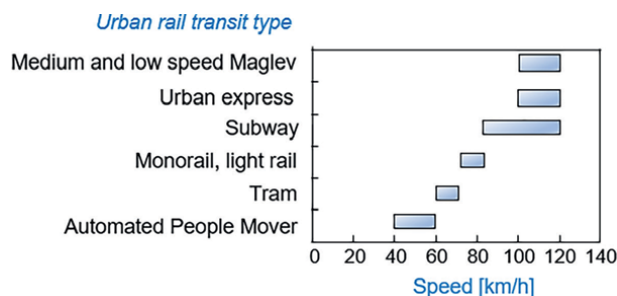


Figure 6.
Maximum operating speed range of various urban rail transit systems.

Maglev vehicles and urban rail systems creates a functional ambiguity, hindering the broader adoption of Maglev technology.

2.1.2.2 Efficient and energy-saving operation

The Maglev vehicle uses side contact shoe rail current collection to transmit electric energy. Research is needed on high-performance linear motor traction control, SiC-based traction converters, and auxiliary power supply systems to enhance traction efficiency and reduce vehicle energy consumption.

2.1.2.3 Vehicle lightweight design

Lightweight design is crucial for improving the carrying capacity of Maglev vehicles under limited suspension force. While most current research focuses on the vehicle body, further development is needed in the lightweight design of the running mechanism, which, due to complex working conditions, requires higher structural strength.

2.1.2.4 Improved safety and comfort

The small levitation gap and nonlinear factors of active levitation force in medium and low-speed Maglev vehicles can cause complex dynamic interactions with elevated bridges. To prevent coupling vibrations, it is essential to select appropriate suspension control systems and vehicle and bridge parameters. Future analysis should also consider aerodynamic effects and linear motors to enhance the vehicle-bridge coupling vibration model.

2.1.2.5 Maglev fault diagnosis technology

Magnetic levitation fault diagnosis is crucial for ensuring the safe and reliable operation of Maglev vehicles, enabling quick detection, location, and repair of faults. Ongoing research is needed to improve diagnostic accuracy, real-time capabilities, and resistance to interference. Additionally, standards for medium and low-speed Maglev systems should be refined based on technical research and the experience of existing commercial lines.

2.2 High-speed EMS transportation

The medium-low-speed Maglev lacks an independent guidance system, relying on the edge effects of levitation electromagnets, limiting its guidance capability. In contrast, high-speed Maglev includes an independent guidance system and typically uses long stator drives.

Germany's Transrapid (TR) represents advanced high-speed Maglev technology, developed over 50 years. Starting with the TR01 in 1969, which introduced EMS technology, the technology progressed to the TR08, which achieved a test speed of 501 km/h on the Shanghai Maglev line in 2003. Although plans for a 400 km/h Maglev railway between Hamburg and Berlin were canceled in 2002, commercial operation was successfully realized in Shanghai. The TR09, tested in 2009, reached a maximum speed of 550 km/h, showcasing the maturity of Transrapid technology.

2.2.1 Shanghai Maglev demonstration line

The high-speed EMS Demonstration Line connecting Shanghai Pudong International Airport with Longyang Road Station, started trials in 2002, as shown in **Figure 7** [9]. The 30-kilometer double-track line includes two stations, two traction substations, an operation control center, and a maintenance center. With a design speed of 430 km/h [10], the one-way journey takes about 8 minutes, offering a fast and efficient alternative to conventional railways.

The Shanghai Maglev Demonstration Line comprises four subsystems (**Figure 8**) [11]: vehicles, operational control, traction power supply, and track. China managed the installation and construction, while Germany supplied the vehicles, control systems, and technical support. Key features include active control and a relatively small air gap (8–10 mm), necessitating smooth track surfaces and minimal control delay. This collaboration allowed China to absorb key high-speed Maglev technologies and gain valuable operational experience. Between 2001 and 2015, China developed and validated functional prototypes for subsystems, transitioning Maglev from theory to engineering. After 15 years of research, China has mastered the core technologies of high-speed Maglev, laying the groundwork for further advancements. This line has demonstrated the practical use of long-stator Maglev technology, offering insights into maintenance and operational management. Key challenges like track alignment



Figure 7.
Shanghai Maglev demonstration line [9].



Figure 8.
The vehicle of the Maglev train [11].



Figure 9.
600 km/h Maglev transportation system [12].

precision and control delay have been addressed through advanced engineering and active control systems. Future efforts will focus on enhancing ride quality and system reliability.

2.2.2 Development of the 600 km/h Maglev transportation system

From 2016 to 2021, supported by the National Key R&D Program, CRRC developed key technologies for a 600 km/h Maglev system, building on the Shanghai Maglev Line's principles [12]. This effort addressed challenges in system integration, vehicles, levitation, traction power, and operational control. In July 2021, China unveiled its first 600 km/h Maglev prototype, developed with independent intellectual property rights [13], in Qingdao, as shown in **Figure 9**, but has yet to complete high-speed trials.

Leveraging China's high-speed rail expertise, the 600 km/h Maglev system was developed through iterative optimization via “numerical simulation—ground testing—line testing” [14]. Building on prior innovations and focusing on engineering applications, top-level indicators were established and refined using data and experience from the Shanghai Maglev Line. This process led to the successful development and validation of core components and systems, including vehicle systems, traction power supply, operational control, communication, and track systems for the 600 km/h Maglev.

During the development of the 600 km/h Maglev system, various enterprises, research institutions, and universities contributed to building research platforms. CRRC Qingdao Sifang established a full-speed vehicle vibration test rig, capable of simulating dynamic operations up to 600 km/h, including track irregularities, bridge vibrations, aerodynamic loads, and coupler forces [15]. This platform is essential for testing system dynamics and levitation control stability. While China's high-speed Maglev technology has advanced significantly and a domestic industrial chain is emerging, challenges remain.

2.2.3 Challenges of high-speed EMS transportation

China's high-speed Maglev technology has made significant progress with the initial establishment of a domestic industrial chain, yet several challenges persist [16].

2.2.3.1 Comprehensive levitation/guidance control

For the 600 km/h high-speed Maglev transportation, the control technology contains the nonlinear stability control, coupled vibration suppression control, fault diagnosis, and fault-tolerant control of the suspension/guidance system, which comes from the following changes in high-speed scenes:

Control method limitations for a wide speed range: Most of the existing control methods for suspension/guidance systems are designed to address specific problems. As the operational environment of high-speed Maglev trains becomes more complex and harsher, these relatively singular control structures often face instability.

Track irregularities at high speed: The instability of the suspension and guidance system is exacerbated by track irregularities at high speeds. Relying solely on the parameter matching and optimization of secondary suspension systems cannot yield optimal dynamic performance. Therefore, a coordinated optimization control combining the suspension and guidance system is required.

Aerodynamic and system coupling challenges: At high speed, aerodynamic issues such as crosswinds and aerodynamic lift, as well as coupling problems between the traction and suspension systems. Therefore, it is essential to develop high-stability control strategies for the suspension and guidance system to handle unknown modal disturbances.

2.2.3.2 Coupled mechanisms and model validation under high-speed conditions

Fundamental interdisciplinary research is needed to explore the coupled mechanisms in high-speed Maglev operation. Further studies should focus on understanding multi-body, multi-field interactions—such as vehicle-track, mechanical-electromagnetic systems, and traction-levitation fields—under complex high-speed conditions like track settlement, irregularities, and crosswinds.

2.2.3.3 High-speed Maglev testing environment

A dedicated high-speed Maglev test line is urgently needed. The 600 km/h Maglev system has not yet been tested at full speed under real-world conditions. Currently, CRRC uses the existing demonstration line to validate core components up to 430 km/h, with a maximum test speed of 501 km/h. However, the line's limited length restricts full-speed testing, highlighting the need for a proper high-speed testing environment in China.

2.2.3.4 Comprehensive validation and evaluation

A coordinated evaluation methodology for high-speed Maglev systems is urgently needed. China has yet to conduct a comprehensive validation of the entire system or establish a theoretical framework for its assessment. Developing methods for testing and evaluating complex coupled systems, including synchronized vehicle-track and traction-control-communication tests under high-speed conditions, is crucial for establishing this coordinated evaluation approach.

3. Development status of passive Maglev transportation systems

Passive Maglev transportation systems are emerging as a promising technology for enhancing rail transport efficiency and sustainability. Unlike traditional Maglev systems that rely on active electromagnetic forces for levitation and propulsion, passive Maglev systems utilize permanent magnets and passive magnetic forces. The concept of EDS was first proposed by Powell and Danby at the Brookhaven National Laboratory in 1966 [17]. This approach offers several advantages, including reduced infrastructure costs, lower energy consumption, and compatibility with existing rail networks.

3.1 Superconducting EDS train

3.1.1 Structural principle and development status of EDS train

Superconducting EDS trains, known for their large air gaps and self-stabilizing capabilities, were initially developed by the Japanese National Railways (JNR) around 1970 [18]. The schematic diagram of the superconducting EDS is shown in **Figure 10**. The onboard superconducting magnet and the ground propulsion coils form a long-stator synchronous linear motor for vehicle propulsion. The onboard superconducting magnet and the ground 8-shaped null-flux coils are used for vehicle suspension and guidance, which is based on Lenz's law of electromagnetic interaction between coils. Once a specific speed is reached, these forces balance with gravity, levitating the train. Despite significant magnetic drag at lower speeds, EDS shows excellent suspension properties at higher speeds due to decreasing magnetic resistance [19]. In addition, this type of EDS train has the advantages of large suspension gaps, high lift-to-drag ratios, lower requirements for track irregularities, and reduced CO₂ emissions compared to airplanes. Therefore, it attracted various countries to develop prototypes for it.

Over the years, the Central Japan Railway Company (JR-Central) and the Railway Technical Research Institute (RTRI) have made continuous structural enhancements and technological advancements [20]. The first-generation vehicle series L0 set a world record speed of 603 km/h for manned rail transport in 2015, as shown in **Figure 11(a)**. Based on various test data collected from the original L0 Series, an improved version of the Series L0 began operation in 2020, as depicted in **Figure 11(b)**, fully adopting the inductive power transmission method. Their

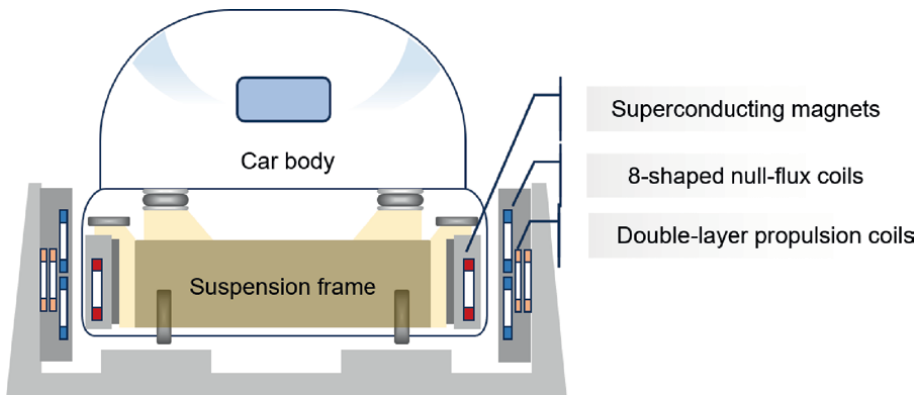


Figure 10.
Schematic diagram of superconducting EDS.



Figure 11. Superconducting EDS train on Yamanashi test line in Japan [20]. (a) Series Lo Version. (b) Series Lo Improved Version.

efforts are focused on developing a Maglev system capable of reaching speeds up to 500 km/h. This ambitious project is scheduled for completion, with plans to operate on the Tokyo-Nagoya route by the early 2030s.

In recent years, the improvement in High-temperature Superconducting (HTS) material performance has prompted numerous institutions to develop EDS systems [21]. The Korea Railroad Research Institute (KRRI) initiated the foundation for the subsonic tube train HyperTube in 2009 and constructed a scaled test line for superconducting magnets (SCMs) and propulsion motors, as illustrated in **Figure 12** [22, 23].

In January 2023, the 3rd Research Division of China Aerospace Science and Industry Corporation (CASIC) [24] completed a superconducting navigation test on a full-scale test line for an ultra-high-speed, low vacuum tube Maglev transportation system based on HTS tape, as shown in **Figure 13(a)**. In December 2023, CRRC Changchun Railway Vehicles Co., Ltd. completed a comprehensive test system and successfully conducted its initial operation, as illustrated in **Figure 13(b)** [25]. This system integrated HTS magnets, linear synchronous motors, inductive power supply, and single-stage low-temperature cooling.

3.1.2 Application trends of EDS train

These achievements represent a significant advancement in high-speed rail transportation, highlighting the potential for more efficient and advanced rail systems. There are still the following research challenges in the study of the HTS EDS train.

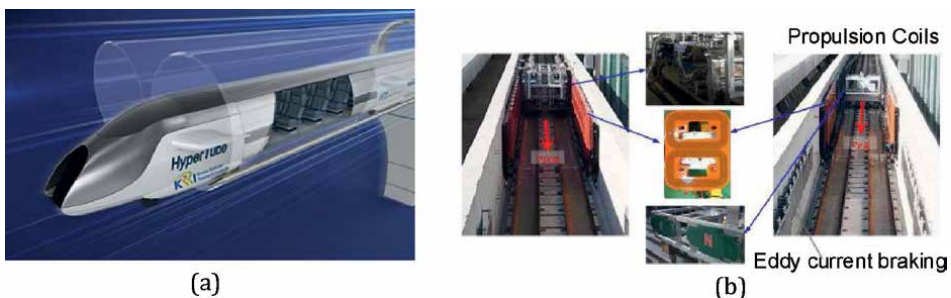


Figure 12. South Korea's EDS layout and scaled test line. (a) Conceptual diagram of HyperTube [22]. (b) Scaled test line and propulsion test [23].



Figure 13. Superconducting EDS principal prototype in China. (a) CASIC's HTS EDS test [24]. (b) CRRC Changchun's HTS EDS test system [25].

3.1.2.1 Durability verification of HTS magnets

HTS magnets are a core component of the EDS systems. A significant challenge is verifying the long-term durability and stability of these HTS magnets. Over time, environmental factors such as temperature fluctuations, mechanical stress, and electromagnetic vibration can affect their performance. Ensuring that these magnets can maintain their superconducting properties over extended periods is critical for the reliability and safety of Maglev trains.

3.1.2.2 Noise, ground vibration, tunnel micro-pressure wave

Although Maglev trains eliminate friction between the train and the tracks, other sources of noise and vibration emerge, especially at high speeds. Aerodynamic noise, such as turbulence around the train, becomes significant. Ground vibrations caused by the train's electromagnetic coupling can affect nearby infrastructure and residents. Tunnel micro-pressure waves, which occur when a high-speed train enters a tunnel, can create a loud shockwave, disturbing the environment and causing discomfort to passengers. These issues must be addressed through careful design of the train's components and infrastructure.

3.1.2.3 Magnetic field shielding: ICNIRP guidelines compliance

Maglev trains generate strong magnetic fields for levitation and propulsion, raising concerns about potential health effects on passengers and nearby residents. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) sets guidelines for safe exposure to magnetic fields. Ensuring that the magnetic field levels produced by Maglev systems remain within these limits is critical to passenger safety and public acceptance. This challenge involves developing shielding technologies and controlling magnetic field intensities, particularly in passenger compartments, to mitigate any potential health risks while maintaining system efficiency.

3.1.2.4 Improvement of passenger comfort

It is important to focus on the vibration suppression systems, which play a key role in ensuring a smooth ride, particularly at high speeds. Two critical systems that

contribute to reducing vibrations are the primary suspension bogie and the secondary suspension systems for the car body.

In conclusion, the challenges faced by EDS train technology span from improving aerodynamics and maintaining the durability of critical components to reducing noise, managing magnetic fields, and enhancing passenger comfort. Addressing these issues will require interdisciplinary innovation in materials science, engineering, and infrastructure design.

3.2 Superconducting pinning suspension

Superconducting pinning technology integrating suspension and guidance without inherent magnetic drag, facilitating high speeds. Utilizing the flux pinning properties of non-ideal type II HTS bulks, the HTS levitator can be stably levitated above or suspended below a permanent magnet guideway (PMG), as shown in **Figure 14**. Research on HTS pinning Maglev has also been ongoing for the past 20 years.

The first manned HTS pinning Maglev, “Century,” was developed by Southwest Jiaotong University (SWJTU) in 2000 [26]. Afterward, Germany, Italy, and Brazil continue to advance research on high-speed experimentation and engineering applications and explore the superconducting pinning suspension train [27], as shown in **Figure 15**. In 2014, the world’s first evacuated tube superconducting Maglev system, “Super-Maglev,” was established [28], leading to the creation of the first HTS high-speed Maglev prototype and test track in 2021 [29]. Further testing on long-distance tracks is needed to validate the high-speed capabilities of superconducting pinning Maglev systems.

This type of Maglev system has not yet been built into a commercial operation line, so its future development and challenges need further in-depth research. The HTS high-speed Maglev engineering project and the dynamic model test platform are required to verify the long-term operational feasibility of this technology. In addition to the challenges mentioned in the EDS section, the problem of pinning Maglev also requires the investigation of improving the load capacity and stability of the suspension system.

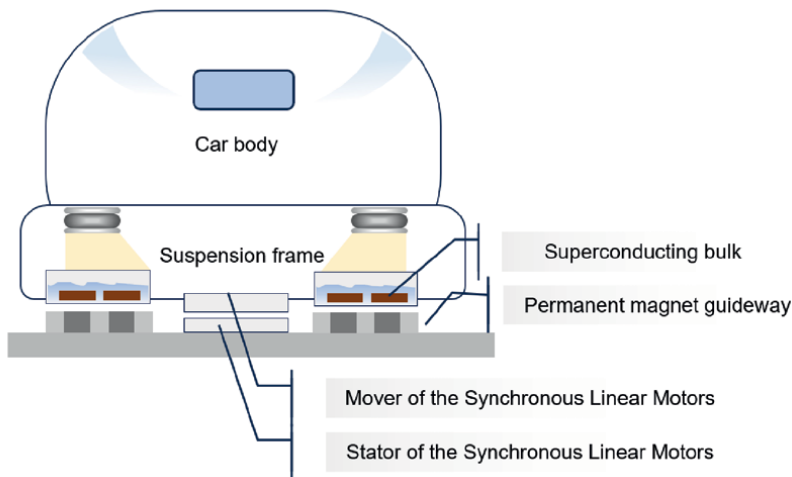


Figure 14.
Schematic diagram of superconducting pinning Maglev.



Figure 15.
HTS pinning Maglev in the world.

4. Potential projects of evacuated tube transportation systems with high-speed Maglev

Evacuated tube transportation (ETT), or Hyperloop [30], is a novel technology aimed at overcoming the limitations of dense atmospheres in railway transportation. By operating Maglev trains in evacuated tubes, aerodynamic drag and noise pollution are significantly reduced, potentially enabling transonic or supersonic speeds. This technology is environmentally friendly, energy-efficient, and aligns with carbon neutrality goals, making it a key area of research. Several countries, including the United States, South Korea, China, the Netherlands, and Spain, are actively exploring this transportation innovation.

4.1 Research Progress on ETT system projects

4.1.1 Hyperloop in the United States

Several U.S. companies, including SpaceX, Hyperloop Transportation Technology (HTT), and Virgin Hyperloop One, are advancing Hyperloop research. Elon Musk's 2013 white paper outlined the Hyperloop design using reduced-pressure tubes, leading to SpaceX's creation of a 1.6 km test track in Los Angeles, where the TUM Hyperloop team set a speed record of 463 km/h.

HTT, founded in 2013, established a Hyperloop R&D center in Toulouse, France, and completed a 320 m test track in 2019, as shown in **Figure 16** [31]. They also unveiled the Quintero One passenger train, designed to reach speeds of 1223 km/h. Virgin Hyperloop One, founded as Hyperloop Technology in 2014 and rebranded in 2017, completed its first passenger test in November 2020 at the DevLoop test track in Nevada, reaching a top speed of 172 km/h, as shown in **Figure 17** [32].



Figure 16.
HTT test track and full-scale train Quintero one [31].



Figure 17.
Virgin Hyperloop one passenger test in DevLoop test track [32].

4.1.2 South Korea HyperTube

In early 2017, South Korea announced the HyperTube project as shown in **Figure 12**. Aiming to develop a super high-speed rail system with speeds up to 998 km/h, reducing travel time between Seoul and Busan to 20 minutes [33]. The system uses electromagnetic force to propel a train within an evacuated tube at 0.001 atmospheres, accommodating 40 passengers. In December 2020, a scaled model reached 1019 km/h, with recent tests indicating a maximum speed of 1152 km/h.

4.1.3 China hyperloop

Several organizations in China are developing Hyperloop technology using various approaches. SWJTU employs superconducting pinning suspension Maglev technology. In June 2014, SWJTU successfully commissioned the world's first evacuated tube HTS Maglev circular test track, the "Super-Maglev" system as shown in **Figure 18** [28], with a maximum test speed of 50 km/h due to small turning radius limitations. In January 2016, SWJTU developed an HTS side-suspended Maglev test system, overcoming centrifugal force limitations and enhancing the system's speed potential, as shown in **Figure 19** [34].

In 2019, a 400 km/h evacuated tube HTS Maglev test platform was completed, as shown in **Figure 20(a)** [35]. By May 2020, the "Multimodal Coupled Rail Transit

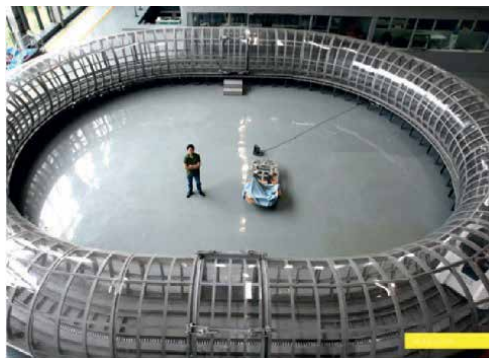


Figure 18.
"Super-Maglev" test system [28].



Figure 19. Side-suspended HTS Maglev circular test track system [34].



Figure 20. Evacuated tube HTS Maglev test platform. (a) 140 m long evacuated tube [35]. (b) Multimodal coupled rail transit moving model test platform [36].

Moving Model Test Platform” was built, featuring a 1620 m long evacuated tube for Maglev transportation with a maximum test speed of 1500 km/h [36]. This platform addresses key scientific and technological challenges, including multi-scale modeling, low-pressure conditions, and the Maglev (wheel-rail) relationship in high-speed and ultra-high-speed rail transit.

In 2017, CASIC announced plans to develop a hyperloop capable of reaching 1000 km/h [37]. In January 2024, a successful full-scale superconducting EDS test for an ultra-high-speed evacuated tube Maglev system was completed as shown in **Figure 21**. The test verified key technologies, including the coupling dynamics and control of the “vehicle-track-tube” system, stable levitation of large superconducting vehicles, high-power traction drive, and safety coordination throughout the process.

4.1.4 Hardt hyperloop

The Hardt Hyperloop company, founded in 2016, developed its first full-scale Hyperloop test system in 2019, as shown in **Figure 22**, which includes suspension, propulsion, a circular track, and a vacuum environment. Hardt uses a top-mounted EMS system and linear motors for propulsion, with the braking system also recovering electrical energy. The company has built a full-scale sealed test tube at its headquarters and signed an agreement to plan a Hyperloop line from Amsterdam to Frankfurt, Germany [38].



Figure 21.
The first phase of the China high-speed flying car system test line by the CASIC [37].



Figure 22.
Conceptual design diagram of the Hardt Hyperloop transport system and its 30 m test tube [38].

4.1.5 Zeleros hyperloop

In 2016, Zeleros was founded by a team that participated in Elon Musk's Hyperloop competition, winning awards for Best Design and Propulsion System [39], the 1:7 scaled Prototype is shown in **Figure 23**. This design features a train that utilizes magnetic levitation and aerodynamic propulsion technology powered by jet engines. This approach significantly reduces the blockage effect within the tube while providing substantial thrust and acceleration.

The European Hyperloop Center (EHC) announces the completion of its hyperloop test infrastructure and opens up for the first tests [40]. This facility, featuring a 420-meter hyperloop test tube, can demonstrate all essential hyperloop technologies including a full lane switch. The EHC is part of the Hyperloop Development Program (HDP): a public-private partnership of more than 25 partners to advance the Hyperloop technology (**Figure 24**).

4.2 Potential projects

The evacuated tube Maglev transportation system is a groundbreaking and disruptive technology that encompasses multiple disciplines such as transportation, civil engineering, mechanical engineering, electrical engineering, control systems, and communications. It integrates various subsystems including vehicle-track-tube-gas-electric-thermal, representing a complex systems engineering challenge. As this



Figure 23.
Zeleros Hyperloop vehicle powertrain prototype (1:7 scale) [39].



Figure 24.
European Hyperloop center opens up for the first test [40].

research is in its nascent stages, numerous critical technical issues need to be explored and resolved. This section will describe several important topics that urgently require solutions.

1. Efficient methods and strategies for controlling the internal thermal environment of tubes
2. Methods to mitigate flow choking and shock wave effects
3. Mechanisms of coupling between ultra-high-speed Maglev vehicles and tracks, and characteristics of dynamic stability
4. Maglev vehicle internal environmental control technology
5. Emergency rescue technologies for ETT systems.

5. Challenges and solutions in integrating Maglev systems with existing infrastructure

The establishment of the Maglev line and its integration with existing infrastructure presents several challenges, involving technical, economic, and infrastructural aspects. **Table 1** provides a comparative overview of Maglev and high-speed rail in various operational and infrastructural aspects. Both systems offer unique advantages, and the decision between them should be based on regional demands, long-term planning, and the specific goals of the transport network.

The following discusses these challenges and proposes potential solutions in greater detail.

5.1 Integration with existing railway networks

One possible solution is the application of different Maglev types: High-speed Maglev trains can be used for intercity travel, while medium- and low-speed Maglev systems can serve tourism or transportation around urban and suburban areas. In addition, multimodal transport hubs and flexible station design are required to be designed. The hubs can integrate different transportation modes (e.g., conventional trains, Maglev, and urban transport systems) to facilitate smoother connections. Stations could be modified or expanded to accommodate Maglev trains.

5.2 Infrastructure costs and land use

Maglev systems require significant capital investments in infrastructure, including the construction of elevated tracks, power systems, and specialized maintenance facilities. Additionally, land acquisition for new Maglev lines could face legal,

Aspect	Maglev	High-Speed Rail (HSR)
Speed	Up to 600 km/h	Up to 350 km/h
Infrastructure cost	Higher due to specialized tracks and technology	Lower as it uses conventional rail tracks
Energy efficiency	High efficiency due to low friction	Lower efficiency due to friction on rails, Bow-net
Land use	Requires new tracks, elevated structures	Can use existing railway lines with some upgrades
Maintenance	Lower long-term maintenance due to non-contact system	Higher due to wear and tear on the rails
Operational cost	Higher initial investment but lower operational costs	Moderate operational costs
Noise levels	Quieter due to the lack of wheel-rail contact	Louder, especially at higher speeds
Environmental impact	Lower, especially in terms of emissions	Higher, particularly during construction
Integration with existing networks	Challenging requires separate infrastructure	Easier integration with existing railway networks

Table 1.
Comparative table: Maglev vs. High-Speed Rail (HSR).

environmental, and social challenges, especially in densely populated areas. To minimize disruption and land acquisition costs, Maglev lines could be built along existing railway or highway corridors.

5.3 Operational and maintenance compatibility

The operational models for Maglev trains differ significantly from those of traditional rail systems. This includes differences in speed, braking systems, and maintenance requirements. Integrating both systems operationally could pose a challenge, especially concerning shared facilities like depots and control systems. Establishing integrated operational standards and communication systems between conventional and Maglev lines can ensure better management and coordination.

5.4 Economic feasibility

The high initial cost of building Maglev infrastructure, combined with uncertain ridership levels and long-term profitability, makes it difficult for governments and companies to justify large-scale investments. Detailed studies should compare the long-term benefits of Maglev, such as faster travel times, reduced environmental impact, and increased ridership, against its high capital costs.

5.5 Public and political acceptance

Maglev systems often face public opposition due to concerns about noise, electromagnetic radiation, and land use. Additionally, political support is necessary for allocating the large amounts of public funding needed for these projects. Policies that offer tax incentives or subsidies for green transportation solutions like Maglev could encourage political and public support.

6. Conclusions

Maglev and ETT technologies represent significant advancements in high-speed ground travel. The two primary types of Maglev systems—EMS and EDS—differ in their mechanisms of levitation and stability. EMS, like the Shanghai Maglev, requires precise control systems for stability, while EDS, developed in Japan, uses superconducting magnets for self-stabilizing levitation.

Successful implementations of medium and low-speed Maglev systems in urban areas, such as Japan's Linimo and South Korea's Incheon Airport Maglev, have demonstrated the technology's practicality in reducing travel time, improving comfort, and minimizing environmental impact. Meanwhile, high-speed Maglev systems, like the Japan Yamanashi Maglev test line, show the potential for even greater advancements in speed and efficiency. The Maglev technology is central to projects like the Hyperloop, which aims to achieve ultra-high-speed travel by combining Maglev with evacuated tubes, reducing air resistance and enabling supersonic speeds.

However, significant challenges remain, including the need for dedicated high-speed testing environments, comprehensive simulation system validation, and integration with existing infrastructure. Continued research and development are crucial to overcoming these challenges and unlocking faster, more efficient, and sustainable transportation options that could redefine global mobility. By addressing

these problems, Maglev technology can be a viable complement or alternative to high-speed rail networks.

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Author details

Huan Huang¹, Haitao Li², Yougang Sun^{1*} and Xiao Hu³


1 Key Laboratory of Railway Industry of Maglev Technology, Tongji University, Shanghai, China

2 State Key Laboratory of Rail Transit Vehicle System, Southwest Jiaotong University, Chengdu, China

3 School of Mechanical Engineering, Lanzhou Jiaotong University, Lanzhou, China

*Address all correspondence to: 1989yoga@tongji.edu.cn

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Chapter 4

Literature Review on Applications of Ontologies and Knowledge Graphs in Railway Transport Safety

Habib Hadj-Mabrouk

Abstract

The ontology allows the representation of knowledge in a formal, explicit and reusable way by considering the semantics and interoperability of the application domain. These characteristics give ontologies a useful role in knowledge engineering with a view to formalizing, structuring, representing, capitalizing and reusing domain knowledge with the power of explanation and interpretability of data and knowledge, thus making it possible to mitigate the problem of bias involved in AI systems (black boxes), notably deep learning by providing a clear explanation in the decision-making. This article provides a literature review of applications of ontologies and knowledge graphs in the field of rail transport safety. This study shows that despite the significant impact of ontologies and graphs for railway risk management and accident prevention, several applications face obstacles. A new conceptual model called “HEXA-Onto” is proposed which is structured around six iterative and complementary dimensions: (1) knowledge acquisition, (2) identification and specification of the domain, (3) formalization, structuring and representation of knowledge, (4) knowledge extraction techniques, (5) ontology development phases and (6) components, constraints, languages, tools and ontology editors.

Keywords: artificial intelligence, railway safety, ontology, knowledge graph, knowledge acquisition and representation

1. Introduction

In recent years, in the rail transport sector, researchers and experts in the field have become increasingly interested in the application of artificial intelligence (AI) techniques to solve certain decision support problems, such as diagnosis of rolling stock breakdowns, management of servicing and maintenance operations based on operating data, analysis of the behavior of driving operators, traffic planning and forecasting, management of vehicle compatibility train routes, mining relevant data from accident and incident investigation reports, etc. The main objective is to explore the raw text in order to extract relevant information for explanatory or decision-making purposes. In the field of railway safety and from accident investigation texts and

reports, these methods are generally used to better understand the factors contributing to these accidents, in particular the causes or consequences of accidents, recurring accidents, or causal relationships. Several AI techniques are implemented in particular machine learning (supervised, semi-supervised, unsupervised), deep learning such as artificial neural networks (ANN), natural language processing (NLP) and case-based reasoning (CBR). The lack of interoperability between AI tools often based on different modes of knowledge representation, the difficulty of structuring knowledge in a field, the insufficiency of these approaches to bring together and capitalize on knowledge bases and the inability to share and reuse these knowledge bases have motivated and directed research toward the development of new approaches based on ontology and knowledge graphs. These new approaches, based essentially on a formal representation of knowledge and considering the interoperability and reusability of this knowledge, have experienced significant growth in recent years.

This study shows that ontology and knowledge graphs will certainly have a greater impact on the field of rail transport safety and in particular on the management and prevention of rail accident risks. Two major chapters are developed: a characterization of the ontology followed by a bibliographic study on the applications of the ontology and conceptual graphs in the field of rail transport safety. The first part offers a literature review on the contribution of these techniques to the analysis and evaluation of railway safety. It successively presents: (1) safety analysis approaches based on ontology, (2) safety analysis approaches based on knowledge graphs, and (3) a summary of the applications studied. The second part allows you to understand, apprehend, and characterize all the concepts involved in an ontology. To this end, a new conceptual model called “HEXA-Onto” is proposed. It is structured around several iterative and complementary dimensions including: (1) the stages of knowledge acquisition, (2) the crucial phase of identification and specification of the area of expertise, (3) methods of formalizing structuring and representation of knowledge, (4) knowledge extraction techniques, (5) phases of development of the ontology (6) constraints of development of the ontology which are inherent to the knowledge engineering process, (7) ontology development languages and tools, 8) the main components of an ontology and (9) Ontology Editors.

2. Definition of ontology

Gruber [1] proposed a specification of a common vocabulary to support the sharing and reuse of knowledge in AI. In this context, Thomas R. Gruber defined the notion of ontology as an “explicit specification of a conceptualization” or even “a specification of a representational vocabulary for a shared domain of discourse” whose main objective is the definition classes, relationships and functions. In the context of Knowledge Engineering, the ontology is “a formal and explicit specification of a shared conceptualization” [2]. To refine these definitions, Feilmayr and Wößl [3] stated: “An ontology is a formal and explicit specification of a shared conceptualization that is characterized by high semantic expressiveness required for increased complexity.” It is a form of formal, explicit and shared reproduction of knowledge by considering the semantics of the application domain, by identifying inconsistencies and inadequacies in the data, by establishing a shared common vocabulary for better information sharing and thus improving knowledge interoperability. These characteristics give ontologies a useful role in knowledge engineering with a view to formalizing, structuring, representing, capitalizing and reusing domain knowledge with great

power of explain ability and interpretability of data and knowledge. In addition, a clear and structured representation of domain knowledge makes it possible to understand and mitigate the problem of bias involved in AI systems (black boxes) especially deep learning in providing a clear explanation in the decision-making process.

3. Status of applications of ontology and knowledge graphs in transport railway

3.1 Ontology-based approaches

Data integration in the railway domain based on ontology was proposed in Verstichel et al. [4]. The authors proposed a methodological framework based on the “Network Statement Checker” ontology which is based on an infrastructure database describing the railway network. This ontology integrates network declarations from different countries into a single information model to determine whether a given route can be used, from a compatibility perspective. The user of the tool can select a route on the European railway map and find information on the characteristics of each track section of a route. The results of this study were evaluated using a demonstrator developed as part of a European research project called Intelligent Integration of Railway Systems (InteGRail). Indeed, to resolve the problem of compatibility of European rail routes and in the context of Directive (EU) 2016/797 relating to the interoperability of the rail system of the European Union, the European project InteGRail was financed by the Commission European Union which brings together 39 stakeholders representing the main players in the railway industry. InteGRail aimed to strengthen the sharing of information between infrastructure managers (IM) and railway undertakings (RU) and is based in particular on the “Network Statement Checker” ontology presented above. Rail interoperability often refers to the ability of the rail system to operate trains safely and seamlessly on different rail networks located in different Member States. Under Commission Implementing Regulation (EU) 2019/777 of May 16, 2019 on common specifications for the railway infrastructure register, the European Infrastructure Register (RINF) makes it possible to define the characteristics of the railway network European by providing the main parameters to be used to check the technical compatibility between the vehicle and the route.

Based on the requirements linked to the European Infrastructure Register (RINF) which are imposed by Directive (EU) 2016/797 of May 11, 2016 relating to the interoperability of the railway system within the European Union, Tutchter et al. [5] proposed a tool based on the ontology called “RaCoOn” making it possible to give, for example, the (approximate) location of the train based on the known positions of the track circuit. Infrastructure and location data are stored and used as the basis for modeling train movements. Track circuits were added manually, using simulated track circuit distances. Finally, a demonstrator for validating this principle was presented, based on a new ontology of the railway domain created at the University of Birmingham. In the same context and in the field of railway infrastructure, Bellini et al. [6] presented the Railway Infrastructures and Signaling Ontology approach (RAISO) which is based on a railway signaling ontology making it possible to formalize the route of a network railway including the position of track elements (signals, train detector, etc.). Bischof and Schenner [7] also developed a railway infrastructure topology ontology to represent infrastructure characteristics in accordance with domain standards. In the context of urban freight transport systems, Bouhana

et al. [8] proposed a personalized route search approach. The route retrieval mechanism uses both case-based reasoning (CBR) to provide the user with an optimal route and therefore an ontology to extract information urban traffic. In the field of railway control, command and signaling, Hoinaru et al. [9] proposed an ontology with a view to modeling the European rail traffic management system (ERTMS) and in particular the European Train Control System (ETCS). Sango et al. [10] also proposed a railway ontology to take into consideration the temporal aspect in the ERTMS/ETCS ontology. To consider user needs, Oliveira et al. [11] proposed a transport ontology allowing the personalization of the content of user interfaces. The concepts used are Calendar, City, Connection link, Connection point, Interchange hub, Journey, Operator, Rail element, Rail junction, Road element, Crossing and Stopping point. To support performance monitoring in public transport systems, Benvenuti et al. [12] developed an approach based on an ontological representation. Key performance indicators (KPIs) considered include, for example, actual dwell time, scheduled dwell time, advanced dwell time and average lead time/advance.

Debbeck et al. [13] established an ontology of railway equipment malfunctions based on terminologies (extracted from standards) such as failure, causes, effects and safety measures. The idea of taking dysfunctions into account is very important but requires more modeling. This is a high-level ontology that requires the in-depth instantiation of knowledge from the railway safety domain. The work of Shynkarenko and Zhuchyi [14] aims at the ontological harmonization of information systems of rail freight transport in Ukraine and in particular the automated control system of freight traffic.

In the field of railway accidents, Zhao et al. [15] proposed an approach to construct ontologies of the railway domain and in particular to process accident data relating to the derailment of a train, as for Maalel et al. [16] their approach to helping model railway accident scenarios is based on two complementary ontologies: (1) a generic ontology which brings together high-level concepts involved in railway safety such as context, dangerous elements, dangerous events and the causes of the accident and (2) an ontology of the domain centered on the railway system, the human operator and the environment. The concepts involved in the domain ontology are specializations of other concepts in the generic ontology. This is a feasibility study focused on rail collisions with a view to better formalizing and structuring the knowledge involved in rail accident scenarios. Still in the context of modeling railway accident scenarios, Hadj-Mabrouk [17] developed an approach based jointly on ontology and machine learning, the objective of which is the prevention of potential accidents. The proposed example of ontology formalizes accident scenarios according to four dimensions: (1) Symptoms (general context of the scenario, potential accidents, level of risk), (2) Causes (system, human factors, environment, interactions), (3) potential dangers and (4) safety measures adopted (protective measures and preventive measures).

In the field of railway maintenance, several works based on ontology have been developed. Lewis et al. [18] used the ontology to integrate railway condition monitoring data; Umiliacchi et al. [19] developed an ontology-based modeling approach to carry out predictive maintenance operations on railway subsystems and Rahmig et al. [20] developed several conceptual models based on ontologies to improve railway maintenance. By exploring explicit and tacit knowledge from domain experts, Ragala et al. [21] also developed an ontology to manage railway maintenance. Finally, Louadah et al. [22] proposed an approach to support the management of rolling stock maintenance with a virtual depot based on an ontology. In the context of autonomous

driving, Chouchani and Debbech [23] proposed the ontology called Autonomous Train Map Ontology (ATMO) intended for autonomous trains.

Considering the importance of ontologies in the transportation sector, Katsumi and Fox [24] presented a survey of existing ontologies in the field of land transportation by examining several characteristics of the developed ontologies such as precision, generality, granularity and the competence. Several ontologies are examined in this study which focuses largely on road safety:

- Road accident ontology to capture accidents and their relevant information;
- Road traffic management ontology to provide decision support to drivers;
- Transport ontology for personalizing information for travelers (presented above);
- Ontology of transport disruptions;
- iCity ontology to capture data collected and generated on the urban system and
- Network Statement Checker ontology to check the feasibility of running a train on a given track (presented above).

According to Katsumi and Fox [24], data in land transportation comes from different organizations, sensors and surveys and is varied, complex and published in different formats, with different granularities and with different and sometimes ambiguous properties. There is no single ontology covering all concepts relevant to transportation research. No single ontology captures the entire high-level transportation taxonomy. Yang et al. [25] carried out an inventory of systems engineering based on ontologies, considering in particular product systems (concurrent engineering), service systems, business systems and the ISO standard /IEC/IEEE 15288. The authors provide important insights related to systems engineering by successively examining the knowledge areas supported, the contribution of existing ontologies and the techniques adopted. The emphasis is placed on the main advantages of an ontology in terms of interoperability, communication, explicitness, reusability of knowledge, homogeneous terminology to eliminate inconsistencies, unified vocabulary, controlled semantics, common understanding of a domain and reasoning on logical axioms [25].

3.1.1 Ontologies for the harmonization of risk management standards

The objective of the work of Pardo et al. [26] aims at the harmonization of standards, in particular the ISO 27001 and ISO 20000 standards. This study is essentially based on the implementation of an ontology providing a vocabulary, terms, concepts and specialized relationships in harmonizing multiple models. The objective is to eliminate inconsistencies, confusion and terminological conflicts at the different hierarchical levels and therefore propose precise definitions, a simple representation of processes and a uniform and formal vocabulary. This article describes an ontology that provides consistent terminology to support the harmonization of multiple models. In this same context of harmonization of standards, Ansaldi et al. [27] proposed an ontology to support the implementation of ISO standards relating to risk management with a view to facilitating the choice of risk management techniques

most appropriate to the needs of a specific risk management activity. The objective of this ontology is to support the implementation of ISO standards on hazard identification, risk analysis and assessment. For this purpose, several ISO standards were examined: ISO 31000 (Risk management—Principles and guidelines), ISO 31010 (Risk management—Risk assessment techniques) and ISO 73 (Risk management—Vocabulary). Using the “Protégé” tool, the authors have developed an ontology called “OntologyRATIS” which brings together the basic concepts extracted from the ISO 31010 document. In order to facilitate the choice of risk management techniques best suited to the needs, the ontology can be questioned through general questions, such as: “What methods are used for risk identification?” For a risk analysis? For the evaluation? Which methods provide quantitative results? Or qualitative?

According to Henderson-Sellers et al. [28], the semantics of terms used in international standards (ISO) can often be contradictory or at best misaligned, between pairs of standards with similar objectives. The authors showed how conceptual modeling and ontology engineering can be effective in reconciling the variation of disparate standards particularly engineering standards. The objective is to investigate the potential usefulness of ontologies for streamlining the suite of international software engineering standards. In this context of harmonization of ISO standards, the authors identified five areas in which ontologies could be useful: (1) the definitional area often called fundamental ontologies or higher-level ontologies, (2) the modeling domain and 3) the domain of practice. Building on the work of Henderson-Sellers et al. [28] and Gonzalez-Perez et al. [29], a project was initiated within the framework of ISO/IEC, the objective of which is to provide a shared ontology for SC7 standards. According to the authors, software engineering standards often use different underlying metamodels and ontologies, which sometimes differ from one standard to another. To this end, the harmonization of these standards through the use of a domain ontology was created from existing ISO/IEC standards, in particular ISO/IEC 24744 and 24,765 which is based in particular on the ontology of definitional elements (DEO) and the configured definitional ontology (CDO). The following **Table 1** presents a summary of railway safety analysis and evaluation approaches based on the ontologies previously studied.

3.2 Approaches based on knowledge graphs

3.2.1 Preliminary remark

The difference between ontology, knowledge graph and semantic network is still debated. The three approaches are based on a taxonomy (or taxonimy) which often refers to the science of classification. Taxonomy is an approach to classifying domain-specific concepts and terms. It is often used to organize terms in natural language processing (NLP). The ontology constitutes an enriched taxonomy and the concepts (or class) and relationships are also organized in the form of a conceptual graph allowing the different semantic relationships to be visualized. Web Ontology Language (OWL) is the semantic web standard dedicated to the description of ontologies. Coming from semantic networks, the conceptual graph is a knowledge representation formalism proposed in the work of Sowa in 1976 [30]. The knowledge graph is a multilateral relationship graph composed of nodes (entities) and edges (relationships between entities). Therefore, ontology, taxonomy and knowledge graph are all used to structure, organize and classify concepts in a hierarchical structure.

Areas of expertise	Ontology type	Objective	References
Artificial intelligence (AI)	Ontology (in general)	Common vocabulary to support knowledge sharing and reuse in AI	[1]
Knowledge engineering	Ontology for Knowledge Engineering	Ontology for Knowledge Engineering	[2]
Knowledge engineering	Ontology for Knowledge Engineering	Ontology for Knowledge Engineering	[3]
Rail transport	Ontology of railway accident scenarios	Modeling of accident scenarios resulting from return of experience	[16]
Rail transport	Ontology of railway accident scenarios	Accident prevention based on ontology and machine learning	[17]
Rail accidents	Ontologies for derailment accidents	Ontology based on railway data	[15]
Railway signaling	ERTMS/ETCS (European Rail Traffic Management System)	Ontology for modeling ERTMS/ETCS	[9]
Railway signaling	ERTMS/ETCS (European Rail Traffic Management System)	Temporal ontology for ERTMS/ETCS	[10]
Railway signaling	RAISO (RAilway Infrastructures and Signaling Ontology)	Railway Signaling Ontology	[6]
Rail infrastructure (Route Compatibility)	“Network Statement Checker” ontology	Data integration in the railway domain based on ontology	[4]
Rail infrastructure (Route Compatibility)	“RaCoOn” Ontology (Rail CoreOntology)	Train location based on track circuit positions	[5]
Rail infrastructure	Railway Infrastructure Topology Ontology	Represent infrastructure characteristics in accordance with domain standards	[7]
Rail transport	Transport ontology for customizing user interface content	Customizing user interface content	[11]
Freight transportation	Ontology for searching personalized routes for freight transport	CBR-based personalized route search	[8]
Public transport	Ontology based on performance indicators	Ontology to support performance monitoring in public transportation systems	[12]
Rail Transport Safety	Ontology based on terminology extracted from standards	Ontological for the analysis of dysfunctions in the design of railway systems	[13]
Rail freight transport	Ontology for automated freight traffic control system	Ontological harmonization of information systems of rail freight transport in Ukraine	[14]
Railway maintenance	Ontology for railway condition monitoring	Using Ontology to Integrate Railway Condition Monitoring Data	[18]
Railway maintenance	Ontology for railway predictive maintenance	Predictive maintenance of railway subsystems using an ontology- based modeling approach	[19]

Areas of expertise	Ontology type	Objective	References
Railway maintenance	Ontology for railway maintenance	Ontology based on the explicit and tacit knowledge of domain experts	[20]
Equipment maintenance rolling	Ontology for maintenance of rolling stock	Support the management of maintenance of rolling stock with an ontology-based virtual depot	[22]
Autonomous train	ATMO ontology	ATMO: autonomous train card ontology	[23]
Land transportation	Road traffic management ontology to help drivers; Ontology of road accidents; Ontology for the personalization of traveler information; The ontology of transport disruptions; iCity ontology to capture data collected and generated on the urban system; Network Statement Checker ontology to check the feasibility of running a train on a track railway.	Survey on ontologies in land transport	[24]
Concurrent Engineering	Ontologies of product systems (concurrent engineering), service systems, business systems, etc.	State of the art of ontology-based systems engineering	[25]
Standards ISO 27001, ISO 20000, etc.	Ontology for the harmonization of several standards	Main concepts related to the harmonization of several models and standards	[26]
ISO 31000 and 73 standards (Risk management)	Ontology for identifying the most appropriate risk management approach	_ “OntologyGuide73” is built from the document ISO 73; _ “OntologyRATIS,” created at from OntologyGuide73 and contains concepts extracted from ISO 31010	[27]
ISO Software Engineering Standards	Ontology for ISO standards	1) Creation of the infrastructure	[28]
ISO software engineering standards: ISO/IEC 24744 and 24,765	Ontology for ISO standards	2) Proof of concept and application	[29]

Table 1.
Summary of approaches studied based on ontology.

3.2.2 Approaches investigated

In recent years, several works focused on knowledge graphs have been developed to improve the safety of rail transport. Based on railway accident investigation reports (published on the UK RAIB website), Liu et al. [31] proposed a knowledge graph-based

approach to explore the causes of railway operational accidents. In the framework of railway accident causality networks, nodes represent accidents and/or their causal factors, for example, hazards, and the edges connecting the nodes represent the relationships between the nodes. In the field of maintenance of railway rolling stock and based on the fault tree method, Ragala et al. [32] proposed an approach to construct a knowledge graph with a view to assist the maintenance technician; maintenance in its task of researching the causes and remedies for failures (or breakdowns) of rolling stock. Based on “FAR” accident data from American railways, Yan et al. [33] proposed a knowledge graph based on an ontology with a view to identifying, preventing and controlling the main points of risk as well as the risk paths of railway fire accidents. The study proposed by Wang et al. [34] focuses on the development of a knowledge graph to model the correlations between the dangers linked to rail accidents in the United Kingdom covering a decade. In the context of the construction of railway bridges Lai et al. [35] developed a method for the dynamic updating of a knowledge graph based on multisource data in the bridge construction process. The authors propose a scientific basis necessary for bridge management and thus help to improve the level of management of bridge computerization. To prevent railway operating accidents Liu et al. [36] proposed an interesting hazard prediction approach based on knowledge graphs. This approach to modeling railway operating accidents called ROAKG made it possible to identify the main lessons:

- Missing or late deceleration applied by a train driver;
- Error of assessment of the current dangerous situation;
- Deterioration or damage to rolling stock including bogies and wheels;
- Failure of a signaling system or equipment.

Several other approaches to preventing railway dangers and accidents are presented in Liu et al. [36] in particular the distribution of freight rail accidents in Canada from 1995 to 2015 according to fatigue, the distribution of accidents at railway crossings level in the United States between 2009 and 2014, the distribution of the severity of rail accidents in the United States from 2000 to 2016 according to the types of accidents, the study of the frequency of fatal accidents according to different types of level crossings, the evaluation of the frequency of freight train derailments, the study of the frequency of 407 accidents/incidents which led to the most important cause, namely human error, the study of the relationships between human errors and types of railway accidents. In accordance with European regulations on the interoperability of European rail systems, it is mandatory to check the compatibility of routes between the European rail network managed by infrastructure managers and the vehicles for which the railway undertakings are responsible. In 2020, in order to check the compatibility of routes, the European Union Agency for Railways (Agency) developed a knowledge graph which is based in particular on data from two European registers: the European Register of infrastructures (RINF) and the European Register of Authorized Type Vehicles (ERATV). The knowledge graph covers 27 European countries and describes more than 2000 vehicle types, 270,000 track segments and 50,000 stations [37].

According to Rojas et al. [38], the verification of route compatibility is based in particular on: (i) an ontology of the railway infrastructure and the types of authorized vehicles, (ii) a knowledge graph describing the railway infrastructure European; (iii) a system architecture for use case development and (iv) an open source, native

RDF (Resource Description Framework) web application to support route compatibility checks. Aguado et al. [39] also proposed a knowledge graph for checking the compatibility of routes. The objective is to exploit the terminological harmonization achieved in railway legal documents by developing a reference vocabulary based on a reusable knowledge graph that can be used by railway stakeholders and thus improve the interoperability of railway data. The interest and importance of knowledge graphs as tools for explainable machine learning are studied through a detailed investigation in Tiddi and Schlobach [40]. The need to improve interpretability and explainability in machine learning systems and in particular deep learning, often considered as black boxes that are difficult to verify and interpret, has directed researchers toward the development of approaches, techniques and tools allowing explainable learning. According to the authors, knowledge graphs, which naturally provide basic domain knowledge in a machine-readable format, could be integrated into explainable machine learning approaches to provide meaningful explanations and thus improve the interpretability and reliability from the user’s point of view. Indeed, semantic approaches and symbolic representations in the form of ontologies and knowledge graphs make it possible to structure, represent and capture knowledge and data in the domain. The following **Table 2** presents a summary of rail safety analysis and evaluation approaches based on knowledge graphs.

Railway transport subdomain	Objectives		References
Infrastructure and Rolling stock	Route Compatibility	Knowledge graph for checking route compatibility	[38]
Infrastructure and Rolling stock	Route Compatibility	Knowledge graph for checking route compatibility	[39]
Infrastructure Register (RINF) and Vehicle Register (ERATV) held by the European Union Agency for Railways	Route Compatibility	Knowledge graph for checking route compatibility	[37]
Railway operation	Accident prevention	Knowledge graph to prevent railway operating accidents	[36]
Accident investigation reports United Kingdom	Accident prevention	Knowledge graphs to explore railway operational accidents based on UK rail accident investigation reports	[31]
Maintenance of railway rolling stock	Accident prevention	Knowledge graphs to identify fault tree-based railway rolling stock failures	[32]
Railway accident database Americans	Accident prevention	Knowledge graph to prevent railway fires	[33]
Database of railway accidents United Kingdom	Accident prevention	UK rail accident knowledge graph	[34]
Railway bridges	Prevention of railway bridge construction hazards	Knowledge graph for predicting railway bridge construction hazards	[35]
All railway subdomains	Knowledge Graph Survey	Knowledge graphs as tools for explainable machine learning	[40]

Table 2. Summary of the approaches studied based on knowledge graphs.

4. Toward a “HEXA-Onto” conceptual model characterizing an ontology

The design and implementation of a domain ontology requires the use of several means:

- techniques and tools for extracting data and knowledge;
- knowledge representation methods;
- a precise approach to developing an ontology;
- languages and tools to design and create the ontology.

In order to take all of these dimensions into account, we have developed a conceptual model called “HEXA-Onto” (in the form of a hexagon) to provide a general framework and methodology for ontology development. This approach in no way claims to be exhaustive or representative of all research work in the field of ontology. The objective is simply to summarize the ontology development cycle in a fairly basic way. Moreover, in 1997, Fernandez et al. [41] already proposed a methodological framework called “METONTOLOGY” which is structured around six main steps:

- Specification to identify the purpose of the ontology;
- Conceptualization to identify concepts, instances, relationships;
- Formalization to give a structure to the acquired knowledge;
- Integration to know the resources and/or reuse of existing ontologies;
- Implementation to codify the ontology model in a formal language;
- Maintenance.

In addition to these stages, the author [41] also defined three support activities: (1) knowledge acquisition, (2) documentation and (3) evaluation for verification and validation of the ontology. The “HEXA-Onto” model proposed in this study completes the methodological work of Fernandez et al. [41] and takes into consideration six iterative and complementary dimensions (**Figure 1**):

- The first dimension is made up of the knowledge extraction stages;
- The second dimension offers the methods, techniques and tools for acquiring the necessary knowledge during the first dimension of knowledge extraction;
- The third dimension brings together the stages of developing an ontology with emphasis on the stages of verification, validation and maintenance of the ontology;
- The fourth dimension recalls the methods, languages and tools necessary for the construction of ontology;

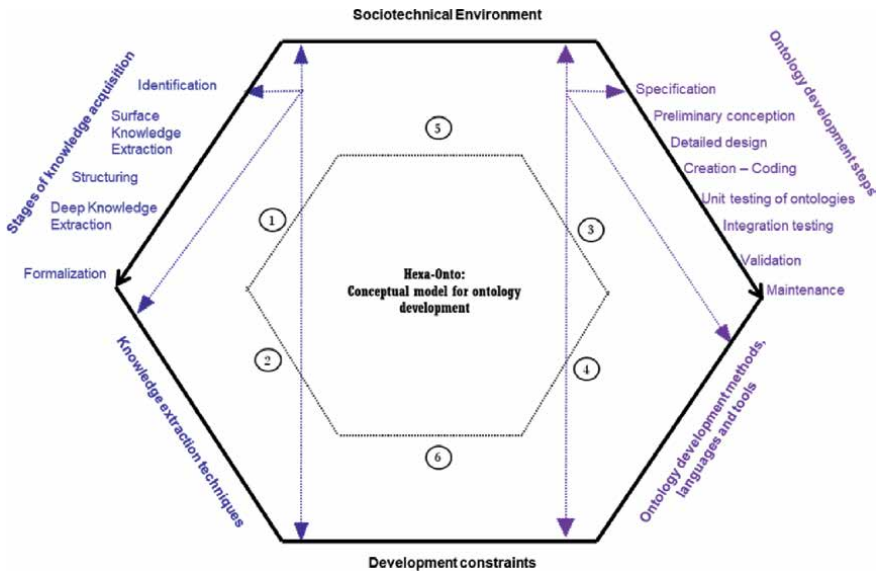


Figure 1.
 HEXA-Onto Model – A methodology for developing an ontological knowledge-based system.

- The fifth dimension involves the socio-technical environment of the domain studied;
- The last dimension focuses on integrating the different constraints inherent to the engineering process of knowledge.

All six dimensions involved in the HEXA-Onto model are presented successively in the following paragraphs. To simplify the articulation of these six dimensions, we have agreed to bring together the last two in a single paragraph which describes both the environment and the constraints involved in the development process. Indeed, these two dimensions are closely linked because they must be considered jointly during the knowledge extraction stages and during the ontology construction stages.

4.1 Acquisition of knowledge

Knowledge acquisition (KT), recognized as a “bottleneck” since the advent of expert systems, is still considered a crucial task in the construction of ontologies. Extraction or “elicitation” refers to the collection of knowledge from the domain expert, while the notions of “transfer” or “transmission” of expertise refer to the collection and then formalization of an expert’s knowledge. The term “knowledge acquisition” refers to all of the steps necessary to develop a knowledge base for a system. CA is a multidisciplinary theme which benefits from the fruitful contributions of cognitive psychology (human reasoning models, knowledge collection techniques), software engineering (description of the life cycle of a knowledge-based system), linguistics (to make the use of documents more efficient or guide the interpretation of verbal data) and ergonomics (analysis of the activity of the expert and the future user). CA constitutes one of the central themes of research on ontology-based

systems and one of the keys not only to the successful development of such a system but also to its integration and use in an operational environment. Initially centered on the Expert/Cognitician couple, CA raised crucial problems such as the identification of user needs or the choice of a mode of knowledge representation. The excessive gap between the language used by experts to describe their problem and the level of abstraction of knowledge representation formalisms has motivated numerous researches aimed at facilitating the transfer of expertise. The design of a knowledge base requires the extraction, analysis, structuring and formalization of know-how in a field which is accessed through one or more individuals, qualified as experts. Therefore, the transfer of this expertise raises several questions: who really holds the expertise? How can we access it? How extract it? How to formalize it without distorting it? Which representation to choose? How to validate and maintain the knowledge collected?

Various researches are carried out to better understand these problems inherent in the acquisition of knowledge and the design of a knowledge-based system (KBS). Means (methods, techniques, tools) for the acquisition of knowledge are accessible to the cognitive scientist and the expert and offer a methodological framework for the development of an SBC.

4.2 Identification and specification of the area of expertise

This step of the knowledge acquisition methodology makes it possible to verify that the context of the problem is favorable for collecting knowledge. It makes it possible in particular to verify the existence and availability of one or more experts, the presence of expertise in line with the objectives of the study and the possibility of attending processing of real cases on the site for example. The domain identification step also makes it possible to understand the nature and origin of the information used by the expert as well as the specification of the form of solution to be developed by the decision support system envisaged. Several knowledge gathering techniques such as interviews or questionnaires can be used to identify the area of expertise. At the end of this stage, the knowledge engineer (cognitician) is familiar with the vocabulary of the field.

4.3 Knowledge extraction

4.3.1 Surface knowledge and deep knowledge

The interest in knowledge extraction allows, among other things, to extract knowledge that is often implicit among experts and to make it more explicit and usable in two forms: surface knowledge and deep knowledge. After having clearly defined the field of study, the surface knowledge extraction step consists of identifying the main lines of the expert's activity when faced with real problems. It aims to generally identify the mechanisms and modes of reasoning of the expert, the strategies and heuristics for solving the problem, the relationships between the key concepts of the domain, etc. The technique of verbalization and/or protocol analysis can be implemented during this stage in order to observe the expert at work. For the extraction of deep knowledge, this involves the detailed specification of the different knowledge modules as well as the refinement of the concepts used and their relationships. This step makes it possible, in fact, to precisely identify the expert's reasoning

mechanisms. To carry out this step, the use of several knowledge collection techniques is necessary. The protocol analysis technique can be applied to acquire the observable part of the expert's activity. On the other hand, the conceptual sorting technique can be used to identify the mental organization of the concepts manipulated by the expert. This extraction step ultimately leads to the identification of the main facets of the expert's reasoning. The results of this step include detailed descriptions of all knowledge (object, class, entity) as well as problem-solving heuristics.

4.3.2 Knowledge extraction techniques

There are currently various techniques, often inspired by work in cognitive psychology, to access and make as explicit as possible the knowledge manipulated by the expert in the field. These techniques are generally referred to as “cognitive” methods, “manual” methods or “empirical” methods. All of these techniques are often classified into two groups according to the mode of access to the knowledge that they allow:

- Direct techniques are generally based on informal collection methods and focus on extracting directly from the expert what he knows how to express verbally;
- Indirect techniques are semi-formal methods which attempt to reveal the expert's skills using indicators interpretable by the cognitive scientist. The data acquired by these techniques are essentially knowledge used implicitly that the expert does not know how to express explicitly.

Before applying a technique, it is fundamental to know what type of information it allows to collect, to know the limits of validity and the conditions of implementation. It is desirable that cognitive scientists have the means to indicate to them the techniques best suited to the fixed or evolving nature of the field of expertise, to the experts' mode of reasoning as well as to the characteristics of the available knowledge. In practice, a single technique is insufficient to extract all of the knowledge and it is necessary to combine several depending on the complexity of the domain. The role of the cognitive scientist is not only to choose the appropriate techniques but also to define their orders of application. There are several collection techniques such as interviews, questionnaires, protocol analysis and conceptual sorting. In order to compensate for the insufficiency and complexity of an empirical knowledge collection approach, extraction tools have been developed. They aim to automate certain stages of the acquisition process by developing even the knowledge base. These tools, such as AQUINAS, ROGET and MOLE, are based on the use of one or more knowledge collection techniques. They are generally dedicated to particular forms of knowledge or categories of problems such as diagnosis or design.

4.4 Formalization, structuring and representation of knowledge

The knowledge acquired previously is then analyzed and structured in modules (in the form of ontologies for example). Each of these modules is associated with a problem-solving task. This involves transcribing the knowledge resulting from the deep knowledge extraction phase into an appropriate representation module such as production rules, semantic networks, frames, knowledge graphs or ontologies, with a view to their implementations. The steps of the knowledge acquisition methodology,

presented above, follow one another in a cyclical manner in order to consider the human variability of experts in the field.

5. Overview of the “HEXA-Onto” model through a conceptual ontology

In order to better explain all of the concepts developed below, this work presents the HEXA-Onto conceptual model in an ontology using the “Protege” tool. Several examples are shown in the following **Figures 2–15**.

5.1 Ontology development languages and tools

In order to represent the information involved in an ontology and to make it jointly interoperable on a syntactic and semantic level, it is necessary to use specific

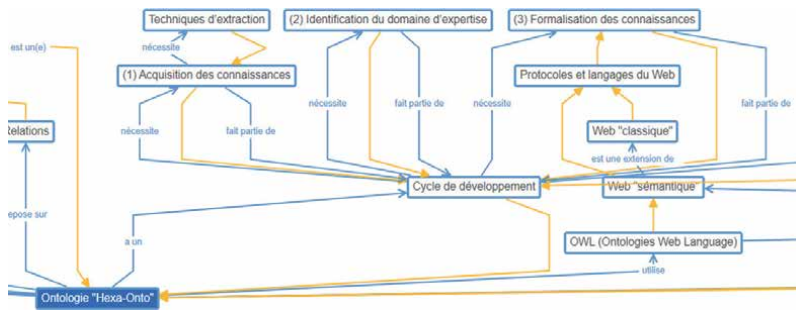


Figure 2.
 HEXA-Onto model: the ontology development cycle.

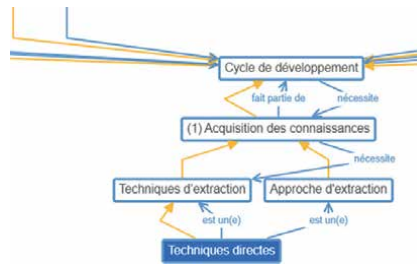


Figure 3.
 Knowledge acquisition techniques and approaches.

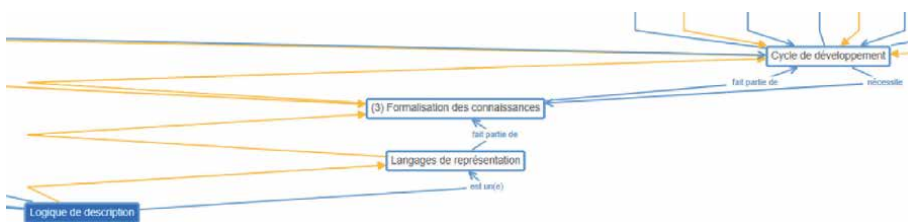


Figure 4.
 Description language.

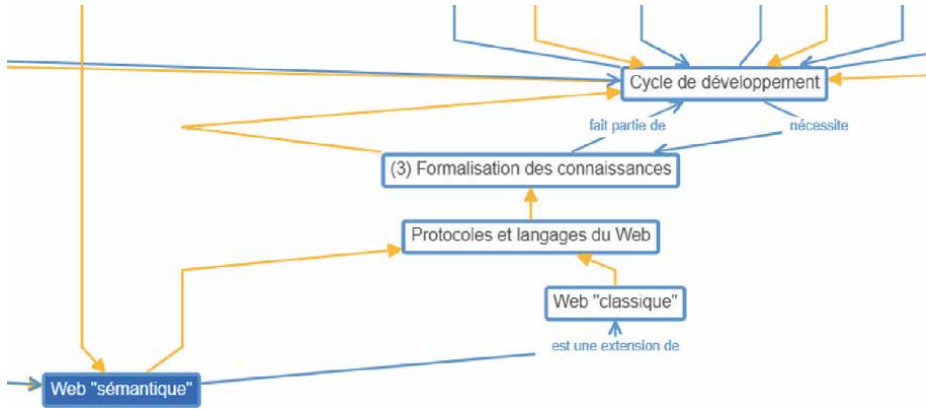


Figure 5.
The Semantic Web.

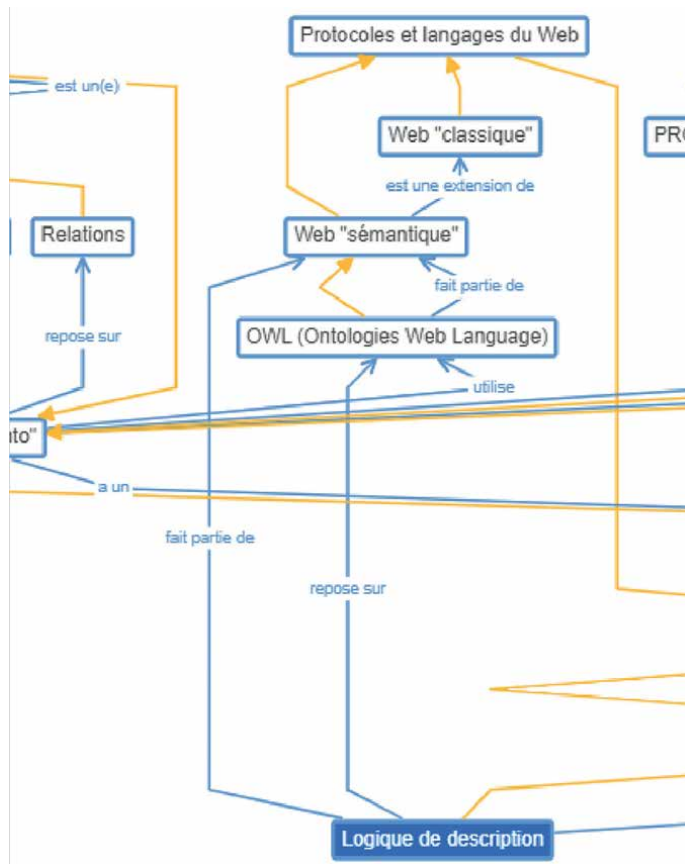


Figure 6.
OWL language.

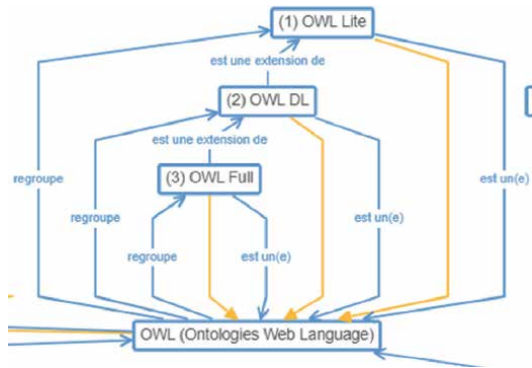


Figure 7.
 OWL and its derivatives.

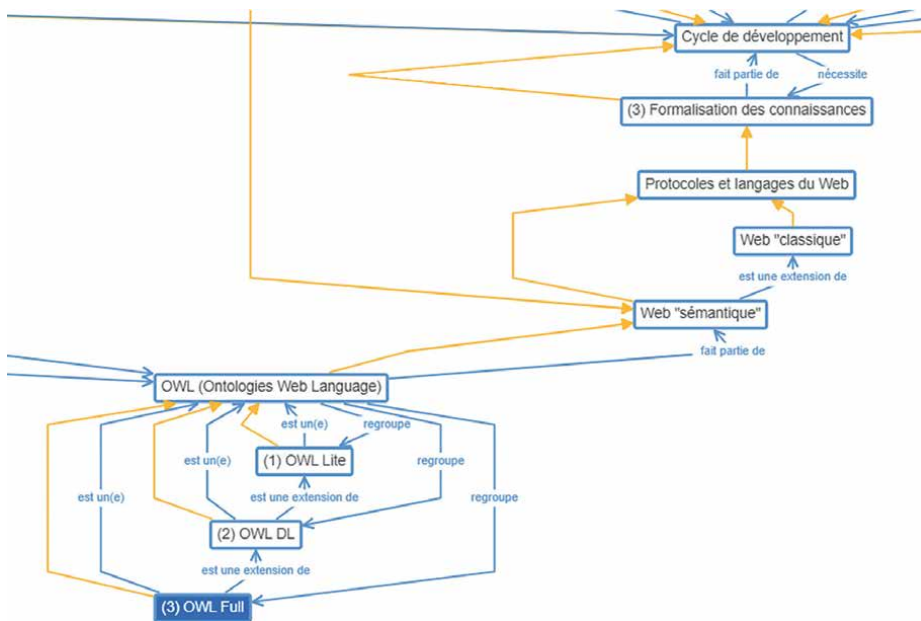


Figure 8.
 OWL Full as an extension of OWD DL.

languages. Some of them are called “high level,” others “low level,” however most of them are based on the technical characteristics of the XML, XML Schemas, RDF, RDF Schemas and OWL languages. Based on description logic, OWL is the most used and best-known language for describing ontologies. According to Sowa [30]: “Conceptual graphs form a knowledge representation language based on linguistics, psychology and philosophy.” A conceptual graph is made up of two types of nodes: “relationship” nodes and “concept” nodes. Concepts represent entities, attributes, states and events, and relationships show how concepts are interconnected. A semantic network is a directed and labeled graph. This is a multigraph. A taxonomy (or taxonomy) whose objective is the classification of elements is a very common structure in the context

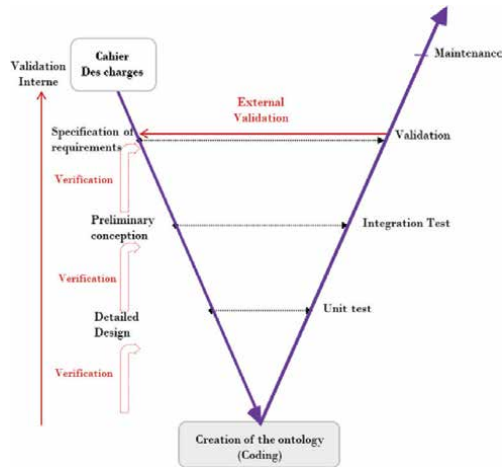


Figure 9. "V" cycle of ontology development.

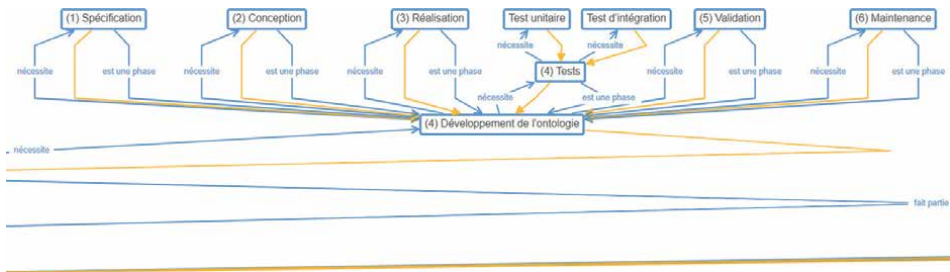


Figure 10. Ontology development phases.

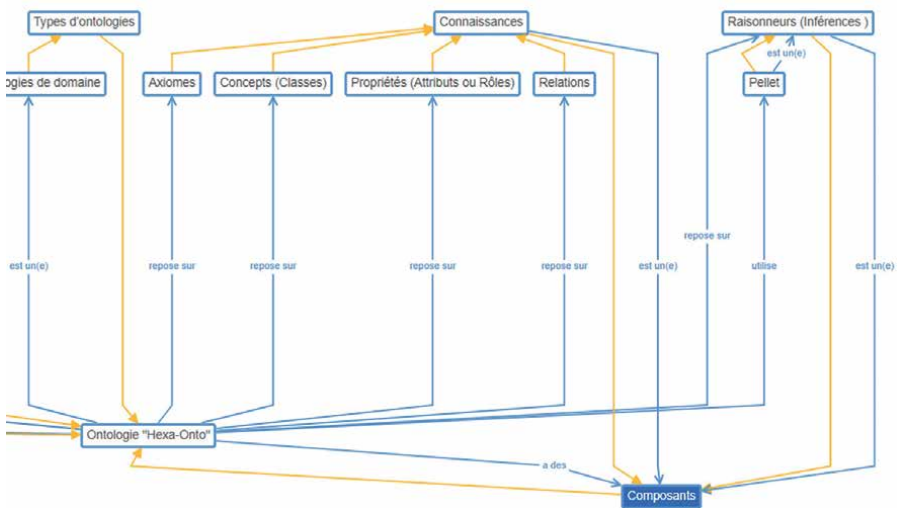


Figure 11. Classes, Instances, Relationship, etc.

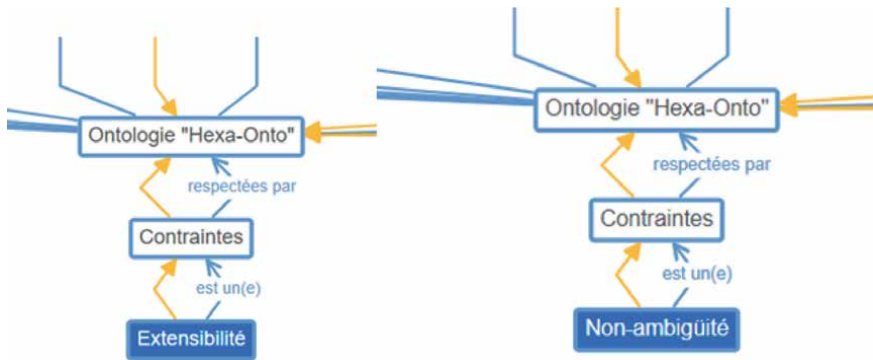


Figure 12.
 Example of constraints.

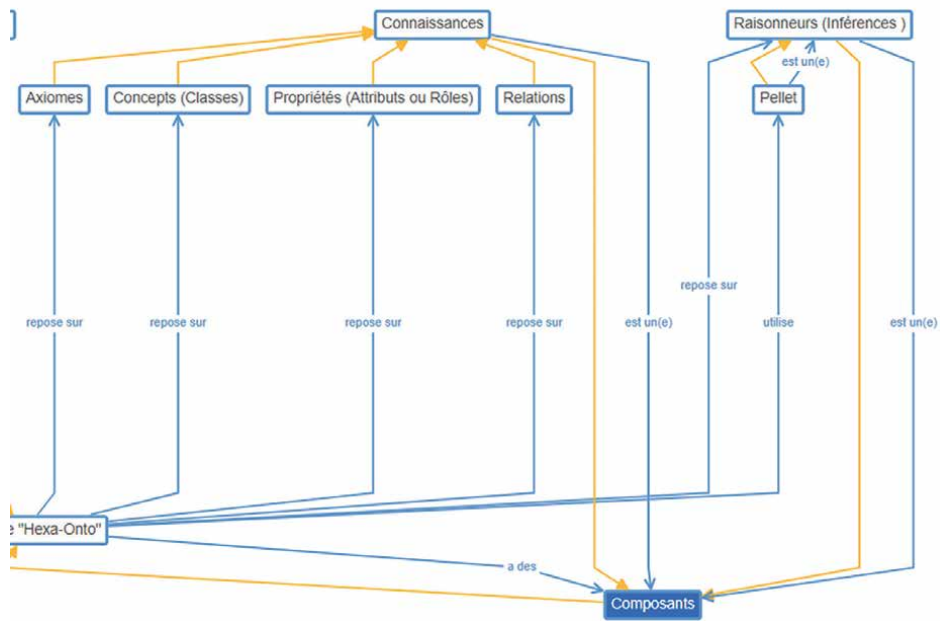


Figure 13.
 The components of an ontology.

of ontologies. The concepts of an ontology are often organized into taxonomies. The name “description logic” can be interpreted in two ways: (1) this language allows you to write the “description” of the concepts of a domain and (2) this language offers formal semantics defined in first-order logic. This knowledge representation language is generally used to represent ontologies because it takes into consideration not only the readability and formalization of knowledge by using, for example, semantic networks but also the notion of expressiveness and decidability by using first-order logic. The semantic web, in particular, the representation of ontologies, automatic processing and representation of knowledge are examples from description logic. We generally distinguish between the “classic” Web and “semantic” Web. In the “classic” web, we find the Extensible Markup language (XML Language) which is often used as a

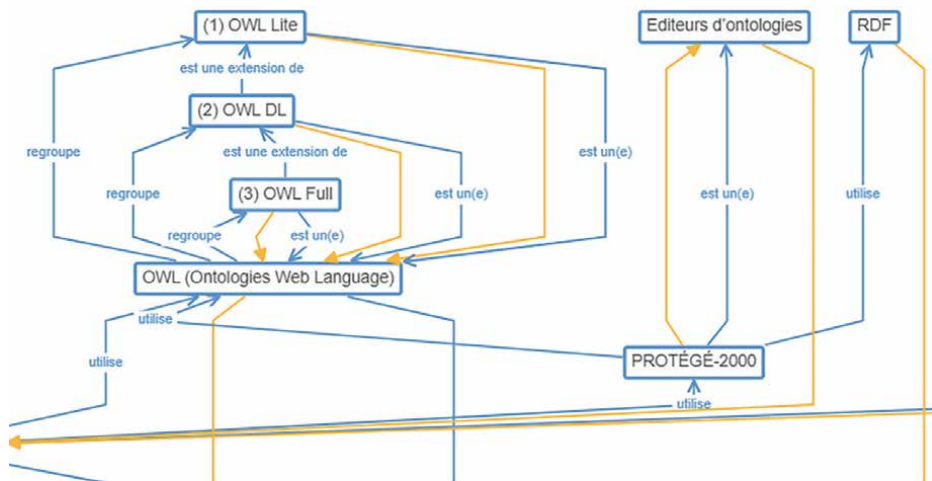


Figure 14.
The “Protege” Editor which uses OWL and RDF.

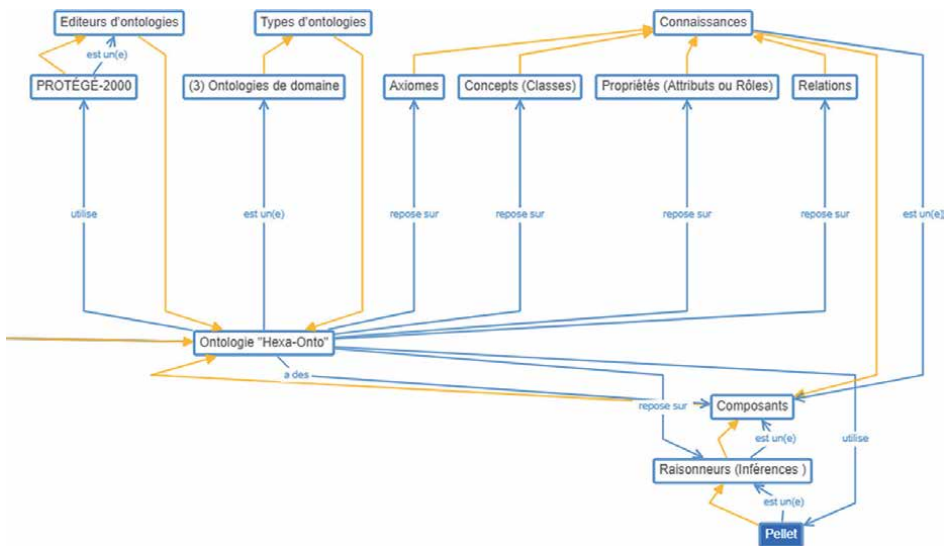


Figure 15.
The “Pellet” reasoner.

reference format for the exchange of data and documents (XML data and XML document). Usually, XML provides syntax for structured documents but does not require any semantic constraints. In the “classic” web, we also find the Hypertext Transfer Protocol Secure (HTTPS) protocol. This secure hypertextual transfer protocol allows the visitor to verify the identity of the website using an authentication certificate. Finally, Uniform Resource Identifiers (URIs) are also part of the “classic” Web, allowing a resource to be identified on a computer network. However, the pages and links offered by HTML are interpretable only by their users and do not offer semantics usable by machines. In the context of the “semantic” Web, several languages which consider the semantics of data have been proposed:

- Resource Description Framework (RDF);
- RDF Schema;
- Web Ontology Language (OWL);
- SPARQL Protocol and RDF Query Language (SPARQL)

SPARQL is a query language whose objective is to search, add, modify or delete RDF data available across the Internet. Coming from the field of description logic, the OWL knowledge representation language was built on the RDF data model and is often implemented to describe ontologies by defining terminologies to describe concrete domains. This terminology is based essentially on concepts (or classes) and properties (or attributes). In the context of description logic, “properties” are also called “roles.” There are three levels of OWL or three sublanguages: OWL-Lite, OWL-DL and OWL-Full. The OWL-Lite language is the simplest version of the OWL language (**Figures 4–8**).

5.2 Development of the ontology

The main characteristics of this approach are as follows:

- The life cycle is summarized by a “V” diagram including a descending branch for the specification and design of the ontology and an ascending branch for the integration and validation of the ontology;
- The chronology of the works is sequential, since each phase is conditioned by the completion of the previous phase. The transition from one phase to the next is conditioned by the review of one or more output documents;
- During these phases, the nature of the work to be carried out and the actors involved are clearly identified;
- These different phases correspond to increasing levels of definition. This is an approach whose phases represent different levels of abstraction (**Figures 9 and 10**).

5.2.1 Specification

This step aims to develop the specifications of the ontology in terms of functional needs and interfaces with the environment. It makes it possible to specify the description of the expected functions and the constraints to be respected by the ontology. A specification must be complete, precise, consistent, clear and controllable. It is recommended to use several complementary modes of expression. Formalized expressions contribute to the precision and coherence of knowledge. It is recommended to use the Structured Analysis and Design Technique (SADT) formalism which is a graphical tool associated with a modular and hierarchical top-down analysis method. A specification constitutes a general design phase (high level of abstraction) during which the choices for dividing the ontological system into subsystems, constituents, modules or functions. The specification is a statement of objectives within the framework of a task specified in the specifications. It relates in particular to a function to

be provided, a concrete object to be produced or an abstract object to be defined. In terms of ontology, the specification stage allows in particular: the identification of terms (vocabulary) and key concepts of the domain, the identification of the “why” of the ontology, the definition of classes and the hierarchy of classes, defining properties of classes and attributes and identifying axioms, taxonomies, instances, etc. This problem specification phase also makes it possible to clarify the objectives to be achieved by the considered ontology, for example, the reuse of domain knowledge, the modeling of domain knowledge for common understanding, analyze and explain knowledge in a field, etc.

5.2.2 Preliminary conception

The preliminary design stage is a process during which the choices for realizing the functions of the ontology are defined and implemented. Unlike the specification stage, the objective of which is to describe the “what” of the problem to be addressed, the design specifies the “how” to address the problem. The design must explain and justify the implementation choices (coding) as well as the types of control to be carried out and the results to be obtained. The preliminary design must answer the question: how to satisfy the needs formalized during the specification phase? This step leads to the development of the general architecture of the ontology, the choice, definition and justification of this architecture. This step makes it possible in particular to limit the exchange of data between modules, to decompose the functions of the problem into tasks then ontological modules and to carry out a hierarchical decomposition of the modules if necessary.

5.2.3 Detailed design

The detailed design must satisfy the needs formalized during the preliminary design phase and allows the results of the preliminary design to be detailed to a sufficient level allowing the coding and creation of the ontology. This is a definition by successive refinements of the data.

5.2.4 Creation of the ontology (coding)

This step allows the results of the previous phase to be translated into a program using a given programming language. It makes it possible to produce clear and commented source code meeting the requirements of the preliminary and detailed design phases. Building an ontology requires consideration of at least the following fundamental components: vocabulary, class, properties, instance, relationship, class hierarchy, etc.

- Identify all the key terms in the field of application in order to develop a common vocabulary (lexicon);
- Identify the list of classes (or concepts). Each class groups together a collection of instances (or objects) possessing similar properties;
- Identify class properties. Each class has properties or attributes or functions. These are the characteristics or functionalities that classes or concepts or objects can possess and share;

- Define the facets and particularities of these concepts, in particular the cardinality of the attributes and the value types of the attributes (enumerated attributes, Boolean attributes, multivalued attributes, symbolic attributes, Instance type attributes, etc.);
- Identify instances of classes (or individuals) which are basic objects and are therefore indivisible in an ontology;
- Identify potential relationships to determine connections (or links) between classes (or concepts) or instances. This involves discovering the correspondence relationships between all the entities of the ontology: between classes of objects (concepts), between instances, between class and instances, etc.
- Develop a hierarchy of classes in the form of conceptual graphs;
- Decide on the levels of abstraction of the ontologies developed: high-level ontology, low-level ontology, domain ontology, etc.
- Integrate, merge, unify, align, match and manage ontologies taking into consideration interoperability (ontology reconciliation) and on the basis of the vocabulary identified previously;
- Code the ontology in order to explain the conceptual representation of the ontology in a formal language like OWL and RDF (**Figure 11**).

5.2.5 Ontology unit testing

Ontology unit testing is an activity whose objective is to verify, for each component (or element) of the ontology taken in isolation, that all the paths (branches), nodes, concepts, links (relationships), the input and output data are explored and traversed (at least once) and that the investigation results conform to the preliminary design file.

5.2.6 Ontology integration testing

This step makes it possible to check the correct functioning of the software after grouping the different modules of the ontology. The goal is to demonstrate that all modules (designed during the preliminary design stage) interact correctly to ensure their functions intended by the specification phase. We can use a Test Plan whose aim is to specify the objectives to be tested, the characteristics to be verified, the logic of the test sequence as well as the methods and tools to be implemented to carry out the unit testing phases, integration and validation.

5.2.7 Functional validation of the ontology

During this step, it is necessary to ensure that the developed ontology complies with the specification file. Validation is a control process aimed at verifying that all the required functions of an ontology are actually obtained. Generally, during this validation phase, the checks are carried out by a team separate from the one which designed the ontology. The progress of this activity requires passing through three types of successive controls: unit control, integration control and functional control. Usually, we distinguish between “external” validation in relation to the objectives

specified during the specification phase and “internal” validation, also known as verification. Verification is an activity which aims to ensure that the results from a phase of the development cycle (descending branch of the V-shaped cycle) comply with the benchmark of the previous phase.

5.2.8 Ontology maintenance

Maintenance refers to the modification made to the ontology after its implementation, to correct faults and improve its effectiveness. The objective is to ensure that the ontology is maintained following the correction, improvement or adaptation operations carried out.

5.2.9 Ontology development constraints

The constraints proposed below must be considered either during the development of an ontology or during the knowledge acquisition phase. These constraints can also be considered jointly during two processes of knowledge acquisition and ontology construction. Some authors specify that the construction of ontologies must respect principles which have been defined by Gruber [1], Uschold et al. [42] and Guarino [43]. Generally, these principles concern the necessary clarity of the definition of the elements that the ontology must contain as well as the separation of the design and implementation phases in a formal language of the ontology. These principles can be summarized as follows:

- Clarity/objectivity, completeness/perfection, consistency, maximum monotonous extensibility, commitments minimal ontological [1];
- Ontological distinction: the classes of an ontology must be separated [44];
- Minimal modularity in order to minimize coupling between modules [45];
- Subdivision of taxonomies, minimum semantic distance, standardization of terms [46].

The HEXA-Onto development model (dimension 6) takes into consideration the following constraints:

- Completeness: this involves describing explicitly and exhaustively all data, functions, concepts, relationships, classes of objects, etc. necessary to meet a well-defined objective during the specification stage;
- Coherence: there must be no contradictions;
- Clarity: the form of an object, a concept, a problem, a relationship, a piece of knowledge, a reasoning, a result, a document, etc. must facilitate understanding;
- Precision: each significant concept, parameter and attribute must be indicated;
- Non-ambiguity: it must not be possible to interpret a concept in different ways;

- **Readability:** it is the suitability of a specification, a model, a language, a program, etc. to be easily understandable. For example, languages, knowledge and declarative representation modes (used in AI) offer good readability. This is declarative knowledge as opposed to procedural knowledge used in computer science;
- **Extensibility:** the objective is to facilitate corrections and updating and scalability of knowledge;
- **Reliability:** ability of an ontology to perform without failures all the functions specified in a reference document (from the requirements specification phase) in a specific environment and for a given duration of use;
- **Modularity:** this characteristic of the software makes it possible to guarantee a modular structure in program units that are highly independent of each other, autonomous and identifiable for compilation, testing and association with other units (modules) (**Figure 12**).

5.3 Ontology and knowledge-based systems (KBS)

As with knowledge-based systems (KBS) or expert systems, within the framework of ontologies, it is also about reasoning and deducing knowledge from new facts. In SBC, domain knowledge, described in a knowledge base generally in the form of production rules, is well separated from the inference engine (reasoner) whose objective is to exploit this knowledge and deduce new facts or conclusions. This idea of separation between “declarative” knowledge and the inference engine for the “procedural” aspect made it possible to quickly develop SBCs by reusing certain generic elements relating to the reasoning or domain knowledge. The objective remains the same when constructing an ontology. Domain knowledge is developed in the form of a reusable ontology and the inference engine makes it possible to reason about this ontology. Compared to SBC, only the mode of representation of knowledge changes from a representation in the form of production rules for example to a much richer representation in the form of ontology.

5.4 The components of an ontology

The development of an ontology requires knowledge of four fundamental components: classes, properties, instances and relationships. A class (or concept) groups together a set or collection of instances (or objects) having similar properties. In the context of the semantic web, a meta-class designates a set of classes that share certain common characteristics. Each class has properties (in RDF) or attributes (slot in XOL) or functions (in OML). Thus, we speak of attributes or properties to characterize a class (concept) or describe an instance. These are the properties or characteristics or functionalities or characteristic parameters that classes or concepts or objects can possess and share. Instances (or individuals) of a class are basic objects that are indivisible in an ontology. Finally, relationships are used to determine connections (or links) between classes (or concepts) or instances (**Figure 13**). The objective is to identify the semantic association between all the classes (concepts) identified in an ontology. These relations between classes are generally formulated by specific terms such as “is a,” “is a kind of,” “part of,” “repealed by” and “imposed by.”

5.5 Ontology editors

For the implementation of an ontology, there are different editors allowing you to systematize and rationalize the engineering of ontologies such as Protégé, Ontolingua, Ontosaurus, WebODE and WebOnto. Developed by a team from Stanford University (<https://protege.stanford.edu/>), “Protégé” integrates Semantic Web standards and in particular the OWL language. It is a free, open source and most widely used ontology editor/framework. In addition to its graphical interfaces such as “OntoGraf” to visualize the constructed ontologies (classes and class hierarchy), Protégé implements reasoners (inference engines). There are several reasoners making it possible to reason about ontologies described in description logic. With the Protégé tool, it is possible not only to create and edit an ontology in OWL format but also to use an inference engine like Pellet (**Figures 14 and 15**).

5.6 Types of ontologies

The literature distinguishes several types of ontology, in alphabetical order, we find Meta-ontologies, Conceptual ontology, Lexical ontology, Application ontology, Domain ontology, High-level ontology, Method ontology, Representation ontology, Task ontology, Task-domain ontology, Task/method ontology, Generic ontology, Light ontology and Heavy ontology. The domain ontology is usually the most used in practice to formalize and structure the knowledge and data of a given domain.

6. Conclusion

An ontology (or knowledge graph) is a formal, explicit, interpretable, reusable and shareable description by a group of individuals. It has the capacity to structure, formalize and represent explicit knowledge from several data sources (domain expert, database, archive, report, etc.). Ontology does not seek to model the ideas and methods of solving a given problem, but rather to specify and characterize the objects, concepts, entities, properties of concepts, attributes, facets and instances as well as the semantic links that exist between them in order to construct an explicit specification while respecting the meaning, syntax and semantics of the objects. Research in this area distinguishes several types of ontology: core ontology, domain ontology, task ontology, application ontology, high-level ontology, etc. In an ontology, objects, concepts, classes or terms are structured in the form of a knowledge graph in a hierarchical and descending manner and always respecting the semantic links between these objects. The leaves of this hierarchical tree are used to represent the instances of a new object in the domain. The following **Table 3** presents a summary of the applications of ontologies and knowledge graphs in the field of railway safety. These applications can be classified into six subareas related to railway safety. In order of involvement:

- Prevention and/or modeling of railway accident and incident scenarios generally based on investigation reports;
- Compatibility and route assignment generally from the Infrastructure Register (RINF) and Vehicle Register (ERATV) held by the European Union Agency for Railways pursuant to Directive (EU) 2016/797 of the European Parliament and

Rail safety field	References
Prevention and/or modeling of railway accident and incident scenarios	[16] [17] [31] [36] [32] [33, 34] [35] [15]
Route compatibility	[4] [5] [38] [39] [37]
Railway maintenance	[18] [19] [20] [22]
Harmonization of standards Standards ISO 27001, ISO 20000, ISO 31000 and 73 standards (Risk management) ISO/IEC 24744 and 24,765 for software engineering	[22] [26] [27] [28] [29]
Railway signaling (European Rail Traffic Management System: ERTMS/ETCS)	[9] [10] [6]
Others	
Rail infrastructure topology	[7]
Search for personalized routes	[8]
Customizing user information	[11]
Control of goods traffic	[14]
Performance indicators	[12]
Analysis of dysfunctions in the design of railway systems	[13]

Table 3.

Summary of applications of ontologies and knowledge graphs in the field of railway safety.

of the Council of May 11, 2016 relating to the interoperability of the rail system within the European Union;

- Railway maintenance and surveillance;
- Harmonization of standards, particularly risk management and software engineering: ISO 27001, ISO 20000, ISO 31000 and 73, ISO/IEC 24744 and 24,765;
- Railway signaling within the framework of the European rail traffic management system: ERTMS/ETCS;
- The other subdomains successively concern the topology of the railway infrastructure, the search for personalized routes, the personalization of user information and the control of freight traffic.

Useful both to researchers involved in the field of knowledge engineering and particularly ontology engineering as well as to researchers and experts in railway safety, this work can serve as a resource and contribute to the present and future development of applications of ontology and knowledge graphs to the field of railway safety. However, certain remarks seem necessary. Despite the certain interest of the works analyzed, each of the ontologies developed concerns a particular application and does not cover all of the concepts involved in railway safety. Rare is the work that focuses on the design, construction and consideration of safety from the specification and design phases of the rail system. The work examined focuses mainly on the operation, maintenance and feedback phases. Data, information and knowledge on safety come largely from accident and incident investigation documents and reports, ISO standards, infrastructure and rolling stock registers, specifications linked to the European traffic management system. Railway: ERTMS/ETCS and user information in terms of needs. Consequently, no ontology can capture, on its own, all the data and knowledge involved in railway safety. The last and most important limitation concerns the terminology and concepts used to develop an ontology related to railway safety. Certain works, such as those linked to ISO standards, ERTMS/ETCS and European registers, take into consideration the imposed terminology. In other works, the vocabulary used suffers from a lack of precision, clarity, in particular, the visible confusion between the term's danger, risk, accident, incident, potential accident, dangerous event, dangerous situation, dangerous element, analysis of risks, hazard analysis, risk assessment, risk management, risk reduction, safety, security, etc.

In this context, the vocabulary used when developing ontologies and knowledge graphs to define classes and properties cannot in any way guarantee the semantics, interoperability and reusability of the ontologies. Consequently, the problem of the validity of certain approaches arises since these are approaches intended for risk management for critical systems such as rail transport. Therefore, it is worth noting the absence (for some applications) of common, identifiable and reusable concepts as initially suggested by the process of developing an ontology. This constitutes an obstacle for future work which sometimes aims to reuse and exploit certain existing ontologies. Thus, the implementation of a common conceptual model, based on an ontology, which considers the semantics of all the terms and concepts used in railway safety and risk management is essential and will be the subject of the next document.

Nevertheless, and initially, a “HEXA-Onto” conceptual model was presented to clarify the concepts involved in an ontology in particular the acquisition of knowledge, the identification of the domain, the representation of knowledge and the development of ontology, constraints, languages and ontology editors.

7. Perspectives on the contribution of ontologies to railway safety and interoperability

In recent years, the field of European rail transport has now been governed by a set of legislative and regulatory acts and in particular the following two directives: (1) Directive (EU) 2016/797 of the European Parliament and of the Council of May 11, 2016 relating to the interoperability of the railway system within the European Union and (2) Directive (EU) 2016/798 of the European Parliament and of the Council of May 11, 2016 relating to railway safety.

Directive (EU) 2016/797 on interoperability clarified all railway subsystems by distinguishing between “*structural elements*” such as infrastructure, energy, rolling stock (locomotives and wagons) and “*functional elements*” such as control-command and signaling subsystems, traffic operation and management, telematics applications (passengers and freight), maintenance and accessibility for disabled people and people with reduced mobility. For each subsystem, a list of “*interoperability constituents*” has been established such as the catenary, the pantograph, the rails, the ballast, the axles, the wheels, etc. This directive also imposed, for each railway subsystem, a set of “*essential requirements*”: “*safety*” of components (for example brakes), “*availability*” (for example, monitoring and maintenance of components critical or essential for safety), “*health*” and environmental protection, “*reliability*” and technical “*compatibility*.”

Technical specifications for interoperability (TSI) for each subsystem or part of a subsystem have also been developed. A TSI specifies all the conditions that an “*interoperability constituent*” must respect as well as the procedure to follow for the assessment of conformity or suitability for use.

Authorization to put the infrastructure into service or to place rolling stock (vehicles and vehicle types) on the market is granted either by the national safety authority or by the European Union Railway Agency in view of a “*technical file*” including all the attestations, declarations and certificates established by accredited bodies such as the notified body and the risk assessment body. In this context, the European Commission has adopted a series of regulations which supplement Directive (EU) 2016/797 with regard to all of these technical aspects mentioned above. The final objective is to guarantee railway interoperability which is often defined by “*the ability of a railway system to allow the safe and seamless circulation of trains which achieve the required levels of performance.*”

To ensure the “*safe movement*” of trains, Safety Directive (EU) 2016/798 established several measures intended to develop and improve rail safety within the EU and in particular the definition of safety objectives common safety indicators, common safety methods, a safety management system, a safety certificate for railway undertakings, a safety approval for infrastructure managers, a system vehicle maintenance carried out by the entities in charge of maintenance, etc. This directive also required investigations into railway accidents and incidents to be carried out by independent technical investigation bodies as well as the control and surveillance of railway safety by national safety authorities.

Remember that a summary of the applications of the ontologies and knowledge graphs studied was presented in **Table 3**. This assessment shows that ontologies and knowledge graphs can contribute in particular to (1) the analysis of railway accidents based on railway accident reports and surveys, (2) establishment and control of route compatibility, (3) railway maintenance, (4) harmonization of ISO standards and (5) railway signaling (ERTMS/ETCS).

The applications of ontologies concerning the “*analysis and prevention of railway accidents*” fall within the framework of Directive (EU) 2016/798 relating to safety and more precisely in the context of technical investigations. However, we can question the consistency and completeness of the data related to accidents from railway feedback; on one hand, how these analyses based on ontologies can really help technical investigators and national safety authorities and on the other, how to establish real collaboration between AI specialists and railway stakeholders. The first decisive step consists, initially, of developing a common and standardized vocabulary between AI researchers and investigation bodies which considers at least the following terms: dangerous elements, causes, dangers, potential accidents, accidents,

incidents, precursors to accidents, frequency (or probability) of accidents, severity of the damage caused, risk or rather level of risk (probability/severity). This proposal is currently being developed by the author.

Applications related to “*route compatibility*” between infrastructure and types of railway vehicles fit well within the framework of Directive (EU) 2016/797 on railway interoperability.

Applications of the ontology to “*railway maintenance*” concern the functional subsystem in accordance with Directive (EU) 2016/797 and contribute to railway safety in application of Directive (EU) 2016/798.

However, applications relating to “*harmonization of standards*” relate to ISO standards and not to standards directly linked to railway safety such as the CENELEC EN 50126 standards (operational safety: Reliability, Availability, Maintainability and Safety), EN 50128 (software safety) and EN 50129 (hardware safety) which are regulatory obligations imposed by European directives. Therefore, to improve the overall efficiency of the railway system, it is appropriate to develop applications based on ontologies with a view to harmonizing and helping to operate these railway standards.

Applications relating to “*railway signaling*” (ERTMS/ETCS) fall within the framework of the “functional” subsystem and relate to “control-command and signaling.” In this context, two studies were proposed by the authors. The first aims at an ontology to model the European ERTMS/ETCS (sic) system and the second study aims to consider the temporal aspect of this same system. However, it seems to us quite difficult to develop a complete ontology of this system which is quite complex and moreover the article in question does not really show this ontological modeling.

In addition to these applications studied, and in accordance with Directive (EU) 2016/798 relating to railway safety, it is interesting to consider research work based on ontologies for decision support, particularly for decision making during the preparation of the safety certificate by the railway companies, during the preparation of the safety approval by the infrastructure manager, during the authorizations to put the railway system into operation granted by the European railway agency and/or the national safety authorities of each Member State. Finally, an interesting application could be the analysis and evaluation of risks from the system design phase and more precisely during the identification of hazards and the development of the hazard register imposed by the safety management system. This last perspective is currently being developed by the author.

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Ethics approval and consent to participate

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Consent for publication

The author of this article consents to its publication.

Availability of data and materials


The data and materials used in this research are available from the corresponding author on request.

Author details

Habib Hadj-Mabrouk
Gustave Eiffel University, France

*Address all correspondence to: habib.hadj-mabrouk@univ-eiffel.fr

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Chapter 5

High-Speed Railway: A Catalyzer for Increasing the Tourism Activity and Income – Evidence from Turkish High-Speed Railway

Ahmet Baş

Abstract

High-speed railways are one of the main transport modes of the twenty-first century that change trip behaviors. Türkiye is one of the advanced countries using and producing high-speed trains and technology even the country started to improve them during the twenty-first century. This chapter will focus on the Turkish HST system in terms of how it contributes to tourism activity and income level as well as accessibility and convergency. Currently, Turkish HST serves 30% of the country's population. As time goes when the whole HST planned lines are constructed it will cover almost four over five of the population. So, tourism activities will be positively satisfied by this investment. Besides, the cities' accessibility will increase by reducing travel time; thus, people will access the service units easily. It helps to converge the income level.

Keywords: high-speed railway, tourism, accessibility, income, convergency

1. Introduction

Construction of high-speed trains (HSTs) first started with the Olympic Games in Japan in 1964, and the HST lines developed in the European continent after 1980; the construction continued in countries such as Türkiye, China, and India as they called economically developing countries at the beginning of the new millennium. HST, as a mode of transportation, is a comprehensive implementation tool that has different effects in many areas such as social, economic, cultural, and service deliveries. According to the data of the International Union of Railways, as of 2022, 58,839 km of HST lines are in operation in the world and a line of 19,710 km is under construction.

About 1.052 km HST lines between Ankara-Eskişehir, Ankara-Konya, Ankara-Istanbul, Konya-Karaman, and Ankara-Sivas cities were either constructed as a new line or rehabilitated from conventional lines between 2003 and 2023 in Türkiye; besides, construction continues for the Ankara-İzmir line. With the lines to be built by 2030, it will be possible to travel from eastern to western Türkiye by HST.

HST services have effects on social, demographic, and economic areas in different components such as time, space, and cost; therefore, it stands out as an important service supplier tool for the tourism sector and tourists, especially with the saving of time that it provides.

This chapter aims to point out the effects and potentials of HSTs on accessibility and tourism through existing and planned HST lines. While the effects of HST on tourism are mostly studied in economically developed countries such as Japan, France, Spain, and Germany, there has not been enough work in this field in Türkiye, and analyses and models for the effects of HSTs have not been produced at the desired level. In this respect, the study is going to be a preliminary work in Türkiye.

With the study, evaluations were made by using qualitative and quantitative data analysis processes on the outputs produced for the travel demands and tourism effects of HST services at the country and regional scale. The study figures out that HST service increases interregional accessibility in Türkiye and HSTs will contribute positively to the formation of alternative tourism routes in Türkiye in the long term and they will increase the income obtained from the tourism sector.

2. Literature review and methodology

Rus and Inglada [1] stated that HST may have negative effects on spatial inequalities, and because of their study on the Madrid-Barcelona line in Spain, it was stated that very detailed quantitative studies and in-depth analyses should be carried out in the process of determining the routes of HST lines. Otherwise, it was pointed out that HST service may bring different social and economic problems, as in the example of Spain, and this situation may negatively affect the development differences between regions [1]. Cascetta *et al.*'s [2] recent study on HST lines serving in Italy also revealed similar results. It is observed that HST lines increase economic growth in the areas where they are built, while they also increase accessibility with time savings, and that relatively less economic growth is achieved in cities outside the network due to the polarization they create on the routes where the line passes [2].

Blum *et al.* [3] conducted a study that evaluated the economic effects of HST on different sectors and travel demands in the short, medium, and long term. In the study, it was stated that there would be an increase in demand for consumption in the short term due to time savings in cities integrated with HST, and this situation would create a corridor effect. It was stated that HST would cause a movement in different economic activity areas and real estate prices in the medium term. Passengers would be able to move their work and living areas to the region they want on the HST line thanks to the relative spatial independence they would gain to live in the place they want thanks to time flexibility. In the long term, it is predicted that cities will specialize in certain areas, and this will contribute to the development of the regions. At this point, the high increase in transportation costs over time makes the savings in time less effective. The stagnation or decreasing trend in transportation costs, on the other hand, provides great flexibility in travel and life standards together with savings in time and increases the welfare level of people [3].

Gutiérrez [4] stated in his study that the HST service has different effects on accessibility at the country, region, and local levels. He pointed out that especially because the high-income level group benefits more from the HST services, there is polarization between regions and the development level increases faster in regions where the HST line is located compared to regions without HST lines. In addition, he

demonstrated with quantitative data that HST also increases access to services at the local level [4]. When its effect on the interregional development level is evaluated, it is predicted that a correctly designed and planned HST service will increase access to interregional services.

One of the studies that have been put forward regarding the fact that HST increases regional imbalances is the study conducted by López *et al.* [5] in Spain in 2008. The study states that HST increases imbalances in cities outside the HST system due to the corridor effect that creates between regions, while in cities where the line is connected, economic development is high due to increased accessibility [5]. Litman's study reveals the multidimensional effect of HST on spatial inequalities and states that transportation services have an important function in the evaluation and solution of regional imbalances [6].

The study conducted by Shaw *et al.* in 2014 reveals the striking effect of the ticket price policy and the frequency of trips on accessibility in the HST service. It is revealed that a ticket policy that can be preferred by passengers with different economic levels changes the frequency of use of the HST and travel behavior. In addition, the flexible schedule of the frequency of trips depending on the demand and the frequency of the trip times increases the economic concentration in the areas where the HST service is provided and makes it possible to access social services. The study reveals that the increases in ticket prices restrict access to the HST and that it is used by people with high-income level groups [7].

The provision of HST services and their accessibility for different users are directly related to the ticket price policy. The study conducted by Bouf and Desmaris [8] in France reveals that although HST services increase accessibility, they are not accessible to all segments due to high ticket prices. For this reason, the ticket price policy should inevitably be subsidized to increase the use of HST services and at the same time to appeal to different income levels [8].

Access to HST stations stands out as an important area of study in railway networks and spatial equity. Kasrian *et al.*'s [9] study of the Randstad region reveals that HST stations are an important component in the distribution of functions and the formation of spatial patterns within a certain area (1–5 km diameter) [9]. Zhang *et al.*'s study in 2016 includes striking results regarding the accessibility of HST stations operating in China. The integration of HST stations with urban transportation systems increases the service's area of influence and contributes positively to interregional accessibility with time savings. Thus, services in different cities become available to different users due to increased accessibility. This situation also positively affects spatial equity [10].

HST stations not only contribute to transportation services in the region where they are built but also lead to the appreciation of the lands around the station. Many local service offices reduce transportation costs by choosing locations around HST stations and stops, contributing to the development of the region [11, 12]. The accessibility of stations and stops in HST services directly affects the usage status of the service. At this point, Loukaitou-Sideris *et al.* reached the following conclusion in the study conducted on three different components: Spatial connections, integrated transportation systems, and operational connections directly affect the usage and accessibility of HST services [13].

In an early study conducted by Hwan on the effects of HST in South Korea, it was stated that HST increased accessibility in South Korea, as in other countries, thanks to the time savings it provided, supported decentralization in spatial location selection thanks to the time flexibility it provided to passengers, and prevented congestion in big cities [14].

Kim and Sultana [15] figured out in their study, which measured the contribution of the HST to show the status of spatial imbalances through accessibility, important outputs for South Korea. It was calculated quantitatively how the HST line affected the accessibility of the regions through weighted average travel times. As a result of the study, it was stated that the economic development level of the routes through which the HST line passes, including Seoul, had higher growth rates due to increased accessibility, while the economic development level in the cities outside the HST line was slow and this situation increased polarization in different regions [15]. A similar study on the effect of the HST on migration movements in South Korea was conducted by Chung and Lee [16]. This study also shows that the HST has a significant effect on the formation of business trips toward big cities and home trips toward the city periphery in migration movements [16].

Brunello's study in 2018 reveals that the rehabilitation of conventional train lines and the start of the HST service on these lines increase accessibility. Thus, the service area of the HST service is expanded, and more passengers can benefit from the HST service. In addition, the polarization effect that has emerged in different studies is reduced by expanding the service area thanks to the integration of HST with conventional lines [17].

The HST lines built in China have fundamentally changed the country's transportation system. In this context, the study by Yang *et al.* [18] reveals the different effects of high-speed railways in China on spatial equality by increasing accessibility. In the study, it was stated that while the accessibility of regions increased by integrating with high-speed railway lines, the spatial imbalances of cities that were not integrated with high-speed railway lines increased. One of the factors in this situation is the migrations that occurred due to high-speed railways. Due to the increase in spatial accessibility of high-speed railways, people migrate to cities on this route, and this creates a situation against cities without railways [18]. Besides, the HST network has a significant impact on tourist firms in Chinese cities. Particularly small and medium firms are affected positively by the lines [19]. Winter-snow tourism benefits from the HST network in Northern China. Shorter travel times changed the spatial distribution of ice-snow tourist destinations and increased the number of tourists. Moreover, day trips and weekend trips increased in the lines due to the promotion of tourism-economy linkages [20, 21].

The study conducted by Delaplace [22] is an important resource for developing countries where there are limited academic studies in the field of the socioeconomic impacts of HST. In Morocco, the only African country where HST operates, passengers from different economic groups can benefit from HST services thanks to the subsidized ticket price policy implemented to facilitate access to the service for people from different income groups. This situation enables convergence between regions with different socio-economic development levels [22].

The study prepared by Pagliara *et al.* [23] shows that various factors affect a tourist's choice, such as the presence of architectural sites, the promotional quality of the routes, the presence of events, and the HST services. However, it has been determined within the scope of the study that the HST system affects the choice of two different cities, Paris and Madrid, in different ways. Regarding the France case study, HST is considered as a real transportation mode alternative among tourists and therefore, HST is chosen both to reach Paris and to revisit Paris. On the other hand, Madrid is chosen by tourists regardless of the presence of HST, while HST is used to reach cities close to Madrid [23].

Bazin *et al.*'s study on France shows that HST supports short-distance daily tourism activities and strengthens transportation connections [24]; Jou and Chen's study on

Taiwan shows that HST affects the tourism market for touristic areas [25]; Delaplace *et al.*'s study on Disneyland Theme Park in France shows that HST directly affects tourists' travel choices positively [26]; Giurao and Soler's study shows that HST provides positive contributions to the tourism potential of small and medium-sized cities in Spain [27].

The study by Albalade and Fageda also shows that the HST service in Spain negatively affects air transportation from other modes of transportation, while it contributes positively to tourism [28]. The positive relationship between HST and air transportation is shown in the study by Campa *et al.* [29]. In this study, the effect of HST shows different effects according to regions, characteristics of museums, and expected tourists. In Spain, a positive effect is more pronounced for destinations that have previously had cultural appeal, and in addition, the centrality of the HST station is shown as a facilitating factor, as well as the growth of the tourism market to surrounding cities. Another interesting result of the study is related to the cooperation effect between HST and air transportation, which encourages the arrival of foreign tourists [29].

In a study conducted on the accessibility of HST in Türkiye, it was determined that the service made a positive contribution to tourism and made daily trips possible due to the time savings provided by HST between Ankara and Konya [30, 31].

The analytical study conducted by Pagliara *et al.* [32] to measure the impact of the recently operating HST lines in Italy on tourism contains important results. The study, which established a relationship between tourists and HST preferences with the regression tree method, revealed that HST made a positive contribution to journeys due to the time savings it provided [32]. In another study conducted by Pagliara and Mauriello [33], the positive contributions of HST to the tourism sector were determined by regression analysis [33].

In the study prepared by Chen and Haynes [34], it was shown that real estate values increased positively in small- and medium-sized cities where there are HST stations, while the effect of HST remained at a lower level in metropolitan areas compared to other cities [34]. The reason for this situation is seen as the high accessibility of metropolitan areas and the presence of different economic sectors in these urban agglomerations. In small- and medium-sized cities, HST service increases the accessibility of cities and contributes positively to the selection of new job opportunities in the city and the formation of economic activity areas. Thus, the effect of HST in small- and medium-sized cities is greater compared to metropolitan areas.

The study conducted by Kurihara and Wu [35] to measure the contribution of Shinkansen HST lines operating in Japan to the tourism sector contains important results. The research, which also includes fieldwork, evaluated the effects of HST on tourism in Japan through data such as tourist numbers, bed capacity, overnight accommodation rates, and tourist spending levels. According to the results of the research, HST has a significant positive impact on tourism, tourist numbers, overnight accommodations, and spending amounts [35].

The results of the study conducted by Pagliara and Mauriello [33] to determine the impact of the HST lines operating in Italy on tourism contain quite striking results. In the study, the impact of the HST line on tourism is measured with the Poisson model based on geographically weighted regression analysis. In this study, the dependent variable is the number of domestic and foreign tourists, while the independent variables consist of variables such as the HST line, the shares of cities in the gross domestic product, the number of tourist places, and the sea neighborhood. In addition, crime rates were also included in the study as an independent variable [33].

Firstly, to determine the effects of HST on access to services, data on basic service levels such as population and tourist numbers of the provinces were obtained from institutions such as the Turkish Statistical Institute (TurkSTAT) and the Ministry of Tourism and Culture. In measuring intercity distances, the transportation network of the General Directorate of Highways was used for highways, the railway network of Turkish State Railways (TCDD) for railways, and the databases of the State Airports Authority for airways. Travel data was also compiled from the official statistics portals of TurkSTAT, and the institutions explained above. In addition to these, other geographical spatial and statistical numerical data were collected from the TurkSTAT, the Statistical Yearbooks of the Republic of TCDD, and provincial governorships.

The study level of relationship is measured by comparing tourism data with transportation data over the years in terms of provinces. Besides, the data are processed spatially, and a distance-sensitive relationship network is examined.

3. High-speed train and tourism in Türkiye

3.1 High-speed train in Türkiye

HST services have been actively developed and constructed in many countries, which reduce travel time, stimulate positive economic activities, and encourage the growth of tourism.

By the year 2003, Türkiye accepted the Transportation Strategic Plan and Türkiye has made significant strides in developing its high-speed train network, which plays a crucial role in connecting major cities and enhancing the country's transportation infrastructure. According to the plan, Türkiye started to construct the HST lines from Ankara to Eskişehir in 2006. As time goes, Ankara-Konya, Ankara-İstanbul, Konya-Karaman, and Ankara-Sivas lines were constructed. By the year 2023, 1241 km of lines were constructed, and 30% of the total population had access to the lines (**Table 1**).

HSTs have a considerable impact on economic activity areas such as transportation, construction, services as well as tourism sector by transforming how people trip and experience destinations. These impacts could be arranged under some titles in terms of tourisms such as accessibility, boosting local and regional tourism, enhancing multi-destination travels, making comfortable journeys available for passengers, increasing event-based tourism activities, and allowing cultural exchange either in countries or between the countries (**Figure 1**).

HSTs make regions more accessible by reducing travel time between cities and regions. It allows tourists to visit tourist areas and destinations that were before considered too far or time-consuming to reach. For instance, passengers travel between Konya and Ankara by bus or private car prior to the opening of the HST line, with 70% made by bus and 29% by car, and less than 1% by air¹. Ankara-Eskişehir journeys had similar rates before HST line was constructed, even though there is a conventional train line between Eskişehir and Ankara that carried 8% of the traffic prior to the opening of the HST line [30]. However, after HSTs, due to time reduction, traveling is easy from one destination to another in a short time. For example, travel time is reduced between Ankara-Konya line from 3 hours 30 minutes to 1 hour 15 minutes. It is the same in Ankara-Eskişehir line. As clarified in **Table 2**, the trip mode distribution changes significantly in favor of HSTs. Besides, the journeys are safe and

¹ There is no direct flight between Ankara-Konya, exchange in Istanbul.

	HST in operation	HST U-construction	HST planned	HST total	Türkiye
Population (2023) (000)	29,744	8,529	26,720	64,994	85,372
Length (km)	1241	1,743	1,000	3,984	3,984
Ratio (%)	35	10	31	76	76

Source: Author, based on Refs. [36–38].

Table 1.
 Population, length of HST lines, and the ratio of covered population by HST lines in Turkey.

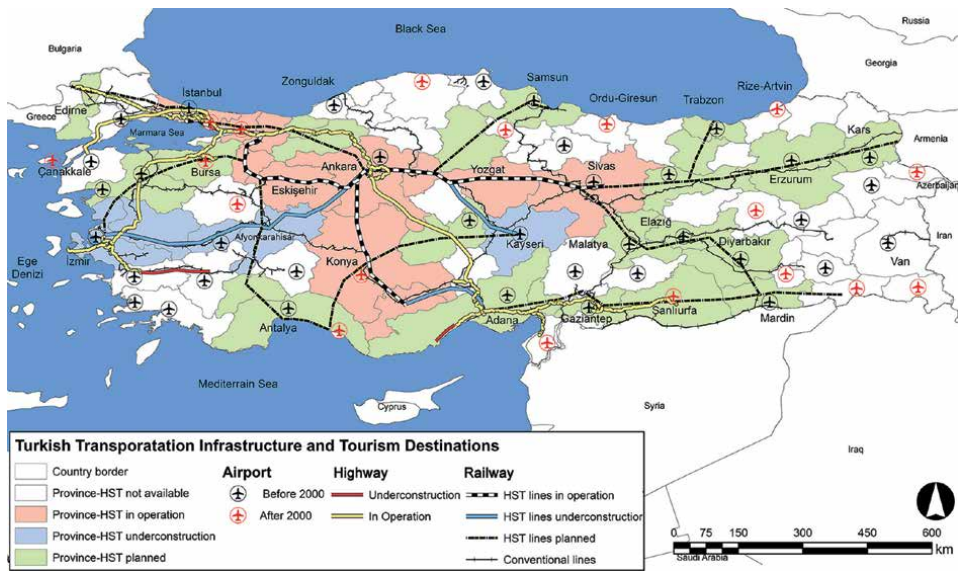


Figure 1.
 Türkiye’s transportation infrastructure and tourism destinations. Source: Map drawn by author based on Refs. [38–40].

Transport modes	Ankara-Eskişehir (%)		Ankara-Konya (%)		Ankara-İstanbul (%)		Konya-İstanbul (%)	
	Before	After	Before	After	Before	After	Before	After
Bus	55	10	70	17	30	22	50	30
Private car	37	18	29	17	35	33	35	31
Train/HST	8	72	—	66	10	15	5	17
Airway	—	—	1	—	25	30	10	22

Table 2.
 HST lines and transportation mode distributions based on 2010–2013 years [41].

comfortable compared to other transportation modes. Increasing accessibility also boosted tourism activities, industries, and tourist numbers not only in metropolitan areas but also in small towns and cities (Table 3). Therefore, small towns and cities benefit from the economic distribution of tourism activities. It helps to increase

Province	Total population	HST	# Tourist (2023)	# Tourist (2010)	Ratio (%O)
Afyonkarahisar	751,344	HST under-construction	753,292	240,918	2.13
Ankara	5,803,482	HST in operation	3,491,749	1,370,326	1.55
Bilecik	228,058	HST in operation	120,315	22,425	4.37
Eskişehir	915,418	HST in operation	537,298	171,438	2.13
İstanbul	15,655,924	HST in operation	13,212,666	4,641,209	1.85
İzmir	4,479,525	HST under-construction	3,293,030	1,305,486	1.52
Kayseri	1,445,683	HST under-construction	501,843	154,999	2.24
Kocaeli	2,102,907	HST in operation	1,015,929	156,639	5.49
Konya	2,320,241	HST in operation	1,040,179	408,696	1.55
Manisa	1,475,716	HST under-construction	474,201	116,053	3.09
Sakarya	1,098,115	HST in operation	588,007	14,090	40.73
Sivas	650,401	HST in operation	272,594	62,203	3.38
Uşak	377,001	HST under-construction	107,680	34,201	2.15
Yozgat	420,699	HST in operation	117,966	35,362	2.34
Karaman	263,960	HST in operation	109,800	13,023	7.43
Kırıkkale	285,744	HST in operation	64,013	1396	44.85
Türkiye	85,372,377		77,298,091	29,760,683	5.39

Source: Author, based on Refs. [37, 38, 40].

Table 3.

HST lines (in operation and under construction), tourist numbers, and exchange of tourist numbers based on 2010–2023 years.

the local commerce and income level for inhabitants. For example, İstanbul is one of the unique and attractive historical cities all over the world. Millions of people visit the city every year. HST allows people who visit the city, to go to different cities located on the HST lines such as Eskişehir, Konya, and Sakarya.

HST service can revive economic growth in the tourism sector, leading to the development of hotels, restaurants, and other tourist services in areas connected by HST. Moreover, HSTs encourage cultural exchange. Tourists can easily experience different cultures, languages, and traditions within a short time.

Ankara-Sivas HST line became in operation in 2023. This line also points out that HST is a catalyzer for tourism activities due to increasing accessibility (**Table 3**). All in all, HSTs play a critical role in designing the current tourism sector and economic activity areas by making travel faster, safer, more comfortable, and more sustainable.

3.2 Tourism in Türkiye

The tourism sector is an important economic component that contributes positively to the cash capital flows and employment capacities of countries under the title of the service sector. Even though it was interrupted for a while because of the pandemic, the tourism sector has experienced a revival in the world and Türkiye after 2021. According to TurkSTAT [42], Türkiye has earned approximately 30 billion dollars in revenue from tourism. In addition, the number of visitors has

increased by 85% compared to 2020, exceeding 30 million. There are different components such as alternative tourism destinations, strong transportation connections, quality of service delivery, and price advantages increasing the number of visitors and income in tourism sector.

Türkiye has many natural and historical sites all around the country. These sites protect not only for their nature and beauty but also for their economic potential. Millions of tourists visit these sites every year and they pay billions of dollars. So, these sites are very critical for increasing the tourism income. Many studies [43] demonstrate that transportation infrastructures, especially roads, damage too many natural and historical sites as well as human health. Profillidis *et al.* study points out that the transportation sector has a negative effect on the natural environment. Besides, the sector also enhances the reduction of environmental conditions in terms of nature and built sides [44]. Skrucaný *et al.* figured out that the railway mode has the lowest ratio in terms of emissions that damage the nature and built environment [45]. So, Turkish HST will preserve the natural and historical sites by increasing the accessibility to these sites.

The travel cost is one of the main inputs for the tourism sector and affects the tourist behaviors either positively or negatively depending on to cost. Turkish HST lines are one of the cheapest lines in the world [46]. So, HST lines engage in tourism, and by reducing travel time, they improve the sector in terms of economic activities as well as improving the accessibility of tourist areas. Moreover, the development of the tourism sector is positively correlated with the development of the HST networks.

Tourism centers and destinations get a share of the tourism pie according to the historical and cultural values, important social organizations and spatial patterns, and alternative service presentation opportunities such as congresses, fairs, and exhibitions. At this point, the choices of centers or destinations by tourists vary according to their attractiveness, presentation methods, and accessibility [47]. As a result, the primary factor affecting the travel preferences of tourists is the accessibility of the focus or destination utilizing transportation types. Focus and destinations with high accessibility levels employing different transportation types are preferred more and get a larger share of the tourism pie.

With the inclusion of new modes of transportation in spatial organization, the tourism potential of the regions also participates in economic activities and develops depending on the increased accessibility. When the accessibility of inactive tourism areas is provided due to a lack of transportation connections, a great tourism movement takes place in the region [48]. This circumstance helps the regions to increase their capacity and income level. As is seen from **Figure 2** all the provinces that either consist of HST lines or are under construction have benefited from the tourism activities for the last decade. For instance, Konya is one of the cities that started to use HST lines by the year 2010. HST makes the city more attractive for tourists who want to visit Mawlana Celaleddin Rumi Museum, which is a very important Sufi and scholar all around the world. According to the TurkSTAT data (2024), more than one million people visit the city. Without HST, nearly four hundred thousand people visited the Museum in 2010. However, this number has increased over the last decade and makes it over one million people by the year 2023 [37]. It is almost similar in Sivas province. HST line starts its trips in 2023 between Ankara and Sivas provinces. In **Table 2**, according to the Ministry of Culture and Tourism (2024), Sivas tourist numbers triple from 2010 to 2023. Particularly, tourist numbers increased much in 2023 due to HST connection to İstanbul *via* Ankara [40]. So, tourism activities increased; thus, the tourism sector benefits from this increase. Besides, the income ratio also changes positively due to opening new economic activity areas such as hotels, dining, restaurants, and guidance.

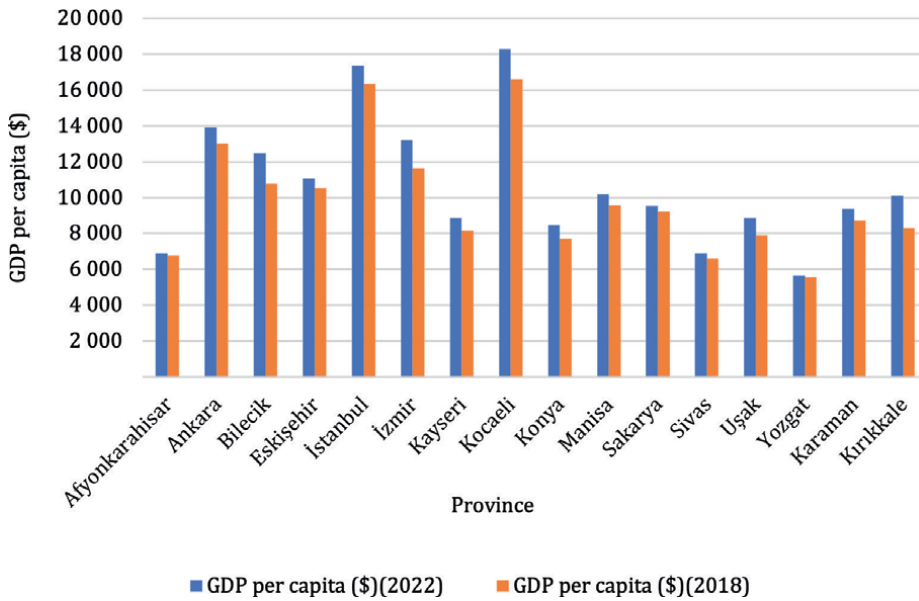


Figure 2. Changing of GDP per capita based on 2018–2022 years and HST lines province [42].

4. Limitation and conclusion

This chapter tries to identify the characteristics of the Turkish HST network from the point of accessibility and tourism impact. One of the interesting views of this study, it is the first time that a paper explores Turkish HST in terms of its relationship with accessibility and tourism. In the beginning, the study focused on the link between HST and tourism by a general literature review on HST lines in the world. It considers that building the HST line encourages the tourism sector by reducing time and enhancing accessibility, and comfortable and safe travel.

According to the chapter’s results, the tourism sector benefits from HST lines. Particularly small- and mid-towns enhance from the lines more due to their lack of capacity. HST also improves the tourism capacity such as bed capacity and hotel numbers, by increasing tourist numbers. This is also an interesting output for Turkish cities.

It is obvious that HST projects would be one of the main transportation modes soon after they are fully capable of their capacity and integrated with other modes in Türkiye due to its capacity and covering almost 75% of the total population. The integration of HSTs with other transportation modes would enhance mobility and accessibility between cities, regions, and countries. The Turkish case shows that HST can be considered a valid transportation mode for developing countries, enhancing both mobility and communication, increasing social interactions and activities, and serving as a tool for the tourism sector. Besides, concerning environmental conditions, HST has more advantages compared to air travel and road transportation due to less pollution and less damage to historic areas. Moreover, it reduces time travel over certain distances with comfortable and safe vehicles.

Turkish HST network has played a critical role in increasing tourist numbers by making travel more convenient, diversifying multiple destinations, and encouraging

regional tourism. This has had a positive impact on both domestic tourism and international tourism, contributing to the overall growth of the tourism industry in Türkiye.


For future studies, after new lines and cities are added to the HST network, it would be clearer to understand how HST lines affect the economic activity areas partly the tourism sector. Particularly, the provinces located in the eastern and southern of Türkiye have big potential for new destinations. So, the main question arises, how will these new routes affect the Turkish tourism sector? Besides, will HST costs still be cheap, or if the prices increase how tourism sector be affected by this new condition?

Author details

Ahmet Baş
Abdullah Gül University, Kayseri, Turkey

*Address all correspondence to: ahmetbas@agu.edu.tr

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Chapter 6

Planning for Wildlife Corridors in the Area of Railway Infrastructure: A Case Study in Slovenia

Samar Al Sayegh Petkovšek

Abstract

Rail transport affects wildlife by creating barriers to their movement, commonly known as the “barrier effect”, and by directly increasing mortality due to collisions with trains. We addressed this issue by preparing a proposal for a protocol designed to ensuring wildlife migration corridors in the area of railway infrastructure and by presenting an overview of mitigation measures and examples of good practices to minimize barrier effects and decrease railway mortality. The protocol was based on findings from relevant scientific literature, on our own experiences, which we gained from planning and monitoring measures to reduce the run-over of wildlife (especially ungulates) on roads and highways, and from studying wildlife train collisions in the area of the Slovenian railway infrastructure in a selected five-year period. With the proposed protocol, we try to unify approaches to improve the methodology for assessment of the impact on wildlife and to obtain the most realistic and comparable results on local, regional and national scales. The proposed protocol will benefit stakeholders, who are involved in the planning, design and construction of new railway lines or the modernization of existing ones, and other stakeholders, who are involved in the environmental assessment process before a decision about implementation is made.

Keywords: wildlife corridors, railways, protocol, mitigation measures, barrier effect, wildlife-train collisions

1. Introduction

Rail transport, which is becoming an increasingly important land transport system, is generally assessed as more environmentally acceptable, especially compared to road transport. The following differences are the most important: (i) railway traffic flow is much lower and characterized by long traffic-free intervals; therefore, lower wildlife mortality is expected; (ii) railway corridors are narrower compared to road corridors, which affects the smaller loss of species’ habitats when new railway lines are built; (iii) the pollution caused by rail transport is lower compared to road transport; especially since many train sets have electric locomotives [1–4].

However, it should not be neglected, that railways can adversely affect wildlife by creating barriers to their movement, commonly known as the “barrier effect”, and by directly increasing mortality due to collisions with trains. The latter can affect

population dynamics and may threaten species survival [1, 4–10]. Train collisions with larger mammal species are an important factor in the mortality of ungulates and large carnivores (especially bears) [8, 11–18].

Habitat loss due to the railway infrastructure and its impacts is also one of the main impacts on wildlife [1, 4, 7]. Dense railway networks fragment habitats into smaller, often isolated habitat patches, which can hinder the passage of individuals between them and consequently limit gene flow. Hence can lead to the endangerment of species and/or even their extinction [4, 7, 9, 10]. For that reason, it is essential to plan and implement mitigation measures to establish ecological connectivity and reduce wildlife mortality on railways. The latter is especially important in the areas of wildlife migration corridors and important habitats of endangered species (e.g., Natura 2000 areas, protected areas).

The purpose of this chapter is to present the most important findings from review works (e.g., handbooks and guidelines) that describe mitigation measures to reduce the negative impact of linear infrastructure, including railways [9, 19–22], and studies that focus on measures and examples of good practices only in the area of railway infrastructure, where a book entitled “Railway Ecology” is to be highlighted [1–3, 14, 23–29].

Furthermore, we presented a proposal for a protocol designed to ensure migration corridors in the area of the railway infrastructure. The protocol was developed based on findings of the above-mentioned literature and our own experience, which we gained from planning and monitoring measures to reduce the run-over of wildlife (especially ungulates) on roads, expressways and highways [18, 20, 30–32] and from studying wildlife train collisions (WTC) in area of the Slovenian railway infrastructure in a selected five-year period [18, 33].

2. Review of mitigation measures and examples of good practice

Mitigation measures along the transport infrastructure (roads, railways) can be divided into two basic types: (i) mitigation measures that increase the connectivity of wildlife populations (bridge structures, crossings), and (ii) measures that increase the safety of road users and reduce the number of animal collisions (safety fences, deterrents, management of habitats and animal populations around railway lines, reduction of train speeds, adaptation of infrastructure) [19, 20, 22, 34].

In practice, the division between these two groups of mitigation measures is often unclear. Measures can fulfill both objectives but also have negative impacts. Such an example is exclusion fencing next to line infrastructure, which although successfully reduces the number of collisions with larger species of mammals, but at the same time increases the fragmentation of space. Fences are an effective and suitable mitigation measure only in combination with wildlife crossings, which compensate for their negative barrier effect, or contribute to the maintenance of habitat connectivity [4, 35]. Besides basic mitigation measures we focus on good practices (e.g., warning systems), which can be important for solving these issues in the future [25, 27, 28].

2.1 Mitigation measures for ensuring ecological connectivity

Mitigating measures and especially bridging facilities (crossing structures) are necessary when linear infrastructure cannot be placed in a space in a way that would not affect the lifestyle or spatial habits of wild animals. The placement of bridging

facilities maintains habitat connectivity by enabling wildlife migration corridors to be passable, while also contributing to the reduction of mortality due to animal collisions with trains [2].

Animals use purpose-built bridging facilities or other facilities (e.g. drainage culverts, viaducts, bridges, tunnels) that cross railways. The latter can be adjusted (e.g., placement of shelves, allowing for natural vegetation and soil) and thus increase their usefulness; such a solution is also more cost-effective. Of course, dedicated bridging facilities, which are placed during the construction of new railway lines, or when upgrading old ones, are the most suitable from the point of view of ecological connectivity. Barrientos *et al.* [4] emphasized that the more similar to natural habitat a crossing structure is, the more effective will be. Design, technical characteristics, location and frequency of crossing structure allow the passage of different species or groups of animals and preserve the ecological connectivity of the area [19, 22, 30, 36, 37]. Detailed technical prescriptions for the design and recommendations for the enhanced effectiveness of measures for wildlife crossings across linear infrastructure, which are reviewed in Refs. [19, 22], are relevant for railways as well.

2.2 Measures for decreasing wildlife mortality due to collisions

2.2.1 Fences and physical barriers and structures

Fences are effective in preventing vehicle collisions with wildlife, especially on expressways and highways [19, 22, 38]. In the area of railway infrastructure, they are generally not cost-justified, as collisions with trains mean (too) little risk for people [14, 27, 39]. Therefore, it makes sense to install fences only on sections of railway lines with a very large collision rate; in some places, they are installed on sections where high-speed trains run [4]. At the same time, some other conditions must be met (e.g., placing in relation to wildlife passages; a sufficiently large length of the fence), which enable the neutralization of the barrier effect caused by the protective fence. Moreover, maintenance of fences is required. Above all, fences must be combined with wildlife passages to which the fence directs animals [4, 19, 22].

Other physical barriers and structures (e.g., trees, diversion poles) can contribute to reducing animal mortality, especially birds and bats [24, 40, 41]. Pole poles are a cost-effective measure to direct medium and large birds away from railway infrastructure. Trees can prevent access to the railway, however, is necessary to plant or maintain trees with high canopies so that birds and bats can stay and fly high enough. On the other hand, planting with vegetation can shape and create an attractive habitat for others and direct them closer to railway lines. Consequently, their mortality may even increase [42, 43].

2.2.2 Artificial deterrents

Artificial deterrents (chemical, light and sound deterrents) are aimed at reducing collisions with wildlife (especially ungulates). Chemical deterrents (olfactory repellents) are mainly intended for herbivorous ungulates. They are natural or man-made substances that are usually a mixture of human and wolf scents and the scents of other predators and are mixed into a foam that triggers the anti-predator withdrawal response of the prey species. This is a carrier material that is applied to trees, stakes

or other places along the railway line. The purpose of chemical deterrents is to deter animals from crossing the railway line; however, their effectiveness is questionable [24, 25, 44].

It is also possible to use light deterrents; however, they have been mainly tested on roads [20, 36, 45, 46]. On railway lines, the light reflectors can be activated by the train's headlights, or a light warning can be triggered even before the arrival of the train. Jasinska *et al.* [29] tested light deterrents (red wildlife warning reflectors) installed on both sides of railway tracks (2.1 km) at a distance of 3 m from the tracks for eight months, in the years 2010–2011. For part of the period, the light deterrents were inactive (covered). The animals' behavior was monitored using digital cameras installed on electric poles along the railway lines. The influence on the reaction of animals (roe deer (*Capreolus capreolus*), red fox (*Vulpes vulpes*), brown hare (*Lepus europaeus*)) was not observed in the presence of an oncoming train. The mean escape time of roe deer was 4–7 seconds and did not vary with time of day or activity of light deterrents. Based on the results of the research, they concluded that light deterrents (red reflectors) do not modify animal behavior, when a train is approaching, and that they are not an effective measure for mitigating collisions on railways [29].

Sound (acoustic) deterrents can be a good alternative to fences, especially since they do not prevent the crossing of railway lines, but only move it to a safe moment (when there is no train nearby). The animal's sound warns of an oncoming train, and the sound barrier deters the animals from approaching the railway line. Systems can be installed in critical areas (sections) of railway lines. Deterrents can be activated (sound) at equal time intervals independently of an oncoming train or only when it approaches [23, 24, 26, 27].

In the past, a reduction in train collisions with moose (*Alces alces*) along railway lines in Canada was found when trains were equipped with an ultrasonic wildlife system [47]. Babinska-Werka *et al.* [23] investigated the effectiveness of sound deterrents installed along two sections of a railway line in central Poland (a total of 3.7 km protected). In the two selected sections, frequent crossing of animals over the railway line was previously observed. The sound of deterrents was combined with various natural sounds, such as warning calls or announcements of endangered animals (Eurasian jay (*Garrulus glandarius*), brown hare, domestic dog (*Canis familiaris*), wild boar (*Sus scrofa*), roe deer, gray wolf (*Canis lupus*)). At the same time, they continuously recorded the behavior of animals in the area of the railway infrastructure; roe deer, red fox and brown hare were recorded most often. The use of sound deterrents that were triggered automatically before the arrival of the train (30 seconds to 3 minutes), increased the proportion of animals that succeeded in moving away from the train tracks (84% vs. 68%); on average, they retreated about 20 s faster. They concluded that the animals did not get used to the emitted sound (habituation), as the proportion of roe deer that reacted to the sound of the deterrent remained the same in the first and second year of the research [23].

In Slovenia, the influence of sound deterrents on reducing the mortality of brown bears (*Ursus arctos*) was studied on selected two railway sections, where the increased number of collisions of this species was recorded [9, 48–50]. Sound deterrent devices, which emit ultrasound and infrasound and were equipped with sensors, which were activated for sound activation by an approaching train. They were installed on electric poles on the railway sections, where was a high probability of a collision between a bear and a train (**Figure 1**). Before the installation of acoustic deterrent devices (period 2011–2015), 15 bear deaths were recorded at both railway sections (total length of both sections: 8 km); annually between 0 and 8 (on average 3.0 per year;



Figure 1. Installation of acoustic deterrents on electric poles (left) and part of railway tracks with higher risks of collision with train (right) (foto: M. Zaluberšek, 2016 and K. Kotnik, 2020).

0.37 individual/km year). After the installation of acoustic deterrents on electric poles (period 2016–2019), the mortality of bears on those railway sections significantly decreased and was only between 0 and 2 individuals per year (average 1.0 per year; 0.12 individuals/km year), despite the fact that the bear population did not decrease during this period [51]. The provided data indicate the effectiveness of such measures.

2.2.3 Reducing train speed

Higher speeds are undoubtedly associated with higher risks of collisions with animals on railways [15, 17, 24]. Carvalho *et al.* [24] emphasized that reducing the speed of trains on critical sections and during the migration period of some wildlife species can significantly reduce collision risk, as fewer collisions are recorded with slower trains [52]. Bertwistle [53] found that reducing train speeds by 20 km/h (from 90 km/h to 70 km/h) on a railway line passing through a national park in Canada (Jasper National Park) contributed to a reduction in wapiti (*Cervus canadensis*) and some other species of larger mammals. Conversely, reducing train speeds on sections of the Alaska Railroad where concentrations of moose collisions (Susitna River Valley) were observed from 79 km/h to 40 km/h, had no significant effect on the reduction of moose mortality [54]. On the Hungarian railways, they analyzed data on wildlife train collisions over a ten-year period (2000–2010) and found that the increase in the average speed of freight trains (from 28.6 km/h to 42.2 km/h) had a significant impact on the increase in the run-over of larger mammal species (red deer, roe deer, wild boar) [15].

2.2.4 Habitat and wildlife population management

The number of collisions with trains is primarily influenced by the density of populations (especially ungulates) in the vicinity of railway lines. A smaller number of wild animals in the areas near the railway infrastructure (and thus lower mortality) can be achieved by regulating populations (e.g., culling), proper habitat management and supplemental feeding [24, 25, 30]. However, all these methods should be used with caution, since the reaction of wildlife on them is in general species-specific. For example, culling in the vicinity of railway lines must not cause additional stress to younger individuals, which are already basically exposed to youthful dispersion (spreading to new areas) and, as a result, to possible run-overs [25]. Removing

vegetation from the immediate vicinity of the tracks, can be useful measure for reducing collisions [25]; however, it is important also how often is carried out. In a study of the impact of removing vegetation on the number of train collisions in Sweden, it was found that if it is removed for more than three or four years, the number of collisions with ungulates increases due to a greater food supply [24, 55].

2.3 Alternative warning systems

An important study on the use of warning systems triggered by an oncoming train was carried out in the area of the Canadian Pacific Railway (the eastern section of the railway in the Banff National Park area), where collisions between animals and trains are frequent [16, 27]. Warning systems were installed at four locations along the railway line, which alerted the animals to the arrival of the train with light and sound emitted by the systems 30 seconds before the arrival of the train. The response of larger mammal species such as brown bear, American black bear (*Ursus americanus*), wolf, coyote (*Canis latrans*), elk, capybara, white-tailed deer (*Odocoileus virginianus*) and the response of smaller species were monitored separately, depending on the method of arrival of the train (straight or around a bend). They wanted to investigate, if the animals could learn and associate the warning with the arrival of the train and move away from the railway line in time. They installed cameras at the test locations and observed the response to the arrival of the train when the warning system was active or inactive (control). For larger mammals, flight responses were 62% earlier (17.0 s vs. 10.5 s), when the warning system was activated; smaller mammals, initiated flight responses 29% earlier (14.6 s vs. 11.3 s). The animals retreated faster, if the train was coming straight. It was summarized that train-triggered warning systems can reduce train collisions by increasing flight initiation time (especially for larger mammals). They also pointed out that a more invasive approach (fencing) may be needed to reduce collisions with large groups of ungulates (e.g., elk herds), which are so large that they would need more than 30 seconds to cross the railway line [27].

The importance of early detection and warning of ungulates was confirmed in Sweden, where they investigated the reaction of roe deer and elk to an oncoming train and the detection of animals by train drivers over a period of five years [28]. The behavior (flight response) of the animals was observed with cameras installed in the train cabin. They study how animals respond to an approaching train and the factors that limit their detectability by train driver. In most cases, roe deer and moose started fleeing from an oncoming train, at an average flight initiation time distance (FID) of 78 and 79 m, respectively. Warning horns differently influences on the flight behavior of roe deer and moose [28]. Earlier warning of a train, by use of warning horns, increased roe deer FED by 44 m, on average; but they usually fled towards the train (in direction of danger). The FID of moose was not affected by the use of warning horns. The speed of the train also had a different effect. As the train speed increased, the moose had a lower FID, but the roe deer FID did not change. The detection of roe deer and moose by the train conductors was hindered by the vegetation along the track and the shape of the terrain. The authors of the research emphasized that early detection and warning of animals reduces the risk of a collision. They suggested that detection systems should include thermal cameras to enable detection of animals in the dark; however, audible warning systems should be activated earlier to allow animals to move away from railway tracks in time/safely [28].

3. Protocol for the determination and implementation of measures for providing wildlife corridors

The placement of the railway infrastructure in the landscape must be planned in such a way that the barrier effect is reduced to the minimum possible extent and that provides wildlife migration corridors. The habitats of the species and the resulting spatial connectivity must be preserved to the greatest extent possible; the latter can be achieved by adjusting the route of the railway line, building bridging facilities, creating alternative habitats, etc. [9, 19]. Therefore, we designed a proposal for a protocol (**Figure 2**) for ensuring migration corridors in the area of the railway infrastructure in Slovenia [56]. We believe that the proposed protocol will be useful mainly for upgrading the existing Slovenian railway network, which is a priority for future investments of Slovenian Railways. Of course, it can also be beneficial in the process of planning and construction of new railway lines.

The phases of the proposed protocol are: (a) spatial analysis to assess the impacts of railway infrastructure on target wildlife species, including run-over analysis and identification of hotspots on selected sections of railway lines; (b) selection and planning of measures to ensure connectivity and reduce congestion; (c) implementation of measures (construction); (d) monitoring the effectiveness of measures during construction and operation of new or upgrade of existing railway lines. For the third phase, which is not presented in our chapter, it is recommended to perform under the supervision of an expert in wildlife and nature conservation.

The existing methodology in the EU (Directive 2001/42/EC), which is part of SEA (Strategic Environmental Assessment) and EIA (Environmental Impact Assessment), enables the assessment of the impact of new railway lines and modernization of the existing ones on the environment (including wildlife); however, the approaches are very different. With the proposed protocol, we try to unify approaches for improving methodology to obtain the most realistic and comparable results on local, regional and national scales. The proposed protocol will benefit all stakeholders, who are involved in the planning, design and construction of new railway lines or the modernization of existing ones, and all other stakeholders, who are also involved in the environmental assessment process before a decision about implementation is made (e.g., wildlife experts; decision-makers on national, regional or local authorities; non-governmental organizations).

3.1 Spatial analysis of study area

The spatial analysis involves assessing habitats and populations of target species, as well as considering the natural and socio-geographic features of the study area data by using geographical information system (GIS) and habitat suitability models [19, 56]. According to Potočnik [19] the following habitat suitability models for large mammal species can be used: spatial explicit habitat suitability model, models for the importance of habitat patches for joint connectivity, and line models of potential corridors.

If WTC data are available, they can significantly contribute to the assessment of the importance of the study area for ecological connectivity and wildlife migration. By overlaying data regarding the natural and socio-geographic characteristics of the area, characteristics of habitats and populations of target species, with spatial data on existing and future railway lines, we can identify sections that pass through ecologically sensitive habitats and determine locations where it is necessary to establish wildlife passages or/and implement other mitigation measures.

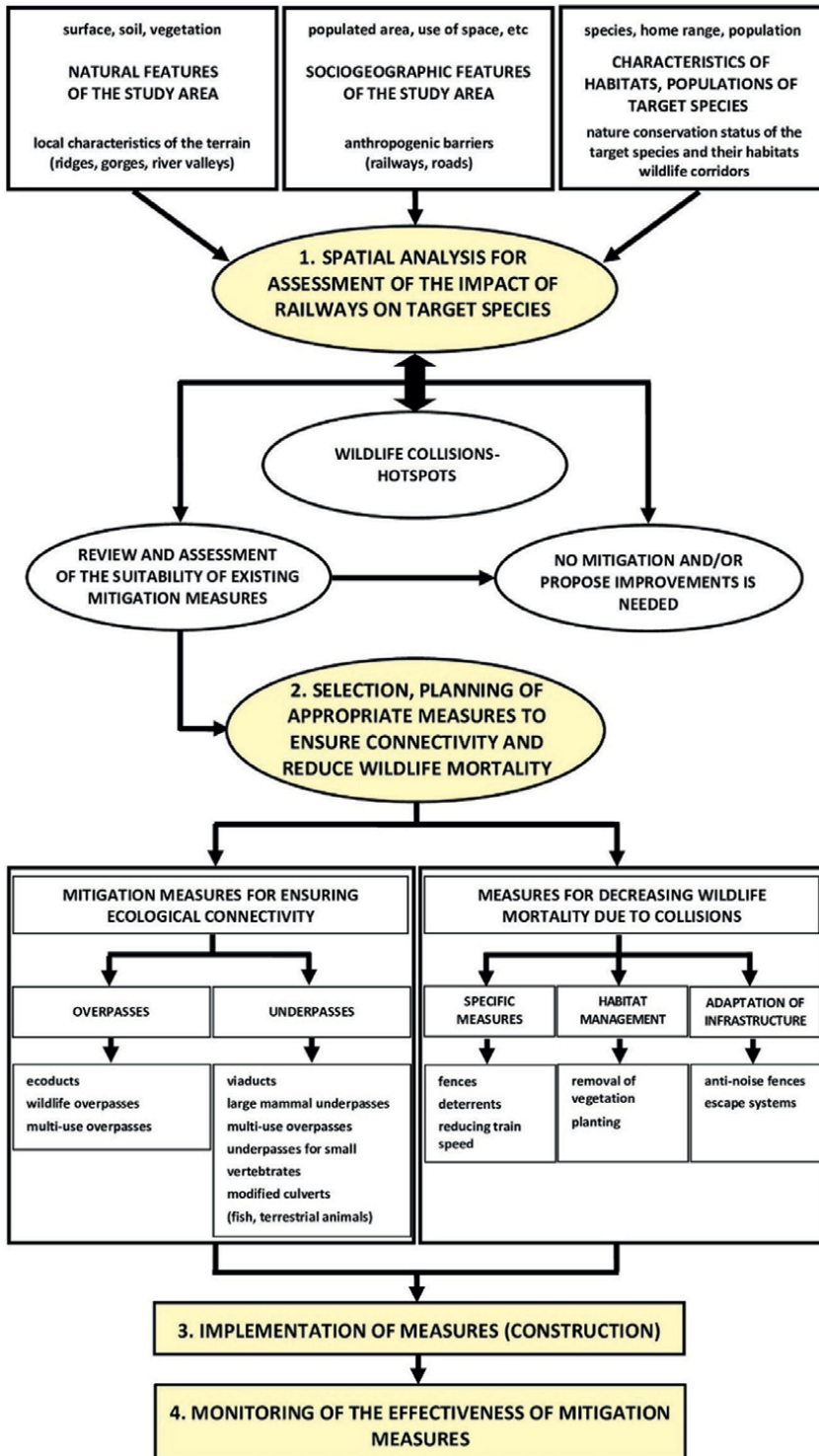


Figure 2. Protocol for decreasing of the railway barrier effect in area of Slovene railway infrastructure (adapted partly from [9]).

3.1.1 Analysis of natural and socio-geographic characteristics and habitats of target species of the study area

According to recommendations from the framework prepared by the *Ministry of Agriculture, Food and Environment of Spain*, when analysing a study area, it is important to focus on factors, which influence the connectivity of the space. The following factors are important: (i) presence of areas that enables the migration of wildlife; (ii) presence of areas where the movement of animals depends on the local characteristics of the terrain (e.g., ridges, gorges, river valleys); (iii) presence of watercourses that direct/funnel many aquatic and terrestrial animal species; (iv) presence of anthropogenic barriers (line transport infrastructure) and settlement, which reduce spatial connectivity (reviewed in [22]).

As part of the spatial analysis to assess the impact of the railway infrastructure on wildlife, it is necessary to identify the habitats of (target) species or taxonomic groups, such as: (i) species that require large and uninterrupted habitat: ungulates (e.g., deer, roe deer, wild boar) and large and medium-sized animals (e.g., brown bear, wolf, Eurasian lynx (*Lynx lynx*), Eurasian jackal (*Canis aureus*)); (ii) species with seasonal migration to breeding areas (eg amphibians); (iii) species that may pose a significant risk for traffic safety or collisions with them can cause significant material damage: all types of ungulates (especially red deer, European roe deer and wild boar) and brown bear; (iv) endangered species that are not included in the previous groups and are legally protected at the European and national level (e.g., bats, Eurasian otter (*Lutra lutra*), wild cat (*Felis silvestris*)) (reviewed in [22]).

For all the listed species or taxonomic groups, it is necessary to determine, whether the railway infrastructure has a barrier effect and increases mortality, reduces the quality of their habitats and the permeability of migration corridors. Knowledge of the biology of the target species or taxonomic groups (e.g., the size of the species' home ranges, migration, population density) is essential for this type of assessment [22]). Although all animal species are important, in certain areas, it is necessary to focus on only one target species or group of species. In such situations, it is possible to use more precise methods for analyzing the mobility of target species. The concept of model animal species (e.g., brown bear, red deer) is also useful, which are crucial for maintaining the ecological connectivity of space at different levels [9, 57, 58]. The nature conservation status of the target species and their habitats and protected areas (e.g., Natura 2000 areas) must also be considered when evaluating impacts [7].

3.1.2 Analysis of wildlife mortality on railways and identification of WTC hotspots

Adequate WTC data on railway lines passing through these areas can also play an important role in making decisions about planning mitigation measures. Data on wildlife train collisions of large mammal species in Slovenia can be obtained from the Central Slovenian Hunting Information System (Oslis) and the Register of train collisions of the Slovenian Railways. A comparison of registered WTC of four large mammal species (European roe deer, red deer, wild boar, brown bear) in those two databases in the selected years (2016, 2018, 2019) was done. We found that the Oslis database is more accurate as compared to a database of Slovenian Railways, where only 17–27% of roe deer, red deer and wild boar collisions, and < 50% of brown bear collisions were recorded [18]. Regardless, that we use a more accurate Oslis database, it is very likely that the actual number of wildlife collisions is even higher than the registered number, this is in line with studies conducted elsewhere [5, 24, 25].

As part of the study on providing wildlife corridors in the area of the Slovenian railway infrastructure [33, 56], we analyzed WTC along entire (1207 km) Slovenian railway lines (32 railway sections) in the period 2015–2019. In the five-year period we registered in total 838 train collisions with large and medium-sized wild mammal species (red deer, roe deer, European mouflon, northern chamois, wild boar, brown bear, grey wolf, Eurasian jackal, red fox, European badger, brown hare); with roe deer, red deer and wild boar being the most exposed species (58%; 15%; 14% regarding all collision cases). Railway sections were divided into shorter subsections; their length varies between 10 and 26 km (mostly 15 km). Afterwards, wildlife traffic collision rate (individuals/km/year) were calculated for subsections. Annual collision rate varied between <0.1 and ≥ 0.3 individual/km/year (max. Collision rate was 0.74 individuals/km/year) (**Figure 3**). In Sweden, during 2001–2011, identified special aggregation of WTC (hotspots) on railway sections, where collision rate was >0.24 (moose) and >0.33 (roe deer) per km per year [14]. Criteria have been proposed for identifying (sub)sections of Slovenian railway lines with elevated WTC of large and medium-sized wild mammal species [56]. For subsections of the railway that have been identified as having an average WTC of ≥ 0.30 individuals/km/year (adapted from [14]) and are undergoing upgrades or reconstruction, it was proposed to provide a spatial analysis of impacts on target species, identify WTC hotspots and propose appropriate mitigation measures. These railway subsections covered 11.3% (137 km) of the Slovenian railway network. Railway subsections with lower average WTC (0.20 to 0.29 individuals/km/year) may be subject to further analysis and procedures, particularly if the number of collisions with species of conservation concern (e.g., brown bear) is high. The proposed criteria were formulated at the national level and therefore, on local and regional scales, local ecological conditions must be considered, and the criteria adjusted accordingly.

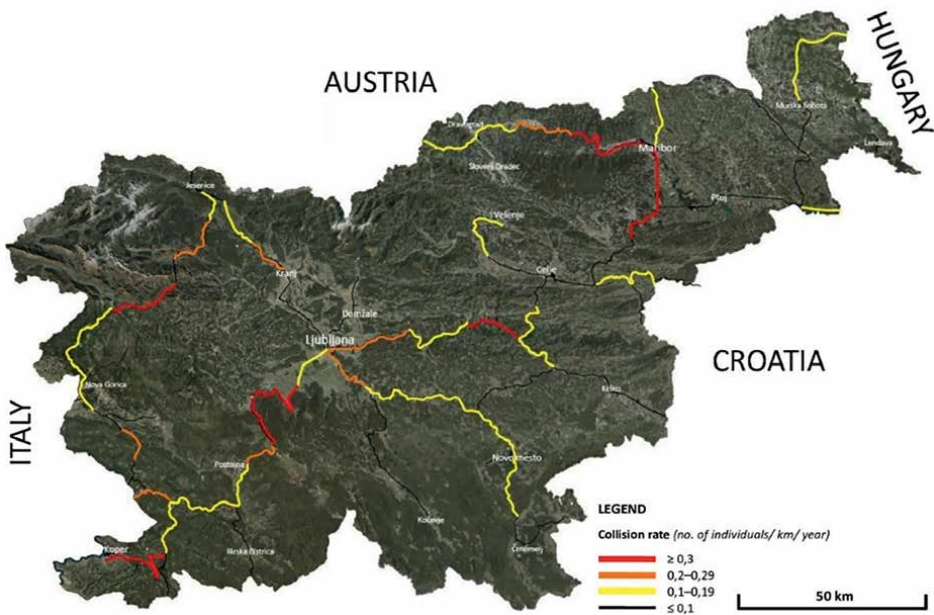


Figure 3. An overview of railway sections in Slovenia with annual collision rate in the period between 2015 and 2019.

To determine hotspots along the line infrastructure, the kernel density estimation method can also be used, where statistically characteristic densities are identified or hotspots, which can then be ranked, and areas/points of high risk determined [59–62]. However, when we use this method, it is essential to collect data with accurate spatial location (e.g., GPS coordinates).

3.1.3 Review and assessment of the suitability of existing mitigation measures

Within the spatial analysis of the study area, it is significant to evaluate the effectiveness of the existing measures. This involves verifying the technical characteristics of the existing crossing structure (height, width, design) and fences, as well as their location and the anthropogenic disturbances in their surroundings. To study their use by wildlife, monitoring can be performed by using various methods (e.g., recording and studying WTC, recording animal tracks in the snow and in beds of sand, using photographs and videos (camera traps) and infrared detectors, capture-recapture data, telemetry data). Afterward, when we provide and assess all results of the first phase, we may summarize that no mitigation is needed and/or propose improvements to the usability of the existing crossing structure and suggest new mitigation measures.

3.2 Selection and planning of appropriate measures to ensure connectivity and reduce wildlife mortality

After confirming the need for mitigation measures, the next phase is to select appropriate measures: ecoducts and wildlife crossings (wildlife overpasses, multi-use overpasses, modified viaducts, large mammal underpasses, modified culverts for terrestrial animals, modified culverts for fish, amphibian tunnels) and other road safety improvement and wildlife mortality mitigation measures (fences, artificial deterrents), which are presented earlier (see paragraphs 2.2 and 2.3). Bridging facilities should be placed wherever they are essential for: connectivity of isolated habitat patches; allowing wildlife access to important areas (breeding areas, feeding and resting areas); and enabling the crossing of railways, which intersect wildlife migration corridors. Ecoducts and wildlife passages are often the best choices [9, 19, 22].

It is also required to select appropriate locations for the placement of wildlife passages, determine the frequency (density) of passages along railway lines, and select suitable types and dimensions of faunal passages or suitable mitigation measures. The type of wildlife passage selected will depend on the conservation value of the study area (habitat types), the characteristics of the terrain through which the transportation infrastructure passes, and the animal species or taxonomic groups for which the feature is intended. Where the wildlife corridors of international/ national importance are or will be intersected by railway lines, specific fauna passages with large dimensions should be selected [19]. Furthermore, it is important that wildlife passages are designed to be used by as many species as possible. However, the location of wildlife passages is equally or even more important than their technical suitability. Wildlife passages that are poorly positioned and integrated into the environment will not be effective, regardless of their appropriate technical characteristics [19, 24, 63].

3.3 Monitoring the effectiveness of mitigation measures

Once mitigation measures have been implemented, their effectiveness must be verified through monitoring. According to Calvarho *et al.* [24] an appropriate method

is to monitor selected parameters (e.g., number of crossings, population parameters) before and after the implementation of measures in the study area (railway section with localized bridging facilities and measures) and in the control area. It was emphasized that whenever possible, the best study design is a replicated BACI (Before-After-Control-Impact) at the mitigation site (where measures are taken) and control site [24]. Further, it is significant to choose the most suitable method (methods that simultaneously monitor a larger number of species are preferred) and a way to minimize errors. The number and spread (dispersal) of species can be predicted and assessed using appropriate methods (use of census and modeling of the spatial distribution of species, hunting, marking and recapture method, use of sand cushions, telemetric studies, photo-video-monitoring), including molecular-genetic analysis of populations [64–66]. Molecular ((non-invasive) genetic) research is an increasingly useful tool suitable for larger animals whose remains (carcasses, hair, feathers, droppings, urine, saliva) can be found and DNA isolated from Ref. [66]. They are most often used to determine the genetic characteristics of subpopulations separated by a railway or to identify individual individuals and determine the abundance of populations [4].

4. Conclusions

Based on the analysis and synthesis of works dealing with mitigation measures and providing wildlife corridors in the area of railway infrastructure and study of railway mortality along Slovenian railways, we can highlight the following conclusions:

- Rail transport, which is becoming an increasingly important land transport system, is generally assessed as more environmentally acceptable, especially compared to road transport. However, it should not be neglected, that railways can adversely affect wildlife by creating barriers to their movement, commonly known as the “barrier effect”, and by directly increasing mortality due to collisions with trains.
- Proposal for the protocol for determining and implementing measures to ensure migration corridors for wildlife, can be used in the process of planning and upgrading and modernizing railway lines in Slovenia and elsewhere. Unifying approaches can improve the methodology for environmental impact assessment, which addresses wildlife, and enables to provide the most realistic and comparable results on local, regional and national scales. This knowledge will be beneficial to target users, such as Slovenian Railways, and to other stakeholders, who are involved in the environmental assessment process before a decision about implementation is made (e.g., wildlife experts; decision-makers on national, regional or local authorities; non-government organizations).
- The proposed protocol follows the general guidelines for reducing the barrier effect of the railway infrastructure and includes the findings of research on the crossing of wild animals in the area of the Slovenian railway infrastructure, which we carried out for the period 2015–2019. The phases of the proposed protocol are: (a) spatial analysis to assess the impacts of railway infrastructure on target wildlife species, including run-over analysis and identification of hotspots on selected sections of railway lines; (b) selection and planning of measures to

ensure connectivity and reduce congestion; (c) implementation of measures (construction); (d) monitoring the effectiveness of measures during construction and operation of new or upgrade of existing railway lines.

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Conflict of interest


The author declares no conflict of interest.

Author details

Samar Al Sayegh Petkovšek
Faculty of Environmental Protection, Velenje, Slovenia

*Address all correspondence to: samar.petkovsek@fvo.si

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