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Editorial

Mainstreaming biodiversity into transport networks by connecting stakeholders across sectors

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Linear Transportation Infrastructure drives global biodiversity loss

Habitat fragmentation and loss are considered the main causes of global biodiversity decline (Barnosky et al. 2011; Hilty et al. 2020) and have received increased attention in recent decades (MacArthur and Wilson 1967; Wilcove et al. 1986; Saunders et al. 1991; Fahrig 2003; Henle et al. 2004; Fletcher et al. 2018). Among the many causes of fragmentation and habitat loss, development of linear transportation infrastructure (LTI), particularly roads, railways and energy infrastructure are the main drivers (Seiler 2003; Geneletti 2004; Rhodes et al. 2014). While LTI plays an important role in providing mobility and connectivity for people, infrastructure occupies land, can disrupt natural processes, facilitates the spread of invasive species and imposes movement barriers to most terrestrial wildlife (Seiler 2003, 2014, 2023; Smith et al. 2015; Soanes et al. 2024). Furthermore, the negative impacts of LTI on the environment, quickly accumulate and spread beyond the site of infrastructure, through, e.g., traffic mortality, noise disturbance, and chemical pollution (Forman and Alexander 1998; van der Ree et al. 2015; Hlaváč et al. 2019; Denneboom et al. 2024). With the planned expansions of LTI networks and expected increase in traffic, the cumulative impact on nature will quickly exceed the carrying capacities of ecosystems (Forman and Alexander 1998; Jaeger and Torres 2021).

In recent decades, scientific literature on understanding and mitigating the negative impacts of LTI has significantly grown (van der Ree et al. 2015; Seiler and Bhardwaj 2020; Sjölund et al. 2022; Barnot et al. 2023). To date, most literature and policies (e.g., Natura 2000; EU Green Infrastructure Strategy) agree that habitat fragmentation effects are best resolved through improving landscape permeability, by provisioning structural connectivity, through, e.g., ecological corridors as part of coherent ecological networks (Loro et al. 2015; Mimet et al. 2016; Vlkova et al. 2024). When ecological corridors successfully facilitate the movement of wildlife, and genes flow through the landscape, corridors are deemed to provide "functional connectivity". Despite the wide array of solutions and tools that have been developed to improve structural and functional connectivity in the landscape, sufficient adoption of such solutions is missing, and function-

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al connectivity is not effectively facilitated on the landscape-scale. It is evident that sustainable solutions require stronger transdisciplinary cooperation among stakeholders and specialists, such as transport administrations and development financiers, as well as the general public (Papp et al. 2022a), to foster the development of clear standards and procedures that ensure the effectiveness of biodiversity conservation efforts while developing transport networks (Papp et al. 2022b).

Infrastructure and Ecology Network Europe in the framework of transport ecology

The Infrastructure and Ecology Network Europe (IENE) has pioneered a transdisciplinary collaborative approach in the LTI sector. Established in 1996, IENE provides an independent, international and interdisciplinary platform for developing and exchanging expert knowledge, with the aim of promoting a safe, meaningful and ecologically sustainable pan-European transport infrastructure (https://iene.info/). The network brings together decision makers, institutions responsible for LTI planning and development, environmental protection agencies, researchers, academia, practitioners, consultants, businesses and relevant NGOs. IENE facilitates dialogue and collaboration between all these key stakeholders, through various initiatives and events, including its biennial international conferences. One such conference, "Connecting people, connecting landscapes" was organised by IENE in September 2022, in Cluj-Napoca, Romania. The conference aimed at finding integrated approaches to mainstream biodiversity into transportation networks by assessing the current state of play, discussing the gaps, needs and solutions, looking back for lessons learned and ahead for future challenges and opportunities, from global, European and regional (Carpathians, Danube, South East Europe and Black Sea) perspectives. The main themes included: (1) Mainstreaming biodiversity into the transport sector (including infrastructure and energy networks); (2) Practical experiences, challenges and opportunities related to transport ecology and (3) Integrated solutions for ecological connectivity. The conference attracted 276 participants from 46 countries across Europe, Asia, Africa, Australia, and the Americas, who exchanged knowledge and expertise over 190 oral presentations, workshops and panel discussions. These sessions addressed a wide range of topics, including sectoral policies, financing, strategic planning for LTI, environmental impact assessments, design, implementation, operation, upgrading, and decommissioning of LTI, as well as monitoring, research, communication, awareness-raising, education, and fostering effective consultations and collaborations. In addition, four thematic field trips were organised for in-person attendees, offering first-hand insights into the challenges and opportunities posed by both green and grey infrastructures. These trips deepened participants' understanding of how infrastructure and biodiversity can coexist and highlighted innovative approaches to overcoming the practical challenges of LTI planning and implementation.

About this special issue

This special issue, titled "*Connecting People, Connecting Landscapes*," features selected research and case studies presented during the IENE 2022 International Conference. The issue consists of 8 papers covering Europe (6), North America (1), and Asia (1); focusing on various infrastructures, including roads (6), railways (3), roads and railways combined (2), waterways and power lines (1). The key topics addressed by these papers include wildlife crossings (3), land use near wildlife crossings (2), ecological connectivity (2), environmental impact assessments and mitigation measures for LTI (2), prevention of animal-vehicle collisions (2), road fencing and electrified barriers (1), and the role of LTI as wildlife habitat and refuge (1).

Wildlife crossings can facilitate animal movement across landscapes and mitigate human-wildlife conflicts, particularly for LTI. Maierdiyali et al. (2024) provide a comprehensive study from the Tibetan Plateau, China, examining factors that influence wildlife use of underpasses along highways, expressways, and railways. They find that the use of underpasses is strongly correlated with their size and location, with larger and more isolated underpasses being preferred by the species studied. Similarly, Jurečka et al. (2024) conducted research in Austria on wildlife crossing structures at the intersection of ecological corridors and road infrastructure. Their study analysed both the usage of wildlife crossings and species richness in relation to land use and human activity. They found that wildlife overpasses are the most effective, but individual characteristics play a critical role in their success. Furthermore, mammal species richness was positively associated with higher vegetation cover and reduced human presence and disturbance. These studies highlight the importance of strategically planning wildlife crossing structures along key ecological corridors while minimising intensive land use and high human activity to maximise their effectiveness.

The appropriate fencing of LTI to reduce wildlife-vehicle collisions (WVC) remains a key focus in road ecology. A study in Montana, USA, investigated the use of electrified barriers to deter black bears (*Ursus americanus*) from entering fenced roads, specifically at low-volume access points, such as side roads and driveways leading to agricultural fields (Huijser and Getty 2024). Conducted on private land at a melon patch—a known attractant for bears—the researchers found that fences with well-designed, operated, maintained, and monitored electrified barriers successfully kept almost all black bears out of the melon patch, effectively breaking their habitual foraging behaviour. These electrified barriers prove especially crucial along road sections where wildlife fences need to exclude species with paws, such as bears, from entering fenced road corridors.

The integration of predictive models and Artificial Intelligence in preventing WVC is a rapidly growing field. Moulherat et al. (2024) developed a pioneering framework in south-western France aimed at managing WVC by mapping collision risks between trains and ungulates, especially roe deer (*Capreolus capreolus*) and wild boar (*Sus scrofa*), using a network of camera traps. This framework utilised population dynamic simulations to pinpoint collision hotspots and optimise sensor deployment strategies. Data collected from camera traps was processed with deep learning algorithms to detect and identify species near LTI. The study highlighted the technical and operational requirements necessary to effectively integrate biodiversity concerns into LTI digital twins. This advancement has significant potential for reducing WVC by enabling dynamic, adaptive mapping systems that could provide real-time alerts to connected (and even autonomous) vehicles across various transport infrastructures.

Wildlife-vehicle collisions involving threatened species pose a significant conservation challenge. Niemi et al. (2024) conducted an analysis of traffic-related mortality of the endemic European wild forest reindeer (*Rangifer tarandus fennicus*) in Finland between 2017 and 2022. The study recorded 259 reindeer killed in road traffic collisions or euthanized later after tracking, and at least 52 individuals killed following railway incidents. Interestingly, adult reindeer were more frequently involved in collisions than juveniles, with nearly equal representation of adult males and females. These findings highlight the urgent need for species-specific mitigation strategies, such as identifying collision hotspots and deploying wildlife detection systems and warning signs. Such measures would not only protect endangered wildlife but also enhance human safety on roads.

Preserving landscape connectivity during the development of new LTI is critical for maintaining ecological processes. Domokos et al. (2024) conducted a study assessing bear presence and genetic connectivity across a proposed highway in the Eastern Romanian Carpathians, while also estimating the minimum population of brown bears (*Ursus arctos*) in the area. The study identified functional ecological connectivity across the planned highway, demonstrated by genetic links between the 24 sampled bears. Bears frequently appeared near the proposed highway, especially in rugged terrain, and were often detected close to human settlements (<1 km). Even before highway construction, connectivity appears limited by an extensive network of settlements, leaving only a few key linkage areas undeveloped. With wildlife crossing structures inadequately planned for this highway, the authors recommend conducting permeability studies post-construction to preserve landscape connectivity, as the highway could otherwise severely disrupt the Romanian and broader Carpathian bear populations.

The impact of new and planned transport infrastructure on biodiversity and socio-economic systems is widely recognized, yet the effects of ageing infrastructure on nature and human society are often overlooked. Dostál et al. (2024) developed and tested a methodological framework in the Czech Republic aimed at addressing environmental issues associated with older transport infrastructure. The framework presents a systematic approach for the preventive identification of problematic hotspots on existing road networks, proposing feasible upgrades or optimizations that can be integrated into routine repairs and small-scale reconstructions. It outlines a process that includes preparation of assessment backgrounds, field survey protocols, and the design and monitoring of mitigation measures. Fourteen key environmental problem areas were identified. The framework's comprehensive methodology has strong potential for application in other countries, including post-project evaluations of newly constructed roads.

François et al. (2024) analysed the role of LTI rights-of-way of roads, railways, waterways and power lines, as an ecological shelter for biodiversity in France. They developed a GIS-based methodology to estimate the linear extent and surface area of these potential ecological shelters, with a focus on local flora and entomofauna. Their goal was to propose and optimise policy actions that could enhance the role of LTIs in providing sustainable habitats. The study suggests that implementing targeted management strategies for these areas could enhance their function as refuges for local wildlife and even serve as source populations for recolonizing adjacent degraded landscapes, thus creating broader ecological benefits. Achieving this requires active participation from a wide range of stakeholders, including state authorities, LTI operators, and local landowners. In some cases, new responsibilities may need to be assigned to ensure effective management. Such an approach not only benefits protected wildlife but also supports common species, which are often overlooked despite their critical ecological roles and functions.

Perspectives

The IENE network holds significant knowledge, experience, and best practices with the potential to effectively integrate biodiversity into transport networks. The IENE 2022 International Conference served as an ideal platform for exploring how to achieve this integration, bringing together a variety of stakeholders, including policymakers, transport and environmental agencies, researchers, academics, and NGOs. The outcomes of the conference proceedings, as well as the findings of various studies, such as those presented in this Special Issue, provide valuable insights that can guide both policy and societal transformations. To ensure success, transdisciplinary collaboration must be encouraged, and stakeholder participation and co-creation should be prioritised from local to international levels. By fostering connections among people, we can create the conditions necessary to preserve landscape connectivity, benefiting both human and natural ecosystems.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

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Data availability

All of the data that support the findings of this study are available in the main text.

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