sustainability

MDPI

Article

A Comprehensive Research Agenda for Integrating Ecological Principles into the Transportation Sector

Maria Vittoria Corazza

Department of Civil, Environmental and Building Engineering—DICEA, Sapienza University of Rome, 00185 Rome, Italy; mariavittoria.corazza@uniroma1.it

Abstract: The paper examines the integration of novel Transportation Ecology principles into transit operations, aiming to address the environmental impacts associated with surface services in urban areas and with the purpose of creating a comprehensive agenda for integrating ecological principles into transit planning and management. The research problem is to quantify the tangible benefits for transit operators, particularly in the context of mitigating wildlife-vehicle collisions and improving overall operational efficiency as a motivator for transit managers to adopt Transportation Ecology principles. The study design, after analyzing the regulatory requirements, implements scenario-based methodology, utilizing data from an average Italian bus fleet to estimate potential monetary savings and benefits. Key parameters, such as maintenance costs, insurance premiums, and collision-related expenses, are analyzed to provide a realistic assessment of the economic advantages of implementing Transportation Ecology measures. The findings reveal that significant cost reductions can be achieved by minimizing accidents involving wildlife, alongside other operational improvements. The scenario demonstrates that even a small fleet, when adopting these principles, can yield substantial financial benefits, thereby making a compelling case for broader implementation. The paper concludes that while the qualitative nature of the analysis necessitates conservative estimates, the results underscore the value of incorporating ecological considerations into transit planning and management. These insights are vital for transit operators and policymakers seeking to balance environmental sustainability with operational profitability and protect urban ecosystems. This also implies the need for a more holistic and interdisciplinary approach to transportation planning and management.

Keywords: transportation ecology; road ecology; transit

check for updates

Citation: Corazza, M.V. A Comprehensive Research Agenda for Integrating Ecological Principles into the Transportation Sector. *Sustainability* **2024**, *16*, 7081. https://doi.org/10.3390/su16167081

Academic Editors: Larysa Neduzha and Iryna Bondarenko

Received: 17 July 2024
Revised: 12 August 2024
Accepted: 16 August 2024
Published: 18 August 2024

Copyright: © 2024 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction to Transportation Ecology: Distant Roots for a Contemporary Study Field

The term "Road Ecology" encompasses the interactions between living organisms and their environment with vehicles and road infrastructure, including structures and artworks [1]. Given that an ecosystem comprises all organisms in an area and their interactions with the physical environment, fostering diversity and cyclicity [2], Road Ecology can be more comprehensively defined as the relationship between road infrastructure, the traffic it generates, and the encompassing ecosystem. This relationship is intrinsic to the concept of mobility infrastructure, which broadly refers to artificial interventions in natural or built environments aimed at fulfilling connectivity needs for people and goods across different locations. Historically, road construction has been viewed as humanity's triumph over nature, achieved through effort (like the Etruscan cuts made in rock to reach necropolises in Tuscia in Central Italy, potentially dating back to the Roman Republican era) or ingenuity, becoming a significant element that generates "place" [3]. Since the rise of ecological thinking in the early 1970s, this dominance has been increasingly questioned, highlighting the adverse impacts of road infrastructure on natural and social environments [4–6]. This shift prompted the need to begin and consolidate research on these impacts [7], develop initial technical specifications for environmental conservation following infrastructure construction [8], and generate numerous studies, many on specific case studies. These studies emerged from diverse investigative fields, such as ecosystem protection focusing on faunal components [9–11], water systems [12], traffic pollutant quantification [13,14], road maintenance [15,16], and public health [17,18], showcasing the multidisciplinary nature of the emerging field of Road Ecology. However, the roots of Road Ecology date back much earlier, addressing issues like mud removal from road surfaces or erosion phenomena, as addressed by John Loudon McAdam in the late 18th and early 19th centuries. Additionally, the focus on roadkill, the phenomenon of animals being struck by vehicles, gained attention in North America following the construction of parkways and scenic routes during the New Deal era [19]. This eventually led to the construction of the first highway overpass in Utah in the late 1970s to facilitate deer migration [1]. Initially, roadkill and Road Ecology were considered synonymous until the term "Straßen-Ökologie" was coined by Ellenberg et al. [20], establishing Road Ecology as a discipline studying the impact of road infrastructure on landscapes. This study was significant not only for coining the term and linking landscape protection with the impacts of road infrastructure but also for introducing other key notions: nature management (Naturhaushalt) and ecosystem (including plant and animal components) integration—major influencing factors (climate, noise, pollutant emissions into the air and infiltration into groundwater and soils, use of deicing salts)—and the development of regulations and design specifications to protect the ecosystem. The analysis also included a case study on the green cover along the Rhoenline, the highway section between Würzburg and Bad Hersfeld, Germany.

The English translation of the term into "Road Ecology" came later, in the 1990s [21], when the scientific literature on the subject was consolidating into several research streams. For example, the negative impacts of road infrastructure are analyzed concerning wildlife mortality, behavioral changes, movement along corridors, and migrations, with areas along roads acting as "ecological traps" for species attracted there in search of food [22]. Regarding the landscape, emphasis is placed on fragmentation and interaction effects in change dynamics [23]. The effects on individual abiotic components of the landscape—such as water, microclimate, light, noise, topography, and soil sedimentation mechanisms—are also highlighted [1,24].

Interestingly, in the 1980s, a related concept, "Natural Disturbance Ecology", emerged in response to the need to preserve natural areas in land-use decision-making processes [25,26]. Based on Odum's definition of an ecosystem, specific characteristics of heterogeneity and dynamism in time and space are subject to disturbance regimes, referring to any event capable of disrupting a natural community, its structure, the resource system it relies on, or the physical environment that hosts it, for natural causes [26,27]. The affinity between the two concepts lies in recognizing the mutability of natural ecosystems and distinguishing between endogenous (Natural Disturbance Ecology) and exogenous—specifically anthropogenic—factors related to road infrastructure construction (Road Ecology) that cause it. Additionally, natural disturbances may not necessarily be harmful [27], while the mutual interaction between nature and roads generates degradation, leading to social costs [1].

In the name and vision of Road Ecology, the disruptive element is the road. However, it would be erroneous to think that other types of road infrastructure are exempt from such a role. Introducing railway connections and their operation can similarly have negative effects, as can any infrastructure related to other modes and forms of transportation, especially if they are high-capacity modes. The shared characteristic of linear terrestrial infrastructure between roads and railways led to the definition of Railway Ecology as an extension of Road Ecology in the early 2000s. However, railway infrastructure impacts on flora and fauna have been studied since the 1980s, in the form of specific case studies, similar to the early stages of Road Ecology. Initially, the focus was on specific structures such as tunnels and underground channels allowing the passage of small mammals [28,29], but the advent of high-speed rail increased interest, highlighting the risks associated with habitat fragmentation [30–32]. However, the provision of passageways is not without risks, especially for smaller mammals that become easy prey due to the size or location of these structures, introducing a central theme in the ecology of road infrastructure: the provision of mitigation or protection measures, addressed later. Despite continuous interest over time, Railway Ecology remains relatively underexplored in the literature, with the predominantly European sources [33] being focused on train–animal collisions, while impacts on habitat (loss and fragmentation), pollution (chemical, noise, light), and the potential for creating suitable environments in areas degraded by railway infrastructure are still relatively under-studied compared to Road Ecology [34].

However, comparing Road Ecology and Railway Ecology introduces numerous points for reflection. Both involve studying the effects on natural ecosystems resulting from the introduction of linear terrestrial infrastructure, prompting the subsequent discussion in this chapter to jointly address rubber and rail modes—their methods of introduction into a given area (earth movement, construction, "sealing" of the area and adjacent strips) are similar, as are the effects of severance and fragmentation of territory and landscape continuity.

1.1. Developing the Transportation Ecology Concept

In both Road Ecology and Railway Ecology, research is addressed in a multidisciplinary manner, but currently, interest within transport disciplines remains marginal and driven by regulatory requirements, mainly in terms of environmental impact assessment. Additionally, railways are considered a less polluting mode compared to roads, but this is not true from the perspective of wildlife impacts, where the presence of catenaries and higher travel speeds can introduce additional hazards [35]. This is compounded by the fact that road accidents, a much more publicized topic than rail accidents, contribute to greater visibility and awareness of the phenomenon. Both Road Ecology and Railway Ecology, which will henceforth be collectively referred to as the broader, and novel, concept of Transportation Ecology, integrate environmental requirements, ecology, and transportation [36], emphasizing territorial preservation and sustainable development. As such, it becomes pivotal not only in quantifying the impacts of roads and railways but also in assessing a territory's sustainability in accommodating these infrastructures and the associated traffic volumes without causing loss or fragmentation. This involves evaluating not only the impact of construction but also the ongoing effects of road and rail operations [19], recognizing that habitat damage is a primary cause of flora and fauna degradation [33].

Therefore, Transportation Ecology and traditional Road Ecology can be considered related fields but have distinct focuses and research agendas. A clear demarcation of their boundaries relies in four main areas—scope, interdisciplinary approach, research focus, and environments considered—is synthesized in Table 1.

Table 1 shows the clear demarcation of the boundaries between Road and Transportation Ecology, and understanding such boundaries between these two areas and their research agendas helps illuminate the critical gaps they aim to fill in the existing literature.

Traditional Road Ecology primarily zeroes in on the environmental effects of road networks, focusing on how roads impact wildlife and ecosystems [1,19,21]. This field has traditionally examined localized effects such as animal mortality due to vehicle collisions, changes in animal behavior, and direct alterations to habitats caused by the presence of roads. However, the research in this domain has often been limited in several ways. One major gap in traditional Road Ecology has been the lack of comprehensive solutions for habitat fragmentation caused by road networks. Studies moved from highlighting the issue to provide infrastructure-based strategies for mitigating these effects, with more recent research beginning to address this by developing and assessing wildlife corridors, overpasses, and underpasses, which aim to enhance habitat connectivity and reduce wildlife mortality, e.g., [23,24]. Another significant gap has been the limited duration of many studies, which often focused on short-term impacts without capturing the long-term effects of roads on wildlife and ecosystems. The field has started to establish long-term ecological monitoring programs to gain a deeper understanding of the chronic impacts of road infrastructure [37,38].

Table 1. Differences between conventional Road Ecology and novel Transportation Ecology.

Areas of Differentiation	Road Ecology	Transportation Ecology
Scope	Primarily focuses on the environmental impacts of roads and highways. It examines the effects of road networks on wildlife, ecosystems, and landscapes. Key topics include wildlife–vehicle collisions, roadkill, habitat fragmentation, and the spread of invasive species along road corridors.	Encompasses a broader range of transportation modes beyond just roads and highways and includes railways and urban transit systems, with a focus on operations in urban environments. It studies the environmental impacts of these various transportation systems on ecosystems and biodiversity. Although marginal, aviation and maritime transportation, if operating in urban areas, can be included.
Interdisciplinary approach	Thusfar specialized, involving ecologists, biologists, and conservationists and focusing on terrestrial ecosystems affected by road infrastructure.	Highly interdisciplinary, involving not only ecologists but also engineers, urban planners, economists, and social scientists. This field considers the full spectrum of ecological impacts from the considered transportation modes.
Research focus	Concentrates on localized effects such as animal mortality, changes in animal behavior, and direct habitat alterations due to road presence.	Looks at broader systemic impacts including air and noise pollution, climate change contributions, landscape connectivity, and the sustainability of transportation networks.
Areas/Environments	Mostly rural, non-urban	Urban, primarily

Furthermore, traditional Road Ecology has not extensively examined how road networks affect ecosystem services, such as water filtration, pollination, and carbon sequestration. This gap is beginning to close as researchers recognize the importance of assessing how roads and operations influence these critical services provided by ecosystems. This has been thus far acknowledged in few cases [39–41].

In contrast, moving from Table 1, Transportation Ecology encompasses a wider range of urban transportation modes, from private vehicles to the whole transit supply. This field adopts a highly interdisciplinary approach, integrating insights from ecologists, engineers, urban planners, economists, and social scientists. Transportation Ecology seeks to understand the full spectrum of ecological impacts arising from all urban transportation systems and operations, addressing several key gaps in the literature, such as:

- The lack of integration of multiple transportation modes into traditional ecological studies. Road ecology has primarily focused on the impacts of roads, often neglecting how different transportation systems interact and their combined effects on the environment. Transportation ecology aims to fill this gap by studying the interactions and cumulative impacts of various transportation modes.
- The limited focus on climate change and energy consumption in Road Ecology. While road ecology has examined localized environmental impacts, it has not fully addressed the broader implications of transportation emissions and energy use. Transportation Ecology can actively research how transportation systems contribute to climate change and exploring sustainable transportation solutions to reduce carbon footprints.
- The lack of integration with urban and regional planning (an area where traditional road ecology has fallen short). Transportation Ecology typically does not address the integration of transportation systems within urban planning frameworks. Transportation Ecology, however, includes the role of transportation in urban sprawl, land use, and regional development, promoting eco-friendly urban and mobility planning practice that consider environmental sustainability.
- Human health and socioeconomic impacts of transportation systems have also been underrepresented in road ecology. Traditional studies rarely consider how transportation affects air quality, noise levels, and overall human well-being. Transportation

ecology can fill this gap by investigating these impacts and addressing socioeconomic disparities in transportation access.

- Lastly, technological innovations in transportation, such as electric vehicles and autonomous transportation, have not been extensively explored in traditional road ecology. Transportation Ecology can help evaluating the environmental benefits and potential drawbacks of these new technologies, aiming to understand their implications for ecological sustainability.

One more gap to consider is that the current knowledge, and scientific and gray literature all reflect the approach from Road Ecology, i.e., how to cope with damages to flora and fauna derived from a given infrastructure, with no attention paid to those generated by traffic (which can be even more disruptive). The proposed novel Transportation Ecology approach considers these gaps and addresses them from the transportation operators' point of view (with a focus on urban transit managers), which differs from that of road planner and managers, since they act on the supply and thus the traffic volumes generated, and not just the infrastructure, per se.

However, the issues above mentioned are not meant to claim Transportation Ecology's superiority over Road Ecology but the need of the transition of the latter towards the former. Both fields together provide a comprehensive understanding of the ecological consequences of human transportation infrastructure and operations, paving the way for more sustainable practice and policies.

1.2. Rationale of the Paper

Moving forward, the paper will briefly describe the impacts of both roads and railways on flora and fauna to highlight their disruptive potential and the need for mitigation with several countermeasures (Section 2), which is partly addressed at the regulatory level (Section 3). However, from the perspective of transport research, transportation ecology remains largely unexplored in impact assessment processes [36,37,41–43]. This is partly due to the lack of a clear definition of which effects to evaluate from the transport operators' point of view. Many studies focus on individual species and isolated case studies [11,28,32,44,45], leading to a selective approach to identifying negative effects, affected territories, and methods for detecting, measuring, and evaluating infrastructure impacts on biodiversity. However, by learning from these case studies, it is possible to transfer Road Ecology criteria and visions to Transportation Ecology and to quantify tangible benefits for key actors in this sector, i.e., transit operators (Section 4). This transfer methodology relies on an exploratory scenario based on assumptions and hypotheses collected partly from the Road Ecology literature and partly from typical operational data from transit management. Results are qualitative and designed to demonstrate that by including the Transportation Ecology criteria in the transit management, monetary savings can be obtained.

The scenario building approach moves from the observation that, although under consolidation, Transportation Ecology is still far from being considered a "regular fixture" in current transportation practice when planning and designing infrastructure, and even less so when operating high-capacity transit systems. This raises a fundamental research question: "How can Transportation Ecology be made integral to the planning and management of roads and rails services?", which also paves the way for a new vision of the relevance of flora and fauna, reversing the current approach that typically seeks to remove natural components (animals and vegetation) as disturbances to operations, as epitomized by efforts to mitigate bird strikes at airports.

To address this, a digression is eventually presented (Section 5) with the goal of establishing a feasible program for transit operators to safeguard local environments from traffic's disruptive effects. Finally, concluding remarks (Section 6) are drawn with the ultimate goal of advancing knowledge in this field further. A flowchart of the work is presented in Figure 1.

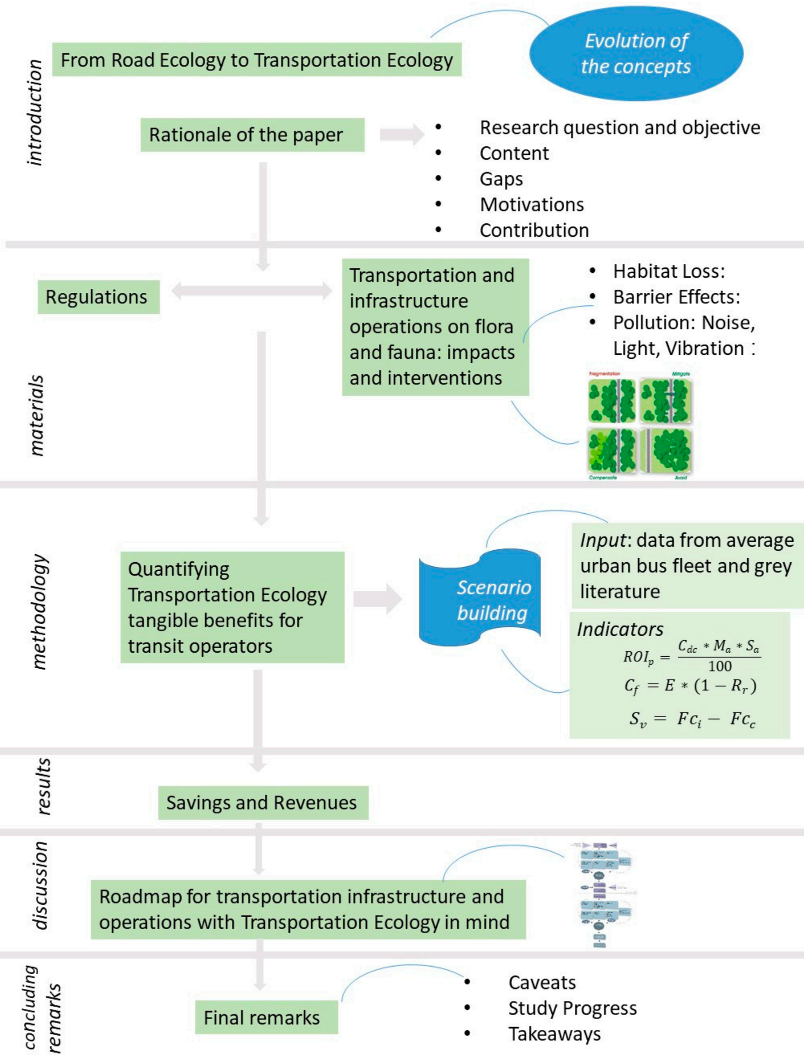

Figure 1. Flowchart of the study.

This study's motivation, thus, stems from the recognition that current approaches to integrating ecological principles within urban transportation systems are limited, particularly in how they address broader environmental impacts beyond localized issues like wildlife mortality and habitat fragmentation generated merely by the infrastructure. While Road Ecology has provided a foundation, the need for a more expansive framework that considers various transportation modes and urban environments has, therefore, become evident. This realization drives the study towards developing the innovative concept of Transportation Ecology, which encompasses not just the infrastructure-based approach of conventional Road Ecology, but also the need to consider operations when assessing the ecological impacts of mobility, especially in urban ecosystems (thus integrating multiple disciplines, including ecology, engineering, and urban planning).

The steps in Figure 1 introduce this novel framework and contribute to the transportation study field. Transportation Ecology not only expands the scope of ecological integration in transportation but also offers practical tools for transit operators. By proposing a scenario-based methodology in Section 4, this study highlights how ecological considerations can lead to economic benefits, such as reduced maintenance costs and lower insurance premiums, thereby aligning environmental sustainability with operational efficiency. This contribution is crucial for advancing both theoretical understanding and practical application in urban transit systems.

2. Transportation and Infrastructure Operations' Impacts on Flora and Fauna: Materials and Methods to Describe the Phenomena

The negative effects due to road or rail infrastructure and operations to consider derive from the well-known concept of "negative externalities" [37]. However, each of these externalities includes further specifics to consider, namely the actual ecological effects already defined by Iuell et al. [38] and summarized in Table 2.

Table 2. Effects on fauna and flora (adapted from [38]).

Phenomena Associated with Transportation Infrastructure and Operations		**Effects on:**	
		Fauna	**Flora**
Wildlife habitat loss	Physical change of soil surface	Changes in species distribution	Destruction of vegetated surfaces and conversion to paved areas or embankments
Barrier effect	Caesura between portions of territory	Isolation, potentially threatening survival	Modification in the continuity of vegetated surfaces
Risk of fatal events	Mortality due to accidents	Population reduction	
Disturbance and pollution	Changes in hydrological setup	Changes in behavior for seeking water sources	Modification in continuity of vegetated surfaces
			Variation in water resources and water regimes
			Modification of wetland and riparian habitats
		Damage to vital and behavioral functions	
	Noise pollution	Population reduction	
	Vibrations	Changes in behavior	
	Light pollution		Modification in growth
Changes in protective strips (e.g., road shoulders) functions	Alterations of functions along protective strips	Creation of corridors	
		Creation of new habitats	
Land use changes	Physical change of soil surface with increased sealed surfaces (concrete, asphalt, etc.), generation of impervious surfaces	Increased risk due to human presence	
New Human settlements resulting from the opening of infrastructure			

At the root of all the negative effects on biodiversity summarized in Table 2 is the habitat fragmentation caused by the insertion and operation of road and rail infrastructure. It is not merely the introduction of a dividing element within a territory but rather the resultant parceling of the area into smaller zones where the infrastructure becomes a barrier to the continuity of the landscape. Moreover, fragmentation introduces issues of size and mobility. If parceling creates smaller areas unable to support the same amount of wildlife populations, these will tend to move toward new territories. However, if the barrier effect is insurmountable, such mobility will not be possible anymore, making the population more vulnerable in a smaller territory. Furthermore, a territory composed of smaller and less permeable habitable areas generates a different and uneven distribution of species, exacerbated by the presence of other land uses (especially urban areas), which can pose additional risks and conflict with the quest for suitable living spaces by migrating populations.

The capacity for movement within a territory (in search of food or shelter) and of dispersal is a pivotal factor in the survival of a species. This introduces the concept of road permeability, which is related to the type of barrier, the traffic it generates, and animal behavior. As evidenced in the literature, large animals may still utilize areas in close proximity to the infrastructure but may not fully do that [1,26,34]. Conversely, small mammals or avian fauna tend to avoid areas in direct proportion to the extent of the infrastructure. For invertebrates, the road surface itself or the less hospitable substrate of the road shoulders may act as a barrier [1,26].

The most evident phenomenon, mortality, is not only associated with traffic intensity but also with the behaviors induced in fauna by the infrastructure as a barrier. The risk of collision with vehicles, whether cars or trains, is a significant hazard for species attempting to cross roads. However, a high number of fatal events may simply indicate a large population of a given species, such as rodents. It is evident that temporal and climatic factors influence behaviors, which is reflected in observations of accident levels and the interaction with human activities, including seasonal livestock migrations, hunting, and seasonal agricultural activities. In a survey conducted in the Czech Republic, a "scale factor" that connects accident events with various species and their surrounding road catchment areas was also observed. For example, at a landscape scale characterized by a catchment area with a 1000 m radius, the highest mortality rates were noted for foxes, martens, and polecats, particularly near agricultural lands and settlements. Intermediate scales were also defined, down to the local scale, with a catchment area radius of 50 m, where mortality included not only landscape-scale species but also otters, badgers, stoats, and weasels, particularly along forested strips adjacent to infrastructure [46].

Anthropogenic activities introduce various disturbance factors, notably pollution. Although railway infrastructure does not impact the environment through harmful air emissions like road infrastructure, it generates similar issues through noise pollution. This noise pollution significantly affects avian fauna, including bats, which can be disturbed even at a distance of 20 m from the noise source [47]. Raptors are particularly sensitive during reproduction and nesting to noise levels above 40 dB(A) in Leq24h [48], and this threshold is also harmful to some terrestrial mammals [49,50]. Chronic and frequent noise disrupts animals' ability to detect essential sounds, while intermittent and unpredictable noise is often perceived as a threat [51]. Additionally, artificial light significantly impacts nocturnal fauna behaviors, particularly in predatory activities [52].

Finally, when vegetated surfaces are converted into impervious surfaces, whether by asphalt or rail, the result is soil consumption and behavioral changes in fauna and flora. It is well-documented in the literature that green areas along roads become new hunting grounds for predators or new propagation surfaces for non-native and/or invasive plant species. Similarly, the creation of drainage channels generates micro-wetlands with the same attractive power.

2.1. Mitigating Impacts Due to Transportation Operations and Infrastructure

The scientific literature offers numerous examples of strategies to reduce the impact of transportation operations and infrastructure on flora and fauna [1,38], and many case studies demonstrate their successful application. The overarching approach to addressing habitat fragmentation and anthropogenic threats involves three main actions—mitigation, avoidance, and compensation (Figure 2)—especially when preventive measures are not feasible.

In this framework, prioritizing actions to avoid fragmentation is essential. When avoidance is not possible, mitigation measures become necessary, though they cannot completely eliminate negative impacts. Mitigation is the most common approach and can be implemented either ex ante, incorporated into the infrastructure's planning and design once avoidance is deemed impossible, or ex post [53]. The consideration of not proceeding with the project remains critical, as emphasized by Forman et al. [1], who instead suggest the following drastic avoidance measures:

- Not constructing the infrastructure at all.
- Modifying the route.
- Building the infrastructure underground.

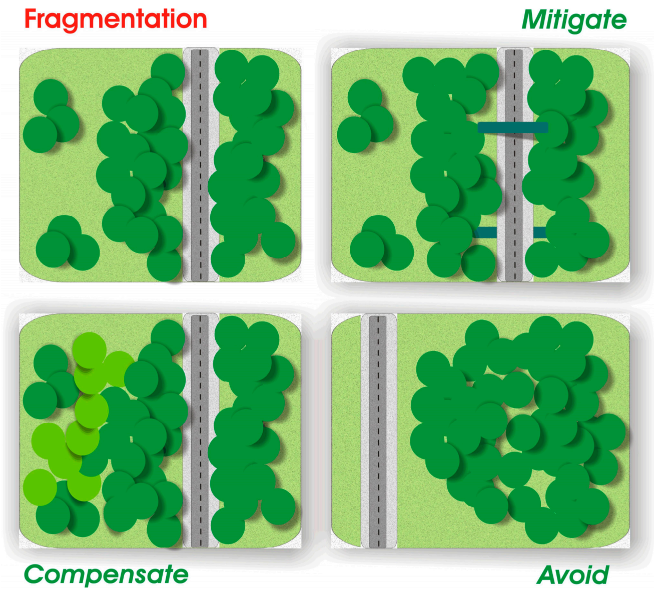

Figure 2. Key actions to counteract fragmentation.

Ultimately, the implementation of compensation measures should be regarded as a last resort, primarily applicable to existing infrastructure. The conceptualization of new infrastructure should, in fact, be founded upon preventive criteria that effectively minimize the necessity for compensation.

Thus, the discussion of Transportation Ecology measures is divided into "preventive" measures for the design phase of new infrastructure and operations, and measures to mitigate the damage from habitat fragmentation caused by existing routes. For new infrastructure, while it is understood that any human intervention alters the natural environment, integrating preventive measures into the design can be categorized into three main areas: (i) route alignment, (ii) earthworks, and (iii) the design of structures as part of the landscaping [38].

For existing infrastructure, the design criteria primarily involve mitigative measures aimed at both fauna and human components [1], typical of transportation operations. Identifying the appropriate locations for these measures requires examining the catchment area, or road-effect zone, which defines the road's interaction with surrounding flora and fauna [1,54]. The extent of this area of influence depends on several factors, including vegetation, terrain morphology, the direction of water and air flows, traffic volumes (particularly in peri-urban areas with frequent railway and road operations), and the characteristics of the road. Determining this area of influence is also crucial for monitoring the effectiveness of mitigation measures and tracking accident occurrences. In addition, the approach based on the three key actions (mitigate, avoid, and compensate) continues to be applicable in this case. The term "avoid" refers to interventions such as reducing railway traffic or closing the road [1]. It is reasonable to conclude that these are drastic actions, difficult to implement in areas where, conversely, it seems more feasible to introduce mitigative actions that, as previously mentioned, influence the behavior of animals or humans. Regarding fauna, interventions fall into two primary categories:

- Creation of structures to reduce risk and safeguard zones or alert animals: This includes crossing structures, barriers, ramps, reflectors, and lighting.
- Habitat modifications: For instance, planting unattractive or unpleasant vegetation along the road.

Studies in the literature address these types of interventions [35,55], highlighting common mitigation criteria that can be summarized as follows:

- Enhancing road permeability: This involves the installation of overhead or underground crossings.

- Modifying the roadbed: Lowering or raising the roadbed relative to the surrounding terrain to reduce traffic disturbances, particularly noise.
- Implementing noise mitigation devices: These can be used both on vehicles and infrastructure.
- Adopting less polluting traction systems: This is essential for reducing environmental impact [56].

Compensatory measures are designed to provide environmental improvements that offset the impacts of infrastructure and habitat fragmentation that cannot be mitigated or avoided. When dealing with habitat loss, degradation, or isolation, the following approach is recommended:

- Creation of compensation areas larger than the impacted areas: These areas should be forested, wetland, etc., rather than making improvements in areas equal in size to the impacted ones.
- Proximity to impacted areas: These compensation areas should be located as close as possible to the impacted areas but outside the zones of influence.
- Re-creation of pre-existing ecological conditions: It is preferable to recreate the same ecological conditions that existed before, rather than introducing different conditions.
- Quality improvement: The aim should be to enhance the quality of ecological conditions compared to pre-existing ones rather than simply restoring the same quality level.

In this context, effective actions include the introduction of larger areas with high-quality avian presence to offset zones affected by traffic noise; further expansion of large areas with natural vegetation; restoration of watercourses or wetlands that have been altered to pre-infrastructure conditions; recreation of corridors or pathways to allow wildlife movement; and eventually, improvement of habitat conditions for rare species and in high biodiversity sites [38].

2.2. Additional Issues

The aforementioned measures are exemplified in well-documented case studies available in the literature thus far reported and are collated in Table 3 for convenient reference.

Table 3. A synthesis of criteria and measures to counteract fragmentation.

Criterion	Type of Infrastructure/Operations	
	New	**Already Operational**
Avoid	Do not build/operate at all	Reduce traffic flows
		Operate less polluting vehicles
Mitigate	Adapt the layout to local morphology	Define road effect zones
		Introduce stuctures and devices to reduce the risk for wildlife
	Design elevated or underground layouts	Modify the habitat (also Landscape the infrastructure area)
		Design permeable infrastructure (also Create passageways for wildlife)
	Reduce earthworks	
	Create passageways for wildlife	
	Landscape the infrastructure area	
Compensate	Create compensation areas larger than the impacted ones	
	Locate the compensation areas as closer as possible to the impacted ones	
	Recreate the previous ecological conditions	
	Improve the quality of the previous ecological conditions	

Despite the fact that a considerable number of these measures have become standard practice, there are still instances where issues arise. For example, a common practice involves the installation of transparent noise barriers along roads with bird silhouettes to prevent bird collisions, typically conducted retrospectively. However, bird fatalities resulting from collisions with transparent surfaces have been largely documented, with identifiable occurrences [57]. This further substantiates the necessity for accurate, multi-step decision-making processes, as discussed in Section 5.

It bears noting that the aforementioned considerations collectively raise a caveat: the underlying premise is that the majority of interventions pertain to infrastructure, with traffic operations constituting a secondary consideration. In urban environments, however, impacts are predominantly attributable to the latter, thereby reinforcing the initial research question (how to integrate Transportation Ecology into the planning and management of road and rail services) and the relevant research objective to quantify benefits for key actors in this sector, specifically transit operators.

3. Regulatory Requirements, the European Vision

After highlighting the critical role of Transportation Ecology in aligning infrastructure projects with environmental and urban considerations, it is equally important to focus on the regulatory frameworks (taking the European framework as an example) that should guide its enforcement, ensuring compliance and ecological integrity. In fact, as evidenced in the preceding Sections, Transportation Ecology is of paramount importance in the comprehensive assessment of the environmental consequences of new infrastructure and transportation operations. At the same time, environmental regulations mandate the implementation of comprehensive impact assessments. While this role may be self-evident in the context of decision-making processes pertaining to the construction or management of public infrastructure, given the existence of specific regulations pertaining to strategic assessment, it is equally important in the context of transportation services and especially transit management.

3.1. Regulations on Strategic Assessment for Transport Infrastructures

In Europe, supranational regulatory tools such as the Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA) promote sustainable development by incorporating environmental considerations into the decision-making process for various interventions. Both SEA and EIA must align with other supranational instruments, like the EU Habitats Directive (92/43/EEC), which focuses on the conservation of natural and semi-natural habitats and wild flora and fauna, and the Birds Directive (2009/147/EC), which is dedicated to the conservation of wild birds.

A key component of the Habitats Directive is the Natura 2000 network, which connects Special Areas of Conservation (SACs), as defined by Directive 2001/42/EC and Directive 85/337/EEC, and Special Protection Areas (SPAs) dedicated to wild bird protection in accordance with the Birds Directive. The Habitats Directive sets conservation targets for natural habitat types and species of Community interest within these areas. When initial screening suggests potential impacts on local ecosystems, a focused study is required to assess the significance of a plan or project on any SACs or SPAs. If such a plan or project must proceed for reasons of public interest, compensatory measures must be implemented. These measures, consistent with the approach stressed in Section 2, can be:

- Conservative: Aimed at maintaining or restoring natural habitats and populations of wild species.
- Contractual: Ensuring compliance through agreements.
- Preventive: Designed to avoid degradation and disturbances around the affected sites.

These measures must align with the essential abiotic and biotic factors necessary for the conservation of different habitat types and species, including their interactions with the physical environment (air, water, soil, vegetation, etc.).

Applying these regulatory criteria in the realm of transportation raises a fundamental query: How should the areas of influence for impact assessment and their implications be defined? Case studies demonstrate that a single road infrastructure hosts animal species with diverse habits and movement ranges, while the disruptive impacts of associated human activities (in this case, traffic) vary accordingly. Moreover, Natura 2000 sites exhibit considerable diversity in size and number. For instance, in the Latium region of Italy, the network encompasses approximately one hundred sites, comprising over 200 SACs and SPAs, with about 90 distinct habitats (some of them within consolidated urban environments) [58].

As a result, determining the influence area for assessing impacts from regulatory tools concerning transportation surface infrastructures and operations (such as municipal transit plans, masterplans, and sustainable urban mobility plans) necessitates a multidisciplinary approach. This approach should integrate technical planning with pertinent scientific knowledge to elucidate behavioral traits of fauna and flora modifications, underscoring the pivotal role of Transportation Ecology in this process.

3.2. Additional Environmental Regulatory Requirements

While the above-mentioned regulations appear to focus on the physical environment, with road and rail infrastructure as the main areas of intervention rather than transportation services, additional regulatory tools require the full involvement of transportation operators, particularly in the fields of transit planning and management. Transportation operators face significant environmental challenges primarily stemming from strict regulatory demands aimed at reducing emissions. These challenges are particularly salient in light of international obligations such as the Nationally Determined Contributions (NDCs) established under the 2015 Paris Agreement. The NDCs mandate each participating nation to implement domestic measures for mitigating emissions, including the establishment of broad-based reduction objectives. Despite their global policy scope and emphasis on emission control, supplementary regulations impose heightened responsibilities on transit operators and infrastructure administrators to evaluate environmental repercussions effectively.

In continuity with the NDCs, the 2024 European Commission Directive on Corporate Sustainability Due Diligence (COM/2022/71 final) mandates that companies identify and mitigate adverse environmental impacts resulting from their operations. Concurrently, the 2024 European Nature Restoration Law (COM/2022/304 final) focuses on enhancing urban ecosystems by addressing the depletion of green urban spaces and tree cover. Together, these directives are poised to synergistically contribute to the preservation of urban flora and fauna. For transit operators, compliance may involve a range of actions, such as integrating more green spaces into infrastructure developments, incorporating vegetation along railway lines and bus routes, implementing water management systems to mitigate runoff pollution harmful to local ecosystems, constructing wildlife passages, restoring indigenous flora along transit corridors, and conducting rigorous environmental impact assessments. These measures emphasize the critical role of both SEA and EIA, ensuring that flora and fauna preservation remains central to transit projects.

- Evidently, a multidisciplinary approach is essential for the effective application of these regulatory tools, SEA and EIA included, to Transportation Ecology. However, the lack of established practice and awareness suggests these regulations may be overlooked due to several factors:
- Firstly, their comprehensive scope spans multiple sectors and industries, potentially diluting specific focus on Transportation Ecology.
- Secondly, sector-specific regulations that are already in force may take precedence over broader regulations such as the Due Diligence Directive and the Nature Restoration Law.
- Lastly, corporate strategies often prioritize compliance with regulations that directly and immediately affect operational aspects, such as emission reduction targets, co-

herently with NDCs and national regulations, and waste management, rather than long-term ecological considerations like Transportation Ecology.

- To address these gaps, targeted efforts are required, with increased advocacy and awareness being of particular importance. In addition, the development of practical solutions is essential, including the formulation of specific guidelines for Transportation Ecology actions, the provision of financial and technical support for projects in this field to encourage implementation by transit operators, and the undertaking of research and data collection to highlight the impacts of transit operations and infrastructure on biodiversity, thereby demonstrating the benefits of integrating Transportation Ecology into broader sustainability efforts and within regular traffic planning and infrastructure management practice.

4. Quantifying Tangible Benefits for Transit Operators

As stressed in the previous Section, the imperative to integrate Transportation Ecology into traffic planning and infrastructure management is mandated by environmental legislation. The crucial question centers on how to quantify the advantages of Transportation Ecology, transforming it from a legal obligation into an appealing practice for transportation managers, especially those operating transit companies, and decision-makers. Key areas of focus might involve quantifiable monetary benefits, serving as foundational elements for a roadmap that facilitates the adoption of Transportation Ecology in planning and management practices.

The literature already offers several studies that assess cost-benefit analyses related to measures discussed in Section 2 [59,60]. However, these typically focus on quantifying expenditures for road managers versus benefits to communities and the environment, primarily through reduced social costs. Specifically, many studies emphasize cost analyses traditionally used to evaluate infrastructure impacts [60,61] yet neglect operational effects.

Nevertheless, potential monetary savings can also be computed for operations, particularly benefiting key stakeholders such as transit managers. In this context, an initial scenario is proposed to quantify monetary benefits specifically for public transport operators, starting from basic indicators.

4.1. A Scenario of Potential Monetary Benefits

Monetary benefits can be associated with a number of parameters, which, in turn, give rise to savings and revenues. While maintenance and insurance costs are the most immediately apparent, there are numerous other potential expenses to consider. It is noteworthy that in the United States, collisions between vehicles and large mammals (e.g., deer and bears) result in damages amounting to 8.4 billion USD and account for nearly 2 million accidents annually. A comparable analysis in the United Kingdom reveals that these incidents result in 42,500 to 74,000 accidents with associated costs of approximately 25 million Euros [62].

To this end, a qualitative scenario is built by considering an average Italian bus fleet (Table 4) a small part of which—20 vehicles—is the scenario fleet potentially involved in collisions. Table 4 also presents the relevant parameters in transit management and planning, used to build this scenario.

Table 4. The scenario input data.

Features	Scenario Input	Source
Average fleet composition (units)	20 as part of the average Italian bus fleet of 457 vehicles	[63]
Average yearly vehicle mileage (km)	55,000	[64]
Average yearly maintenance cost (Euro × km)	0.35	[64]
Average collision cost per vehicle (Euro)	1400	[65]
Estimated basic insurance premium (Euro)	10,077	[66]

It is noteworthy that although qualitative, the Table 4 parameters feeding the scenario reference data describing typical fleet consistency and operations as well as cost parameters and market rates as reported in the literature to describe general real-life operations [63,64,66] or specific case studies [65] on Road Ecology. Given the novelty of Transportation Ecology, no specific inputs are available in this field. For what concerns the scenario settings, the fleet size of 457 buses, with a focus on a subset of 20 vehicles allows for a manageable yet representative sample size, reflecting typical urban transit operations and supply in Italy (but also elsewhere in Europe, for example) and ensures that the findings are scalable and relevant to real-world conditions. In turn, the yearly vehicle mileage, set at 55,000 km, is based on operational standards [64] and therefore, reflects typical usage patterns and provides a solid foundation for cost and savings calculations. Likewise, the maintenance cost data, which are sourced from detailed operational cost analyses of similar fleets [64], and insurance premium rates, which are derived from a major Italian insurance company, ensure accuracy and relevance [66]. Thus, the scenario settings are carefully chosen to provide a realistic and conservative analysis of the economic benefits of wildlife collision mitigation and other operational improvements. In the same way, for the basic equations used in the coming Sections 4.1.1 and 4.1.2 to estimate potential savings and revenues, the assumptions suggested by the cited literature are more prudent to avoid overstated figures and ensure the robustness of the estimates. Therefore, the resulting scenario, although qualitative, is corroborated by representative data and assumptions as provided by the industrial and scientific literature and uses conservative figures for collision reduction and fuel efficiency improvements to avoid overestimating benefits and instead provide a cautious estimate of potential savings that is reliable and tailored on a subset of 20 vehicles, which allows for detailed insights that can be scaled up to larger fleets, making the equations' results thorough, practical, and transferable to a large set of different operational case studies. The scenario's resulting figures presented in Sections 4.1.1 and 4.1.2 can represent qualitative—but convincing—arguments for transit operators willing to adopt the Road Ecology principles in their everyday practice.

4.1.1. Benefits Associated with Improvements

Areas for improvement include reducing accident costs and increasing the attractiveness of the service. Studies have shown that mitigation measures can significantly reduce wildlife–vehicle collisions. For example, the installation of wildlife crossings and fencing along the Trans-Canada Highway led to an 80% reduction in wildlife–vehicle collisions at Banff National Park [67]. Similarly, an animal-detection system on a section of State Route 206 in Arizona resulted in a 97% reduction in collisions with elk [68]. These findings demonstrate that incorporating road biodiversity-conscious design elements, such as wildlife crossings or habitat preservation, can potentially reduce collisions between vehicles and animals. In turn, this can lead to lower vehicle maintenance costs, as they are less likely to be involved in accidents caused by wildlife crossings. Assuming a conservative (if compared to those in [67,68]) reduction rate of 40% and an estimated 20 collisions per year for the total fleet (a prudent estimate given that such incidents are often underreported), the reduced collision frequency is calculated using Equation (1):

$$C_f = E * (1 - R_r) \tag{1}$$

where:

C_f is the new collision frequency per year (unit)
E is the number of events (unit)
R_r is the reduction rate (%)

Equation (1) calculates overall savings of EUR 16,800 for a fleet of 20 vehicles based on the average collision cost of EUR 1400 per vehicle [65], consistent with other sources [69]. According to Table 4 [64], this reduction translates to yearly general maintenance costs per vehicle decreasing from EUR 19,250 to EUR 18,410. Additionally, further savings can be achieved by reducing accidents involving wildlife, which helps public transport operators avoid legal liabilities and associated costs. Collisions with animals may lead to legal actions, compensation claims, and other expenses that can be mitigated through ecology-conscious operations. Similarly, the infrastructure itself benefits: wildlife crossings and other road ecology measures help prevent damage to transportation infrastructure caused by collisions with large animals, thereby reducing the need for costly repairs and maintenance.

According to Bil et al. [62], following a collision with wildlife, drivers' immediate second concern after calling the police is to contact their insurance company, a fact which highlights the significance of these costs. A decrease in wildlife-related accidents can lead to lower insurance premiums for public transport operators; in other words, insurance companies consider risk factors when determining premiums, and fewer wildlife collisions can contribute to a safer (and less expensive) operating environment for transit managers. Online simulations of insurance premiums for buses operating in urban areas in central Italy show varying rates. However, reducing just one accident per year can result in savings of around EUR 1000 per bus, decreasing from EUR 10,077 (with one accident per year) to EUR 8918 (with zero accidents), according to rates provided by one of the major insurance companies in Italy [66]. This means that if the overall basic insurance premium for a fleet of 20 buses was EUR 201,540, applying the same reduced frequency from Equation (1) would lower the new insurance premium to EUR 187,632, resulting in an average savings of approximately EUR 696 per bus.

Additional areas of savings to consider are those associated with strategic operations that consider wildlife habitats when planning and designing the services. Once implemented, they can lead to smoother traffic flow and reduced congestion. This can result in improved fuel efficiency for public transport vehicles and increased overall operational savings. Also in this case, assuming very prudent values and transferring experience from other fields of transportation planning and management, it is possible to quantify the potential fuel savings. This can be achieved by estimating the improved average fuel cost and the savings per vehicle via Equations (2) and (3), respectively, i.e.,

$$Fc_i = Fc_c * \left(1 - \frac{P}{100}\right) \quad (2)$$

$$S_v = Fc_i - Fc_c \quad (3)$$

where:

Fc_i is the improved average fuel cost (EUR)
Fc_c is the current average fuel cost (EUR)
P is the expected improvement in fuel efficiency (%)
S_v are the savings per vehicle (EUR)

In the literature, numerous sources provide different values for P, depending on the type of traffic management. For example, eco-driving has been shown to reduce hard-braking events by 7% and collisions by 4% in a test case in Canada [70]. Similarly, the enforcement of low speed limits, combined with cruise control, can save around 5% to 7% in fuel use [71,72]. Conversely, urban environments with frequent intersections that impose changes in vehicular flow might lead to higher fuel consumption [73]. It is challenging, therefore, to assign a specific value to P for reduced speeds to safeguard fauna in urban environments due to the lack of specific studies. Based on the lessons learned from the aforementioned literature, a very conservative value of P as 1% can again be assumed. Considering an average annual fuel cost of around EUR 3500 per vehicle [74], the savings per vehicle—according to Equations (2) and (3)—are approximately EUR 35.

4.1.2. Potential Revenues by Increasing the Attractiveness of the Service

There is also potential for increasing the attractiveness of the service and generating additional revenues. A commitment to environmental safeguards can enhance a company's brand reputation, making it more attractive to investors, partners, and customers. For a transit company, such a commitment could lead to increased patronage. While specific figures on the propensity to ride from companies committed to environmental issues are hard to find, a holistic approach combining policy, infrastructure, and public awareness is essential to increase bus patronage while addressing environmental challenges. In this, investments in innovation, particularly in greener technologies for the bus sector, can attract more passengers and generate more revenue. A study in the United Kingdom indicates that for each GBP 1 spent on innovating transit operations, an economic return of GBP 4.4 to 8 can be expected [75,76]. Public transport services that demonstrate environmental consciousness and a commitment to wildlife preservation are likely to enhance their reputation similarly. This positive image may attract more passengers, leading to increased ridership and revenue. This is also consistent with customer surveys, where respondents are more likely to purchase goods and services from companies engaged in innovation and inclusivity, with a likelihood of up to 59% [77].

Accordingly, by assuming: (i) a large transit company budget for marketing of around EUR 650,000 per year (as in the case of one of the largest transit company in Italy, operating around 2000 vehicles [74]); (ii) a prudent 5% of consumers who are more likely to travel using companies that are committed to sustainability and innovation, and (iii) an average increase in sales per customer estimated to be about 5%, a return on investment generated by a commitment to achieve more transportation ecology friendly operations for a given company can be estimated by Equation (4):

$$ROI_p = \frac{C_{dc} * M_a * S_a}{100} \quad (4)$$

where:

ROI_p is the potential return on investment a transit company can expect to see as a result of achieving more transportation ecology consciousness (EUR)
C_{dc} is the number of conscious consumers (%)
M_a is the average marketing budget (EUR)
S_a is the average increase in sales per customer (%)

According to all of the above, the potential increase in marketing ROI_p for a transit company that achieves 5% more sales per customer would be about EUR 162,500, corresponding to around EUR 81 per vehicle. Additional returns can be associated with public transport systems operating in ecologically sensitive areas; by preserving natural habitats and promoting eco-friendly transportation options, they can attract more environmentally conscious tourists, thus boosting local economies. Thus, it is also to stress again that incorporating road ecology-conscious practices can ultimately contribute to the long-term sustainability of public transport operations. Although upfront investments may be required, avoiding future costs related to accidents, legal issues, and environmental damage can lead to significant savings over time.

5. Discussion around a Prospective Road Map for Transportation Infrastructure and Operations with Transportation Ecology in Mind

Given the findings above, economic potential is certainly a driver for including Transportation Ecology in transit planning and management. The incorporation of scientific knowledge into Transportation Ecology is crucial for complying with regulations that necessitate intricate assessments such as SEA or EIA, or any infrastructural or operational assessment in the field of transport, and more specifically transit. This integration facilitates the development of foundational knowledge beneficial to transit planners and designers, guiding regulatory decisions that align with the conservation requirements of wildlife and plants coherently with the Habitat Directive, which underscores the importance of preserving human activities in harmony with nature. Such an approach could mitigate the need for extensive plan revisions should disturbances to habitats or species be identified during initial or preliminary assessments. Additionally, integrating this knowledge into professional practice could serve as a valuable asset in decision-making and project development for transit. Establishing databases as a result could further aid in monitoring and controlling impacts post-implementation. The literature proposes various methodologies to assess the effectiveness of consolidated Road Ecology measures [38,53,70,78,79], employing similar multi-step approaches, but coherent with the Road Ecology vision, they focus solely on the infrastructure. These methods emphasize the importance of acquiring detailed knowledge about habitat characteristics, wildlife behavior, flora attributes, and both natural and human-induced environmental conditions (such as local weather patterns and land use dynamics). Additionally, it is recognized that assessment phases should extend beyond simple comparisons before and after infrastructure and services implementation, influencing the design of all phases within the decision-making process [80], as synthesized in Table 5, and where adding transit operations assessment increases the level of complexity.

Table 5. Decision-making process (adapted from [78,80]).

Phases	Intervention Areas	Issues	Regulations	Tools
Scoping	Transport policies	Transportation modes and operations (especially where multimodal supply is missing; conflicts analysis with the areas to safeguard	Strategic Environmental Assessment	Transit plans, landscape plans, any safeguard plan, also including Natura 2000 network requirements
	Identification of corridors	Traffic counting and quantification of conflicts with the local fauna		
Planning	Route and operations identification	Evaluation of planning variants, preliminary study of the mitigation measures (e.g., corridors and survey of the habitat's main features		Surveys and counting of fauna; preliminary study on migration effects, economic analyses
Design	Route and operations design	Location and design of mitigation measures	Environmental Impact Assessment Building/Operations permits	Monitoring plan; Focus on mitigation effects; plans updated versions including mitigation measures; ex ante monitoring/specific habitat safeguard plans associated with the building phases
Construction	Prevention of wildlife in the building sites; operations meeting the habitat requirements	Ecological supervision	Infrastructure and operational plans	Monitoring during the building phases
Operations	Operations/Infrastructure-generated impacts assessment and evaluation of maintenance impacts on fauna; mitigation measures effectiveness (including roadkill)		Business plan Management plan	Operation and maintenance monitoring; ex post evaluation

Moreover, this integration could spur the development of innovative landscaping and streetscaping approaches, advancing research into the impacts of infrastructure networks at the landscape or regional scale (a field still in its early stages [38]), largely due to challenges in gathering comprehensive data. Aligned with the above points, specific analytical fields must be developed. These include studying impact zones and compensation areas, determining the selection and placement of mitigation measures, and establishing procedures for monitoring and control plans. Similar to conventional evaluation processes in transportation studies, clear objectives must be defined in line with the conservation regulatory requirements outlined in Section 3. The evaluation methodology should involve using multi-scope indicators, constructing scenarios to assess various time horizons for effects and setting up monitoring networks and techniques as part of a comprehensive monitoring plan, all tailored to meet specific goals and scenarios [80].

Coherently with all of the above, a roadmap is suggested (Figure 3) in which the calculation of monetary benefits and their subsequent achievement, presented in Section 4, can represent an added value in the adoption of Transportation Ecology criteria in the process. In this scheme, a fundamental requirement involves clearly defining zones for analysis, such as impact areas and sites requiring mitigation, determining the specific locations for mitigation measures, and establishing protocols for monitoring and supervision. Similar to how assessments are conducted in transportation planning, this process involves setting explicit goals that adhere to conservation standards, particularly those outlined in environmental impact assessments and the specifics of potentially affected Natura 2000 sites. The evaluation process employs adaptable metrics, anticipates scenarios over different timeframes to gauge impacts and concludes by implementing a monitoring framework and appropriate techniques that align with the monitoring objectives and scenarios. The indicators must be diverse, encompassing multiple assessment categories and capable of capturing various impacts, facilitated by innovative tools. These tools include advancements in digital mapping for data retrieval, community-involved collaborative mapping, and participatory processes aimed at protecting territories. As these methods become integral to evaluating new transportation projects; their importance will continue to grow with the maturation of knowledge and expertise in this field, shaping decision-making processes accordingly.

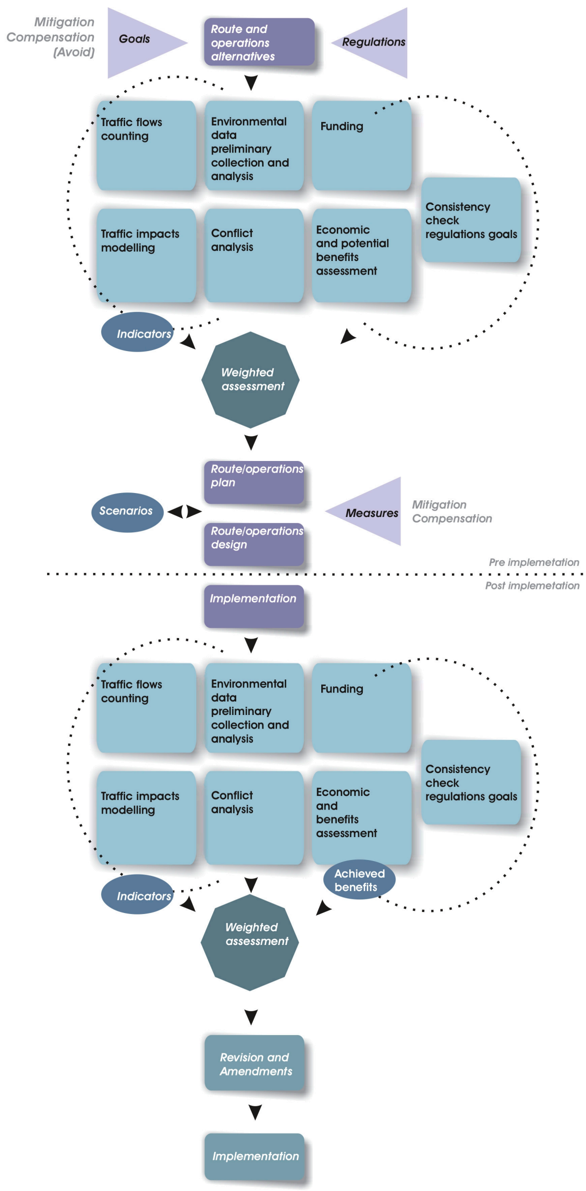

Figure 3. The Transportation Ecology assessment roadmap.

Evaluation should not only focus on environmental aspects but also on economic factors, assessing how human behaviors change with the introduction of measures to mitigate or compensate for impacts. Additionally, it should consider the potential benefits of integrating Transportation Ecology into operations management. This discussion also underscores the financial implications involved. While these measures may not always be expensive (as demonstrated by [1,55]), their implementation and the systems for monitoring and analyzing data should rely on consistent, sustainable funding that aligns with the evolving needs of natural habitats.

5.1. Adapting the Roadmap to Diverse Transportation Contexts

The proposed roadmap is general, but its policy strategies can be applied to different situations and easily integrate Transportation Ecology into transit planning and management, specifically in urban environments (Table 6), starting from the approach of Table 5, i.e., phases and intervention areas.

Table 6 provides a structured approach to integrating Transportation Ecology strategies into urban transportation systems, focusing on rail, bus, and marine networks, with each phase of implementation (from scoping to operations) being detailed to ensure that ecological considerations are embedded throughout the operations lifecycle. More specifically, urban transportation projects should begin with a comprehensive scoping phase, utilizing tools like Strategic Environmental Assessments (SEA) and Geographic Information Systems (GIS), which help map existing urban green spaces and wildlife corridors, ensuring that initial planning stages are informed by robust ecological data. The compliance with urban planning policies, such as Natura 2000, is to underscore the commitment to biodiversity conservation. The Route and Operations Identification phase involves meticulous planning to minimize ecological disruption. Wildlife surveys and the design of green corridors and overpasses are essential strategies to maintain urban biodiversity, when designing surface transit supply. For marine transportation, planning shipping routes to avoid sensitive areas is crucial to protect marine ecosystems. The design phase integrates green infrastructure, such as green roofs and vertical gardens, into urban transit systems. This phase also involves developing detailed mitigation plans to address potential ecological impacts. For marine supply, eco-friendly ship designs are to be incorporated to reduce noise and physical disturbances to marine life. During the construction phase, noise and pollution control measures need to be implemented to minimize environmental impacts, as must ecological supervision to ensure that construction activities are monitored and adjusted as necessary to protect urban wildlife. For marine projects, using silt curtains prevents sediment dispersion, protecting aquatic habitats. When operating, transit supply long-term monitoring of urban ecosystems affected by transportation projects are necessary. Regular updates to management plans ensure adaptive management based on ongoing monitoring data. This phase also includes assessing the impact of ferry operations on marine life, making necessary adjustments to minimize ecological footprints. All the interventions mentioned above (GIS, urban planning policies, regular wildlife surveys, and green infrastructure) are fundamental to implementing these strategies effectively and complement each other, as is adherence to regulations, such as Natura 2000 and marine conservation laws with the final goal of ensuring that urban transportation projects are aligned with broader environmental protection goals.

Table 6. Roadmap policy strategies implementation in urban environments.

Phase	Intervention Area	Policy Strategy	Implementation Examples
Scoping	Transport Policies	Conduct SEA, use GIS for habitat mapping, comply with urban planning policies	Assess impacts on city parks and urban wildlife corridors—e.g., mapping impacts on Berlin tram line expansions on urban parks [81].
	Identification of Corridors	Map green spaces, conduct traffic and wildlife surveys	Identify and map urban wildlife corridors, such as Central Park bird migration paths in New York [82].
Route and Operations Identification	Route and Operations planning	Design green corridors/overpasses, conduct wildlife surveys, plan mitigation measures	Implement wildlife crossings in high-density areas—e.g., wildlife safeguard in Melbourne's urban fabric [83].
		Plan shipping routes to avoid sensitive marine areas	Ensure ferry routes minimize disturbances to marine life—e.g., rerouting ferries in San Francisco Bay to avoid sensitive ecosystems [84].
Design	Route and Operations Design	Integrate green infrastructure, develop detailed mitigation plans	Use green roofs and vertical gardens on transit stations—e.g., green roofs on Utrecht bus stops [85].
		Integrate eco-friendly ship designs	Use quieter propellers and hull designs for ferries—e.g., implementing quiet ship technology in the ferry system of the Vancouver area [86].
Construction	Infrastructure and Operations Plans	Implement noise and pollution control measures, ensure ecological supervision	Limiting impacts—e.g., avoid measures while building the Paris Metro Line 17 [87].
		Implement silt curtains for marine projects	Use silt curtains and other mitigation measures to prevent sediment dispersion during port construction—e.g., several cases worldwide [88].
Operations	Operations/Infrastructure-generated impacts assessment	Monitor long-term impacts on urban ecosystems, update management plans regularly	Ongoing monitoring of urban biodiversity and green space management—e.g., checking birds' vocalization after noise events due to air and surface traffic in San Carlos de Bariloche, Argentina [89].
		Monitor ferry operations' impact on marine life	Assess and mitigate vessels' impacts on marine ecosystems—e.g., continuous monitoring of anthropogenic sounds in 36 locations in the Baltic Sea to ensure minimal impact on marine biodiversity [90].
General Tools		GIS, urban planning policies, regular wildlife surveys, green infrastructure, noise reduction technology	Use GIS to map and protect urban green spaces and wildlife—e.g., GIS mapping of Los Angeles Metropolitan Area urban wildlife corridors [91].
Regulations		Urban planning policies, Natura 2000 requirements, marine conservation laws	Ensure compliance with urban and marine conservation regulations e.g., adhering to Natura 2000 in urban development projects in European cities [92].

The case studies reported as implementation examples demonstrate how various ecological strategies can be effectively integrated into urban transportation planning and management, even when transit is not a priority in the land use management. Moreover, they also evidence the interdisciplinary nature of Transportation Ecology since they originated in other study fields. Transportation Ecology needs different disciplinary perspectives—from economic to scientific, regulatory, and ecological—because it addresses the complex interplay between transportation systems and the urban environment, which involves multiple facets that cannot be understood or managed through a single disciplinary lens. For example, economic insights drive the inclusion of transportation ecology in transit planning by underscoring its potential benefits, making it a key motivator for stakeholders, in the line of the urban ecology studies [93,94]. At the same time, the scientific knowledge, crucial for regulatory compliance, ensures that assessments like the SEA or the EIA are thorough, providing a strong foundation for transit planning that aligns with wildlife and habitat conservation directives [95]. This integration helps mitigate extensive plan revisions by identifying habitat disturbances early on, thus facilitating smoother project development and decision-making processes. Furthermore, the case studies underscore the importance of innovative methodologies and tools, such as digital mapping [96] and community-involved processes [97], to gather comprehensive data and monitor impacts effectively. This holistic approach, combining detailed habitat studies, economic analyses, and strategic regulatory compliance, fosters a robust transportation ecology framework that balances infrastructure development (thus differentiating from the Road Ecology approach) with environmental sustainability, ultimately shaping more informed and responsible decision-making in transportation projects.

5.2. The Role of the Stakeholders: From Management to Awareness to Education

The policy implications reported above, even if qualitatively corroborated by the scenario results to motivate transit operators to adopt Transportation Ecology in their practice, need acceptance and awareness. The benefits and savings described in Section 4 can be drivers in fostering acceptance among transit operators, but raising awareness and providing education on Transportation Ecology are critical steps in ensuring the successful integration of ecological principles into the transportation sector. This process requires the active involvement of key stakeholders, including transit managers, local administrators, and transit patrons. Each group plays a distinct role in fostering a culture of environmental responsibility, and their combined efforts can significantly influence the sustainability of transportation systems.

Transit managers are at the forefront of implementing ecologically responsible practices within transportation systems. For them, education should begin with comprehensive training programs that cover the principles of Transportation Ecology. These programs should emphasize best practices for reducing environmental impacts, such as optimizing transit routes to lower emissions, incorporating green infrastructure into operations, and managing noise pollution effectively. Understanding these practices is crucial for transit managers, who must balance operational efficiency with environmental stewardship. However, to ensure that these principles are put into practice, it is essential to introduce ecological performance metrics as part of the management process. These metrics should be treated as key performance indicators (KPIs) that transit managers are held accountable for alongside traditional operational targets. By linking these KPIs to broader organizational goals, transit managers can better appreciate the importance of ecological sustainability in their decision-making processes. Furthermore, providing incentives for sustainable practices (such as recognition programs or bonuses tied to ecological performance) can motivate transit managers to prioritize environmental considerations in their daily operations.

Local administrators also have a pivotal role in promoting Transportation Ecology through public awareness campaigns and policy development. Within their communities, local administrators are well positioned to educate the public about the environmental impacts of transportation and the benefits of adopting more sustainable practices. Public awareness campaigns can be instrumental in this regard, using community workshops, informational brochures, and public service announcements to disseminate knowledge about ecological transportation.

Collaboration with educational institutions is another effective strategy for local administrators. By partnering with schools, universities, and research centers, they can help integrate the concepts of Transportation Ecology into educational curricula. This collaboration not only raises awareness among younger generations but also helps cultivate a new cadre of environmentally conscious professionals who will carry these principles into their future careers.

Eventually, transit patrons also have a role to play in the adoption of Transportation Ecology principles. Educating patrons about the environmental benefits of eco-friendly transit options is essential. Public campaigns can emphasize the positive impact of adopting Transportation Ecology, and engaging patrons in the feedback process can be vital for the continuous improvement of transit services in the "green" direction. By creating platforms for patrons to share their experiences and concerns regarding the ecological aspects of transit, operators can gather valuable insights and adjust their practices accordingly. The success of Transportation Ecology depends on collaboration between transit managers, local administrators, and patrons. Organizing joint workshops where these stakeholders can come together to discuss and learn about ecological transportation can be a powerful tool for fostering mutual understanding and cooperation. Transparent communication about the environmental impacts of transit operations and the steps being taken to mitigate these impacts is essential for maintaining stakeholder engagement.

By aligning their goals towards a shared vision of sustainable and ecologically responsible transportation, these stakeholders can collectively drive meaningful change. Through education and awareness, transit managers, local administrators, and patrons can become active participants in creating a more sustainable transportation system, ensuring that ecological considerations are at the heart of transportation planning and operations. All these above-mentioned managerial implications are synthesized in Table 7.

Table 7. Managerial implications.

Areas	Action
Corporate Education and Training	Transit managers must receive comprehensive education on the principles of Transportation Ecology, including best practices for reducing environmental impacts. This should encompass optimizing transit routes, integrating green infrastructure, and managing noise pollution effectively.
Performance Metrics	It is essential to introduce ecological performance metrics as key performance indicators (KPIs) alongside traditional operational targets. By linking these KPIs to broader organizational goals, transit managers can better understand the importance of ecological sustainability in their decision-making processes.
Incentives for Sustainability	Offering incentives such as recognition programs or bonuses tied to ecological performance can motivate transit managers to prioritize environmental considerations in their operations.
Quantifying Financial Benefits	Transit operators should focus on identifying and quantifying the financial benefits of integrating Transportation Ecology into their operations. This includes potential savings in maintenance, insurance, and other operational costs as well as avoiding expenses related to environmental damage.
Public Awareness and Education	Effective implementation of Transportation Ecology principles requires collaboration with local administrators and transit patrons. This involves public awareness campaigns, educational initiatives, and active engagement.

6. Concluding Remarks

Transportation Ecology is still in its early stages of development and will continue to flourish if able to incorporate contributions from an increasing number of academic disciplines, as just mentioned. This study identified three primary reasons for integrating Transportation Ecology into contemporary transit operation management practices. Firstly, there is a pressing need to mitigate the adverse impacts of anthropogenic mobility on urban ecosystems, particularly when high-capacity operations are involved. Secondly, the environmental regulatory landscape is becoming increasingly stringent, underscoring the necessity for transport operators to align their operations with the principles of Transportation Ecology. Thirdly, there are tangible financial benefits that can be achieved by adopting Transportation Ecology criteria in operational management procedures. As is the case with any exploratory study, there are numerous caveats to be considered. For example, this study is based on the existing literature on road ecology, which is primarily concerned with extra-urban environments and infrastructure supply rather than the operational aspects of vehicular traffic, including transit. A review of the literature reveals that the majority of case studies place greater emphasis on wildlife than flora. The dominant approach is empirical, whereby best practices are identified and applied. In contrast, vehicular traffic and infrastructure constitute a binomial within the urban environment, which is the actual realm of transportation ecology. The approach and vision remain consistent, yet the actors involved have shifted. In the context of transportation ecology, for instance, the responsibility for managing and regulating infrastructure, as well as planning and designing transportation systems, falls upon a diverse set of stakeholders, including drivers, passengers, transit operators, logistics operators, transit authorities, mobility planners, and land use planners. This suggests the need for further investigation into the reasons behind the apparent lack of interest in Transportation Ecology in urban environments and among the aforementioned urban actors, even in the context of strict regulations. There is also a need for more urban case studies to facilitate the creation of best practices and the transferability of excellence as well as for more discussions, such as those highlighted in [98] about considering the ethical dimensions of road construction and maintenance, particularly in terms of the environmental, social, and economic impacts that must be taken into account before a project can be deemed unethical. This highlights the necessity to integrate ecological liability into road construction and maintenance practices to ensure environmental protection.

As with any empirical study, the many limitations can pave the way for future research directions. A primary limitation concerns the qualitative scenario aimed at quantifying monetary benefits for transit operators. Although this is the first such assessment in the literature, it would certainly benefit from more data from consolidated operations and statistics (currently non-existent), which could provide more indicators and enhance evaluation by developing sensitive analyses that consider alternative maintenance, insurance, and fuel cost parameters to assess their consolidated impact on results. Likewise, the availability of consolidated data would enable the development of scenarios according to different time horizons, regulation and policy changes, and the inclusion of different modes of transportation. Although the focus of this paper is to explore how ecologically conscious considerations can affect public transport, the implications for private vehicles and commercial operations are equally important. For example, promoting the use of green spaces, installing green infrastructure like green roofs and walls, and improving urban tree canopies to safeguard flora and fauna can reduce the impervious surfaces dedicated to private cars and promote non-motorized modes. Similarly, the use of quieter engines to avoid disturbing fauna can improve the street soundscape and mitigate the health impacts associated with private vehicle use. For freight transport, the implementation of mitigation measures can optimize logistics and routing to minimize energy use and emissions through advanced logistics software functions, the reallocation of consolidation centers (often located in urban fringe areas where fauna is a significant presence), and efficient route planning. This consideration extends to the integration of advanced transportation planning methodologies like deep learning [99,100], where traffic flows could be managed by incorporating transportation ecology requirements, or algorithms for transit network design problems [101,102] adapted for the same purpose. Maritime and air traffic can also be significantly affected but are not central within Transport Ecology. For instance, urban waterways often intersect with sensitive ecosystems, and transportation ecology emphasizes their protection through measures such as regulating water traffic to prevent habitat disruption, installing pollution control systems, and conducting regular environmental impact assessments to ensure compliance with ecological standards and using quieter vessel engines [82,84,86]. Airports and air traffic, long criticized for being highly polluting, especially during take-off and landing operations [96], are adopting cleaner technologies for engines and fuels [103,104], which can be further expanded by enhancing green spaces within and around airport premises, using renewable energy sources [104], and improving waste management systems. This not only helps in conserving local flora and fauna but also contributes to a more pleasant environment for passengers and staff. Moreover, implementing noise abatement procedures, such as modifying flight paths to avoid residential areas and scheduling flights to minimize nighttime noise, can significantly reduce the impact on urban populations and wildlife.

To conclude, a clear takeaway is the need for a shift from Road Ecology to Transportation Ecology to better address the cumulative environmental impacts of transportation systems in urban areas. This study recommends that transit operators and policymakers integrate more and more ecological principles into the planning and management of transportation systems to achieve both environmental sustainability and economic benefits. This involves considering the full spectrum of ecological impacts, from infrastructure development to daily operations, and emphasizes the importance of long-term ecological monitoring and the inclusion of transportation in urban planning frameworks.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

Acknowledgments: The author wishes to thank all the members of the UITP Working Group on Transportation Ecology within the Research in Mobility Committee for inspiring this paper.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. Forman, R.T.; Sperling, D.; Bissonette, J.A.; Clevenger, A.P.; Cutshall, C.D.; Dale, V.H.; Fahrig, L.; France, R.L.; Goldman, C.R.; Heanue, K. *Road Ecology—Science and Solutions*; Island Press: Washington, DC, USA, 2003; pp. 12–35.
2. Odum, E.P. *Fundamentals of Ecology*; W.B. Saunders: Philadelphia, PA, USA, 1971.
3. von Herrmann, F.W. (Ed.) *Martin Heidegger. Vorträge und Aufsätze (1936–1953)*; Klostermann: Frankfurt am Main, Germany, 2000; Volume 8.
4. Takeda, F. An approach to make regional developmental effect of road construction compatible with environmental conservation. *Stud. Reg. Sci.* **1971**, *2*, 37–45. [CrossRef]
5. Scheerer, H. *Die Auswirkungen des Fernstrassenbaus und des Fernverkehrs auf Die Natuerliche Umwelt*; Report N. 23; Deutscher Rat für Landespflege: Bonn, Germany, 1974.
6. Mathe, P. Ökologische Gesichtspunkte beim Ausbau und bei der Asphaltierung von Wegen und Strassen mit Verdichtung der Verkehrsnetze auch im landlichen Raum. *Forum Stadte-Hyg.* **1977**, *28*, 189–193.
7. Fielenbach, R. Strasse und Ökologie. *Str. Autob.* **1975**, *26*, 52–54.
8. Bellport, B.P. US Bureau of Reclamation -USBR specifications focus on environment. *Civ. Eng.* **1971**, *41*, 50–52.
9. Muskett, C.J.; Jones, M.P. The dispersal of lead, cadmium and nickel from motor vehicles and effects on roadside invertebrate macrofauna. *Environ. Pollut. A* **1980**, *23*, 231–242. [CrossRef]
10. Ofomata, G.E.K. Impact of road building, urbanisation and general infrastructural development on the Nigerian rainforest ecosystem. *Landsc. Plan.* **1981**, *8*, 21–29. [CrossRef]
11. Davis, J.B.; George, J.J. Invertebrates as indicators of urban and motorway discharges. *Sci. Total Environ.* **1987**, *59*, 291–302. [CrossRef] [PubMed]

12. Dyment, R. Pure waters project includes restoration. *Water Sew. Work.* **1974**, *121*, 52–53.
13. Bacsó, J.; Kis-Varga, M.; Kovács, P.; Kalinka, G. Investigation on the accumulation of lead and other metals in plants caused by motor-traffic and smelting. *J. Radioanal. Nucl. Chem.* **1984**, *81*, 59–65. [CrossRef]
14. Tam, N.F.Y.; Liu, W.K.; Wong, M.H.; Wong, Y.S. Heavy metal pollution in roadside urban parks and gardens in Hong Kong. *Sci. Total Environ.* **1987**, *59*, 325–328. [CrossRef]
15. Bischofsberger, W. Ueber den Einfluss der Tausalze auf Grund- und Oberflaechenwasser. *Str. Tiefbau* **1985**, *39*, 6–10.
16. Scott, N.E.; Davison, A.W. The distribution and ecology of coastal species on roadsides. *Vegetation* **1985**, *62*, 433–440. [CrossRef]
17. Morikawa, T. The influence of road dust on asthmatic children. *Jpn. J. Allergol.* **1985**, *34*, 297–304.
18. Healy, M.A.; Aslam, M. The distribution of lead in a roadside environment and its consequences for health. *Public Health* **1980**, *94*, 78–88. [CrossRef]
19. van der Ree, R.; Jaeger, J.A.G.; van der Grift, E.A.; Clevenger, A.P. Effects of roads and traffic on wildlife populations and landscape function: Road ecology is moving towards larger scales. *Ecol. Soc.* **2011**, *16*, 48. [CrossRef]
20. Ellenberg, H.; Müller, K.; Stottele, T.; Walper, K.H. Straßen-Ökologie: Auswirkungen von Autobahnen und Straßen auf Ökosysteme deutscher Landschaften. *Okol. Straße* **1981**, *3*, 19–122.
21. Forman, R.T.T. Road ecology: A solution for the giant embracing us. *Landsc. Ecol.* **1998**, *13*, III–V. [CrossRef]
22. Harris, L.D.; Scheck, J. From implications to applications: The dispersal corridor principle applied to the conservation of biological diversity. In *Nature Conservation 2: The Role of Corridors*; Saunders, D.A., Hobbs, R.J., Eds.; Surrey Beatty and Sons: Chipping Norton, UK, 1991; pp. 189–220.
23. Coffin, A.W. From roadkill to road ecology: A review of the ecological effects of roads. *J. Transp. Geogr.* **2007**, *15*, 396–406. [CrossRef]
24. Forman, R.T.T.; Alexander, L.E. Roads and their major ecological effects. *Ann. Rev. Ecol. Syst.* **1998**, *29*, 207–232. [CrossRef]
25. Voller, J.; Harrison, S. (Eds.) Connectivity. In *Conservation Biology Principles for Forested Landscapes*; UBC Press: Vancouver, BC, Canada, 1998; pp. 76–97.
26. Parminter, J.V. Natural disturbance ecology. In *Conservation Biology Principles for Forested Landscapes*; Voller, J., Harrison, S., Eds.; UBC Press: Vancouver, BC, Canada, 1998; pp. 3–41.
27. Sousa, W.P. The Role of Disturbance in Natural Communities. *Ann. Rev. Ecol. Syst.* **1984**, *15*, 353–391. [CrossRef]
28. Hunt, A.; Dickens, H.J.; Whelan, R.J. Movement of mammals through tunnels under railway lines. *Aust. Zool.* **1987**, *24*, 89–93. [CrossRef]
29. Yanes, M.; Velasco, J.M.; Suárez, F. Permeability of roads and railways to vertebrates: The importance of culverts. *Biol. Conserv.* **1995**, *71*, 217–222. [CrossRef]
30. De Santo, R.S.; Smith, D.G. An introduction to issues of habitat fragmentation relative to transportation corridors with special reference to high-speed rail (HSR). *Environ. Manag.* **1993**, *17*, 111–114. [CrossRef]
31. Rodriguez, A.; Crema, G.; Delibes, M. Use of non-wildlife passages across a high speed railway by terrestrial vertebrates. *J. Appl. Ecol.* **1996**, *33*, 1527–1540. [CrossRef]
32. Kaczensky, P.; Knauer, F.; Krze, B.; Jonozovic, M.; Adamic, M.; Gossow, H. The impact of high speed, high volume traffic axes on brown bears in Slovenia. *Biol. Conserv.* **2003**, *111*, 191–204. [CrossRef]
33. Popp, J.N.; Boyle, S.P. Railway ecology: Underrepresented in science? *Basic Appl. Geol.* **2017**, *19*, 84–89. [CrossRef]
34. Barrientos, R.; Ascensão, F.; Beja, P.; Pereira, H.M.; Borda-de-Água, L. Railway ecology vs. road ecology: Similarities and differences. *Eur. J. Wildl. Res.* **2019**, *65*, 12. [CrossRef]
35. Borda-de-Água, L.; Barrientos, R.; Beja, P.; Pereira, H.M. *Railway Ecology*; Springer: Cham, Switzerland, 2017.
36. Karlson, M.; Mortberg, U.; Balfors, B. Road ecology in environmental impact assessment. *Eur. J. Wildl. Res.* **2014**, *48*, 10–19. [CrossRef]
37. Santos, G.; Behrendt, H.; Maconi, L.; Shirvani, T.; Teytelboym, A. Part I: Externalities and economic policies in road transport. *Res. Transp. Econ.* **2010**, *28*, 2–45. [CrossRef]
38. Iuell, B. *Wildlife and Traffic: A European Handbook for Identifying Conflicts and Designing Solutions*; KNNV Publishers: BM Zeist, The Netherlands, 2003.
39. Togridou, A. Rail: A test bed for biodiversity innovations. *TCR South—Rev.* **2023**, *26*, 60–63.
40. Goldfarb, B. City of Glass.31.10.2023. Available online: https://www.biographic.com/city-of-glass/ (accessed on 29 March 2024).
41. Transport Infrastructure Ireland. *Design and Delivery of Soft Landscape Treatments in Urban Transport Environments*; Technical Report; TIE: Dublin, Ireland, 2003; pp. 111–113.
42. Naumann, S.; Davis, M.; Kaphengst, T.; Pieterse, M.; Rayment, M. *Design, Implementation and Cost Elements of Green Infrastructure Projects*; Ecologic Institute and GHK Consulting: Berlin, Germany, 2011; pp. 63–109.
43. Biodiversity Andiinfrastructure Synergies and Opportunities for European Transport Networks—BISON. BISON Policy Brief. Available online: https://bison-transport.eu/2023/10/16/bison-policy-briefs/ (accessed on 29 March 2024).
44. Wilansky, J.; Jaeger, J.A.G. Predicting the effectiveness of wildlife fencing along roads using an individual-based model: How do fence-following distances influence the fence-end effect? *Ecol. Model.* **2024**, *495*, 110784. [CrossRef]
45. Wall, A.E.; Biffi, D.; Ackel, A.; Moody, R.W.; Stevens, T.K.; Williams, D.A. Small towns limit dispersal and reduce genetic diversity in populations of Texas horned lizards. *Ecol. Evol.* **2024**, *14*, e70112. [CrossRef] [PubMed]

46. Červinka, J.; Riegert, J.; Grill, S.; Šálek, M. Large-scale evaluation of carnivore road mortality: The effect of landscape and local scale characteristics. *Mammal Res.* **2015**, *60*, 233–243. [CrossRef]
47. Finch, D.; Schofield, H.; Mathews, F. Traffic noise playback reduces the activity and feeding behaviour of free-living bats. *Environ. Pollut.* **2020**, *263*, 114405. [CrossRef]
48. Ortiz-Urbina, E.; Diaz-Balteiro, L.; Iglesias-Merchan, C. Influence of anthropogenic noise for predicting cinereous vulture nest distribution. *Sustainability* **2020**, *12*, 503. [CrossRef]
49. Madadi, H.; Moradi, H.; Soffianian, A.; Salmanmahiny, A.; Senn, J.; Geneletti, D. Degradation of natural habitats by roads: Comparing land-take and noise effect zone. *Environ. Impact Assess. Rev.* **2017**, *65*, 147–155. [CrossRef]
50. Ghadirian, O.; Moradi, H.; Madadi, H.; Lotfi, A.; Senn, J. Identifying noise disturbance by roads on wildlife: A case study in central Iran. *SN Appl. Sci.* **2019**, *1*, 808. [CrossRef]
51. Francis, C.D.; Barber, J.R. A framework for understanding noise impacts on wildlife: An urgent conservation priority. *Front. Ecol. Environ.* **2013**, *11*, 305–313. [CrossRef] [PubMed]
52. Blackwell, B.F.; Devault, T.L.; Seamans, T.W. Understanding and Mitigating the Negative Effects of Road Lighting on Ecosystems. In *Handbook of Road Ecology*; van der Ree, R., Smith, D.J., Grilo, C., Eds.; Wiley: Chichester, UK, 2015; pp. 143–150.
53. Roedenbeck, I.A.; Fahrig, L.; Findlay, C.S.; Houlahan, J.E.; Jaeger, J.A.; Klar, N.; Kramer-Schadt, S.; van der Grift, E.A. The Rauischholzhausen agenda for road ecology. *Ecol. Soc.* **2007**, *12*, 11. [CrossRef]
54. Forman, R.T.T.; Deblinger, R.D. The ecological road-effect zone of a Massachusetts (USA) suburban highway. *Conserv. Biol.* **2000**, *14*, 36–46. [CrossRef]
55. Ciabò, S.; Fabrizio, M.; Ricci, S.; Merten, A. *Strade—Life*; Regione Umbria: Perugia, Italy, 2015.
56. Selva, N.; Kreft, S.; Kati, V.; Schluck, M.; Jonsson, B.G.; Mihok, B.; Okarma, H. Roadless and Low-Traffic Areas as Conservation Targets in Europe. *Environ. Manag.* **2011**, *48*, 865–877. [CrossRef] [PubMed]
57. Loss, S.R.; Will, T.; Loss, S.S.; Marra, P.P. Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability. *Condor: Ornithol. Appl.* **2014**, *116*, 8–23. [CrossRef]
58. Calvario, E.; Sebasti, S.; Copiz, R.; Salomone, F.; Brunelli, M.; Tallone, G.; Blasi, C. *Habitat e Specie di Interesse Comunitario nel Lazio*; Regione Lazio—ARP: Rome, Italy, 2009.
59. Bissonette, J.A.; Kassar, C.A.; Cook, L.J. Assessment of Costs Associated with Deer–Vehicle Collisions: Human Death and Injury, Vehicle Damage, and Deer Loss. *Hum.-Wildl. Interact.* **2008**, *2*, 9.
60. Huijser, M.P.; Duffield, J.W.; Clevenger, A.P.; Ament, R.J.; McGowen, P.T. Cost–benefit analyses of mitigation measures aimed at reducing collisions with large ungulates in the United States and Canada; a decision support tool. *Ecol. Soc.* **2009**, *14*, 15. [CrossRef]
61. Conover, M.R.; Pitt, W.C.; Kessler, K.K.; DuBow, T.J.; Sanborn, W.A. Review of human injuries, illnesses, and economic losses caused by wildlife in the United States. *Wildl. Soc. Bull.* **1995**, *23*, 407–414.
62. Bíl, M.; Grilo, C.; Kubeček, J.; Sedoník, J.; Andrášik, R.; Cícha, V.; Favilli, F.; Stauder, J.; Schwingshackl, F.; Michael, K.; et al. Wildlife Vehicle Collisions: Road Ecology, Monitoring and Mitigation, Citizen Science, Pedagogical and Socioeconomic Aspects. Report ERASMUS+ "EnVeROS" Report, Intellectual Output 1. 2019. Available online: http://www.enveros.eu/ (accessed on 28 June 2024).
63. Automobil Club d'Italia—ACI, 2022. Distribuzione Parco Veicoli per Anno, Comune Capoluogo e Categoria—Open Parco Veicoli Database. 2022. Available online: https://opv.aci.it/WEBDMCircolante/ (accessed on 28 June 2024).
64. Baccelli, O. Scenari e Prospettive Dell'elettrificazione del Trasporto Pubblico su Strada. Un'innovativa Analisi di Benchmark: Il TCRO—Total Cost and Revenues of Ownership. Metodologia e Risultati per l'Italia, Presentation at Bocconi University Milan. 16 November 2021. Available online: https://www.enelfoundation.org/content/dam/enel-foundation/topics/2021/11/211116%20GREEN%20per%20evento%20su%20TCRO%20caso%20Italia_per%20evento%20v7def.pdf (accessed on 29 June 2024).
65. Seiler, A. The Toll of the Automobile—Wildlife and Roads in Sweden. Ph.D. Thesis, Department of Conservation Biology, Swedish University of Agricutural Sciences, Uppsala, Sweden, 2003.
66. Intesa SanPaolo Preventivo Assicurazione Autobus, Autocarri, Caravan, Furgoni, Natanti, Mezzi Agricoli 2024. Available online: https://www.intesasanpaoloassicura.com/preventivatore-altriveicoli (accessed on 29 June 2024).
67. Clevenger, A.P.; Chruszcz, B.; Gunson, K.E. Highway mitigation fencing reduces wildlife-vehicle collisions. *Wildl. Soc. Bull.* **2001**, *29*, 646–653.
68. Gagnon, J.W.; Dodd, N.L.; Sprague, S.C.; Ogren, K.S.; Loberger, C.D.; Schweinsburg, R.E. Animal-activated highway crosswalk: Long-term impact on elk-vehicle collisions, vehicle speeds, and motorist braking response. *Hum. Dimens. Wildl.* **2019**, *24*, 132–147. [CrossRef]
69. Guccione, M.; Gori, M.; Bajo, N. *Tutela della Connettività Ecologica del Territorio e Infrastrutture Lineari*; ISPRA: Rome, Italy, 2008.
70. Robertson, R.D.; Delavary, M.; Lyon, C.; Vanlaar, W. Effect of eco-driving on commercial motor vehicle driver collision risk. *J. Saf. Res.* **2024**, *89*, 190–196. [CrossRef] [PubMed]
71. Litman, T. *Traffic Calming: Benefits, Costs and Equity Impacts*; Victoria Transport Policy Institute: Victoria, BC, Canada, 1999.
72. Haworth, N.; Symmons, M. Driving to Reduce Fuel Consumption and Improve Road Safety. In Proceedings of the Road Safety Research, Policing and Education Conference 2001, Melbourne, VIC, Australia, 18–20 November 2001.
73. Romero, C.A.; Correa, P.; Ariza Echeverri, E.A.; Vergara, D. Strategies for Reducing Automobile Fuel Consumption. *Appl. Sci.* **2024**, *14*, 910. [CrossRef]

74. ATAC Bilancio di Esercizio al. 31 December 2022. Available online: https://trasparenza.atac.roma.it/moduli/downloadFile.php?file=oggetto_allegati/232111122320O__OBilancio+ATAC+al+31.12.2022.pdf (accessed on 29 June 2024).
75. KPMG Greener-Journeys-Maximising-the-Benefits-of-Local-Bus-Services. 2023. Available online: https://greener-vision.com/wp-content/uploads/2020/07/Greener-Journeys-Maximising-the-benefits-of-local-bus-services.pdf (accessed on 29 June 2024).
76. Sustainable Bus. UK Funding Streams for Zero Emission Buses, Well Explained. Available online: https://www.sustainable-bus.com/news/uk-funding-zero-emission-buses-well-explained/ (accessed on 29 June 2024).
77. Piaggio, V. The Global Inclusion Imperative. Available online: https://www.kantar.com/inspiration/brands/the-global-inclusion-imperative (accessed on 22 December 2023).
78. Hlaváč, V.; Anděl, P.; Matoušová, J.; Dostál, I.; Strnad, M. *Wildlife and Traffic in the Carpathians. Guidelines How to Minimize Impact of Transport Infrastructure Development on Nature in the Carpathian Countries. Danube Transnational Programme TRANSGREEN Project*; The State Nature Conservancy of the Slovak Republic: Banská Bystrica, Slovakia, 2019.
79. van der Grift, E.A.; van der Ree, R.; Fahrig, L.; Findlay, S.; Houlahan, J.; Jaeger, J.A.G.; Klar, N.; Madriñan, L.F. Evaluating the effectiveness of road mitigation measures. *Biodivers. Conserv.* **2013**, *22*, 425–448. [CrossRef]
80. Corazza, M.V. Ecologia delle Infrastrutture Viarie a tutela dell'ambiente: Concetti e criteri per una ricerca allargata alle discipline trasportistiche. *Ing. Ferrov.* **2022**, *10*, 787–808.
81. Mihai, F.C.; Schneider, P.; Eva, M. Engineering and green infrastructure in mitigating emerging urban environmental threats. In *Handbook of Ecological and Ecosystem Engineering*; Narasimha, M., Prasad, V., Eds.; Wiley: Chichester, UK, 2021; pp. 95–121.
82. Herrera, D.J.; Fidino, M.; Luther, D.; Mullinax, J.M.; Gallo, T. Historical park planning is associated with modern-day patterns of bird diversity in cities. *Landsc. Urban Plan.* **2024**, *249*, 105132. [CrossRef]
83. Kirk, H.; Soanes, K.; Amati, M.; Bekessy, S.; Harrison, L.; Parris, K.; Ramalho, C.; Van de Ree, R.; Threlfall, C. Ecological connectivity as a planning tool for the conservation of wildlife in cities. *MethodsX* **2023**, *10*, 101989. [CrossRef] [PubMed]
84. Smythe, T.; McCann, J.A.; Fox, C. Spatial Planning for busy waterways: A case study of innovative waterways management in the San Francisco Bay region. In *Case Studies of Marine Spatial Planning Report Series*; McCann, J., Ed.; Coastal Resources Center and Rhode Island Sea Grant College Program, URI Graduate School of Oceanography: Narragansett, RI, USA, 2016; pp. 56–62.
85. Utrecht Municipality. Green-Roofed Bus Shelters in Utrecht. Available online: https://www.utrecht.nl/city-of-utrecht/green-roofed-bus-shelters-in-utrecht (accessed on 1 August 2024).
86. Granger, B.; Burnham, R.; Vagle, S. Soundscape additions from vessels related to transit speed, direction and manoeuvres. *Can. Acoust.* **2023**, *51*, 39–48.
87. Grand Paris Express. Protecting the Environment during the Build. Available online: https://view.genially.com/606574ffda2fe30ce2f43bf5 (accessed on 1 August 2024).
88. Erftemeijer, P.L.A.; Lewis, R.R.R., III. Environmental impacts of dredging on seagrasses: A review. *Mar. Poll. Bull.* **2006**, *52*, 1553–1572. [CrossRef] [PubMed]
89. Bahía, R.; Lambertucci, S.A.; Speziale, K.L. Anthropogenic city noise affects the vocalizations of key forest birds. *Biodivers. Conserv.* **2024**, *33*, 2405–2421. [CrossRef]
90. Nikolopoulos, A.; Sigray, P.; Andersson, M.; Carlström, J.; Lalander, E. 2016: BIAS Implementation. Plan—Monitoring and Assessment Guidance for Continuous Low Frequency Sound in the Baltic Sea, Technical Report. 2016. Available online: www.bias-project.eu (accessed on 1 August 2024).
91. Zellmer, A.J.; Goto, B.S. Urban wildlife corridors: Building bridges for wildlife and people. *Front. Sustain. Cities* **2022**, *4*, 954089. [CrossRef]
92. Ledoux, L.; Crooks, S.; Jordan, A.; Turner, R.K. Implementing EU biodiversity policy: UK experiences. *Land Use Policy* **2000**, *17*, 257–268. [CrossRef]
93. Rautjärvi, S.; MacGregor-Fors, I. Where economic parity meets ecology: Neither biodiversity nor ecosystem integrity values relate to wealth in the context of a medium-sized Finnish city. *Ambio* **2024**, *53*, 292–298. [CrossRef]
94. Dasgupta, P. *The Economics of Biodiversity*; Cambridge University Press: Cambridge, UK, 2024; pp. 107–113.
95. Li, T.; Tian, W.; Zhang, S.; Wang, S. Environmental regulation, high-quality economic development and ecological capital utilization. *Front. Environ. Sci.* **2024**, *12*, 1325289. [CrossRef]
96. Mudalige, U.; Carver, S. Unveiling Sri Lanka's Wilderness: GIS-Based Modelling of Wilderness Attributes. *Land* **2024**, *13*, 402. [CrossRef]
97. Andersson, E.; McPhearson, T.; Pickett, S.T.A. From urban ecology to urban enquiry: How to build cumulative and context-sensitive understandings. *Ambio* **2024**, *53*, 813–825. [CrossRef] [PubMed]
98. Moore, L.J.; Arietta, A.A.; Spencer, D.T.; Huijser, M.P.; Walder, B.L.; Abra, F.D. On the road without a map: Why we need an "Ethic of Road Ecology". *Front. Ecol. Evol.* **2021**, *9*, 774286. [CrossRef]
99. Owais, M. Deep Learning for Integrated Origin–Destination Estimation and Traffic Sensor Location Problems. *IEEE Trans. Intell. Transp. Syst.* **2024**, *25*, 6501–6513. [CrossRef]
100. Owais, M.; Moussa, G.S.; Hussain, K.F. Robust deep learning architecture for traffic flow estimation from a subset of link sensors. *J. Transp. Eng. A* **2020**, *146*, 04019055. [CrossRef]
101. Owais, M.; Osman, M.K. Complete hierarchical multi-objective genetic algorithm for transit network design problem. *Expert Syst. Appl.* **2018**, *114*, 143–154. [CrossRef]

102. Owais, M.; Osman, M.K.; Moussa, G.S. Multi-Objective Transit Route Network Design as Set Covering Problem. *IEEE Trans. Intell. Transp. Syst.* **2016**, *17*, 670–679. [CrossRef]
103. Corazza, M.V.; Di Mascio, P.; Esposito, G. Airports as Sensitive Areas to Mitigate Air Pollution: Evidence from a Case Study in Rome. *Environments* **2022**, *9*, 108. [CrossRef]
104. Di Mascio, P.; Corazza, M.V.; Rosa, N.R.; Moretti, L. Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports. *Sustainability* **2022**, *14*, 9692. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.