HANDBOOK TO MITIGATE THE IMPACTS OF ROADS AND RAILWAYS ON ASIAN ELEPHANTS

From the Asian Elephant Transport Working Group

IUCN
WCPA WORLD COMMISSION ON PROTECTED AREAS
CONNECTIVITY CONSERVATION Specialist Group
SSC Species Survival Commission
ASIAN ELEPHANT SPECIALIST GROUP

HANDBOOK TO MITIGATE THE IMPACTS OF ROADS AND RAILWAYS ON ASIAN ELEPHANTS

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Cover photo: A young Asian elephant crossing the road | Adobe Stock

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Foreword

There has never been a more pressing time for in-depth guidelines on linear infrastructure mitigation measures concerning elephants. These large-bodied, long-ranging proboscideans have been at the receiving end of a number of ill-planned or eco-insensitive development projects that stop their ability to move from habitat to habitat to satiate their basic needs of food, water, and security. Along with the pressures of forest and grassland loss and fragmentation and the threats of poaching, this added dimension of not being able to move between habitats due to linear infrastructure is affecting elephant populations greatly.

Elephants have been driven from their traditional movement corridors and have been forced through human habitation, often confused and disoriented, and cause severe conflict, including loss of human lives. In Asia today, more than 700 human lives are being lost annually due to wild elephants. Hundreds of elephants are also killed in retaliation. Equally problematic, the measures to protect this endangered species (and a critically endangered sub-species) and national laws and regulations have often been at odds because of the need for many nation states to rapidly increase their linear infrastructure to meet national developmental goals.

In order to escape this vortex of bilateral destruction, it is necessary to provide technical solutions to the twin issues. To prove that human developmental needs are concomitant with environmental concerns, there is a need for engineering and technological solutions that have an inherently eco-friendly approach. This Handbook, brought forth by the collaboration of two IUCN specialist groups (the Connectivity Conservation Specialist Group and the Asian Elephant Specialist Group) belonging to two sister commissions (the World Commission on Protected Areas and the Species Survival Commission), attempts to do just that.

Following up on the 'Protecting Asian Elephants from Linear Infrastructure' primer published in 2021, these detailed guidelines provide steps to be taken by developmental agencies when planning any linear infrastructure projects. While avoidance is still considered the ideal option for areas that are high in biodiversity richness, these guidelines have a role in case avoidance is not possible. In such cases, these guidelines can be used for a win-win situation for biodiversity conservation and human development.

I hope this Handbook is widely utilised across the elephant range and that it is adapted and translated into local languages, so that its use across all 13 countries that still have the Asian elephant is encouraged. I would also like to compliment the two commissions of the IUCN, which have come together in such a good example of collaboration for a common purpose.

Vivek Menon
Councillor, IUCN &
Chair, Asian Elephant Specialist Group, IUCN SSC
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A motorbike narrowly passes an elephant on a road in Sri Lanka.
| SREEDHAR VIJAYAKRISHNA

1. Introduction

The Asian elephant (*Elephas maximus*) is an iconic and wide-ranging keystone species inhabiting the biologically rich ecosystems of South and Southeast Asia (Williams et al., 2020). Their historical range covered eastern and southern China, stretching westward across to East Asia, ranging across Bhutan, Nepal, Sri Lanka, Pakistan, Bangladesh, and India, with historical evidence showing the elephant range crossed the Iranian coast and reached the ancient civilisation of Mesopotamia, where modern-day Turkey stands (Calabrese et al., 2017; Fernando & Pastorini, 2011; Mahmood et al., 2021; Sukumar, 2003). The Asian elephant's historical range also extended into Southeast Asia, covering Vietnam, Lao PDR, Cambodia, Myanmar, Thailand, Peninsular Malaysia and the island of Borneo (Sabah, Malaysia and Kalimantan, Indonesia), with the furthest southern range reaching the Indonesian island of Sumatra (Calabrese et al., 2017; Fernando & Pastorini, 2011; Mahmood et al., 2021; Sukumar, 2003). Since 1700, changes in land use and land cover have resulted in a 64% (3.36 million km^2) decline in suitable elephant habitats across Asia (de Silva et al., 2023).

Today, Asian elephants are listed as 'Endangered' (the Sumatran subspecies is listed as Critically Endangered) on the IUCN Red List of Threatened Species (IUCN, 2019). Approximately 52,000 Asian elephants are scattered across 13 countries in fragmented populations (Menon & Tiwari, 2019). Along with reduced habitat and range distribution, anthropogenic activities have contributed to landscape fragmentation, blocking ancient movement routes, reducing gene flow, and contributing to escalating human-elephant conflicts (HEC) (Leimgruber et al., 2003; Menon et al., 2017; Nyhus, 2016; Shaffer et al., 2019). A key anthropogenic threat to Asian elephant conservation is the development of linear transport infrastructure (LTI), such as roads, railways, and canals. LTI development is crucial for achieving global Sustainable Development Goals (SDGs), and funding for new and improved LTI across Asia is expected to increase dramatically. According to the Asian Development Bank, an annual investment of USD 1.7 trillion through 2030 is needed to maintain current growth rates and respond to climate change, with nearly one-third allocated to transport projects (ADB, 2017).

However, without proper safeguards in place, the unprecedented rate and rapidity of LTI development may contribute to global biodiversity decline and have significant negative impacts on Asian elephants (Wang et al., 2022). Construction and expansion of LTI without proper adherence to the mitigation hierarchy (Ekstrom et al., 2015; Figure 1) and other green standards and best practices can hinder elephant conservation and recovery efforts and necessitate habitat, corridor, and related protected area network restoration (Goswami et al., 2014; Hilty et al., 2020; Menon et al., 2017, 2020; Sukumar et al., 2016). In India, home to over half of all Asian elephants, LTI, especially collisions with trains, is a leading anthropogenic cause of elephant mortality (Thomas, 2021). Huang et al. (2020) reported that expanding Asian transport networks will further reduce elephant habitats and isolate herds, exacerbating human-elephant conflicts. Additionally, within the Terai Arc Landscape, the proximity to roads was identified as the most important factor influencing habitat suitability for elephants that prefer habitats away from roads (Sharma et al., 2020).

1.1. The Asian Elephant Transport Working Group

To address the impacts of LTI, the Asian Elephant Transport Working Group (AsETWG) was formed. The AsETWG is a collaboration between the IUCN World Commission on Protected Areas Connectivity Conservation Specialist Group (CCSG) and the IUCN Species Survival Commission's Asian Elephant Specialist Group (AsESG). Its mission is to serve as the hub of expertise and technical support to deliver practical, science-based solutions that avoid and mitigate threats to Asian elephants posed by LTI across all 13 range states.

Read the first AsETWG publication here.

The first publication from the AsETWG (Ament et al., 2021), Protecting Asian Elephants from Linear Transport Infrastructure: The Asian Elephant Transport Working Group's Introduction to the Challenges and Solutions, detailed the impacts of existing and rapidly expanding LTI networks on elephants and provided an overview of the available range of options to address LTI impacts. It stressed the importance of embracing the mitigation hierarchy as a key approach to planning and designing alternative development for LTI projects (Ament et al., 2023; Figure 1).

The AsETWG recognizes the importance of adhering to the Avoid and Minimise approaches to LTI project development when at all possible, especially within protected areas.

We in no way advocate for the pursuit of the Mitigate approach as an alternative to early and thorough consideration of avoidance and/or minimisation strategies.

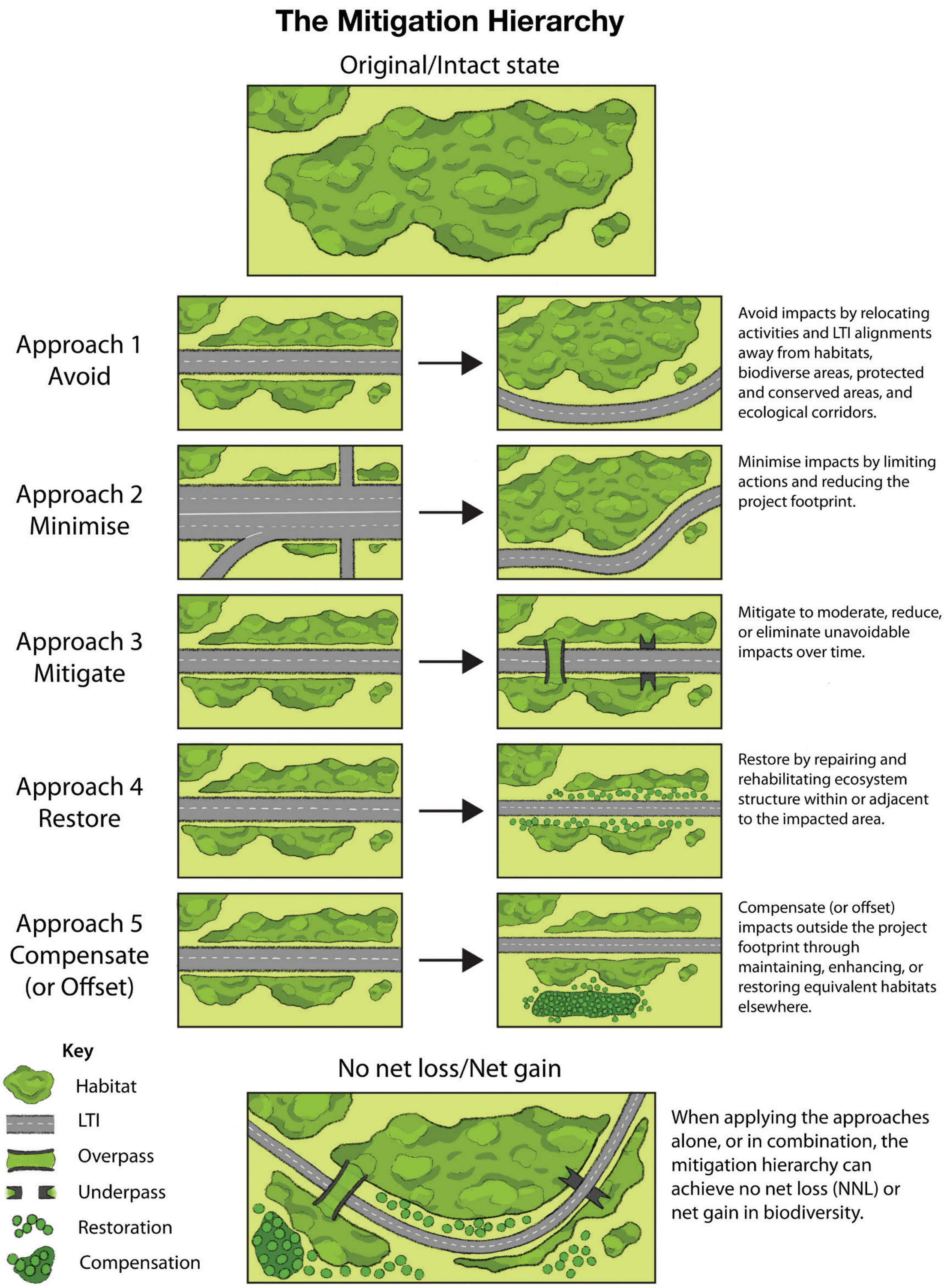

Figure 1. The mitigation hierarchy is a systematic approach used in environmental impact assessment and management to address and minimise the negative impacts of development projects on the environment. It consists of steps to achieve the best possible environmental outcome.

| JULIE JOHNSON AND MADISON MAYFIELD / CENTER FOR LARGE LANDSCAPE CONSERVATION

This publication aims to provide Asian elephant-specific mitigation measures to address the negative impacts of LTI. Mitigation measures have proven increasingly important to help address LTI impacts on Asian elephants and their habitats in the face of rapidly expanding transport networks across Asia (Ament et al., 2021; Alamgir et al., 2017). Over the past decade, considerable insights have been gained from the increasing application of green infrastructure measures to mitigate LTI impacts to Asian elephants and other species to support the development of informed guidelines and recommendations.

With the projected expansion of LTI across Asia, even with concerted efforts to avoid high-biodiversity areas, effective mitigation measures will be critical to reduce project impacts and prevent further habitat degradation for Asian elephants. This handbook aims to foster the application of effective mitigation measures, specifically crossing structures. Growing experience and research worldwide have demonstrated the technical and economic feasibility of crossing structures and management activities in effectively mitigating the impact of new, upgraded, or existing LTI on wildlife (Alamgir et al., 2017; Brennan et al., 2022; Rytwinski et al., 2016).

A herd crosses the B35 in Yala National Park, Sri Lanka.
| JENNIFER PASTORINI

2. The Impact of Linear Transport Infrastructure on Asian Elephants

2.1. Indirect Impact of Linear Transport Infrastructure

Worldwide, LTI constitutes a significant force altering natural ecosystems and impacting biodiversity (Foggin et al., 2021; Nayak et al., 2020). Poorly planned LTI development can have severe impacts on ecosystems and species. Often referred to as 'Pandora's Box,' the expansion or development of new infrastructure can have severe impacts on ecosystems and species, especially in and around protected areas. Some of these environmental problems include:

- loss, fragmentation, and degradation of habitat,
- increased rates of hunting and poaching of wildlife,
- increased resource extraction, such as legal and/or illegal mining and logging,
- pollution due to noise, light, vibrations and chemicals from vehicles and trains,
- increased frequency and intensity of wildfires,
- land speculation or land use change, and
- illegal settlements and increased human activity.

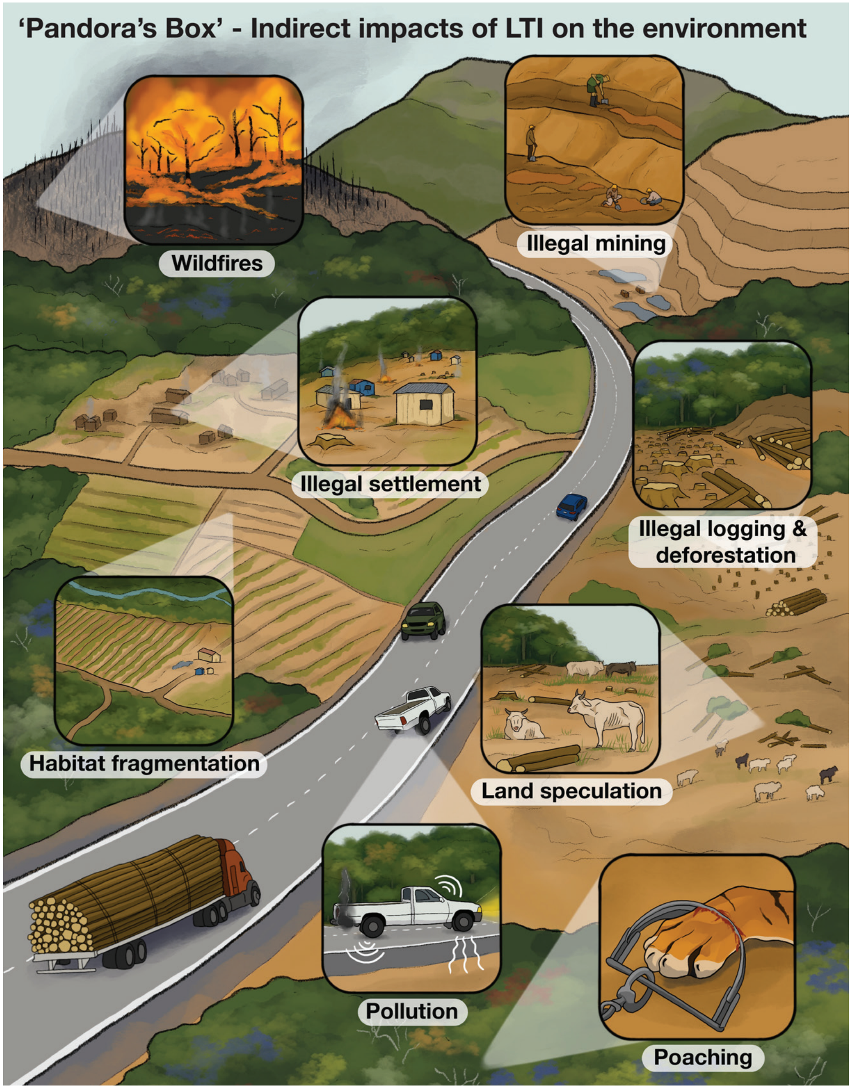

Figure 2. The construction of linear transport infrastructure (LTI) has significant and harmful effects on ecosystems and species. These impacts include habitat loss, degradation, fragmentation, and increased rates of hunting, poaching, illegal mining, logging, and other extractive industries. LTI also contributes to pollution through noise, light, vibrations, and chemicals emitted by vehicles and trains. Additionally, it can increase the frequency and intensity of wildfires, land speculation, and the establishment of illegal settlements.
| JULIE JOHNSON AND MADISON MAYFIELD / CENTER FOR LARGE LANDSCAPE CONSERVATION

2.2. Direct Impact of Linear Transport Infrastructure

Figure 3 highlights the direct impacts of railways on elephants; impacts from roadways and canals are generally considered similar (Ament et al., 2023).

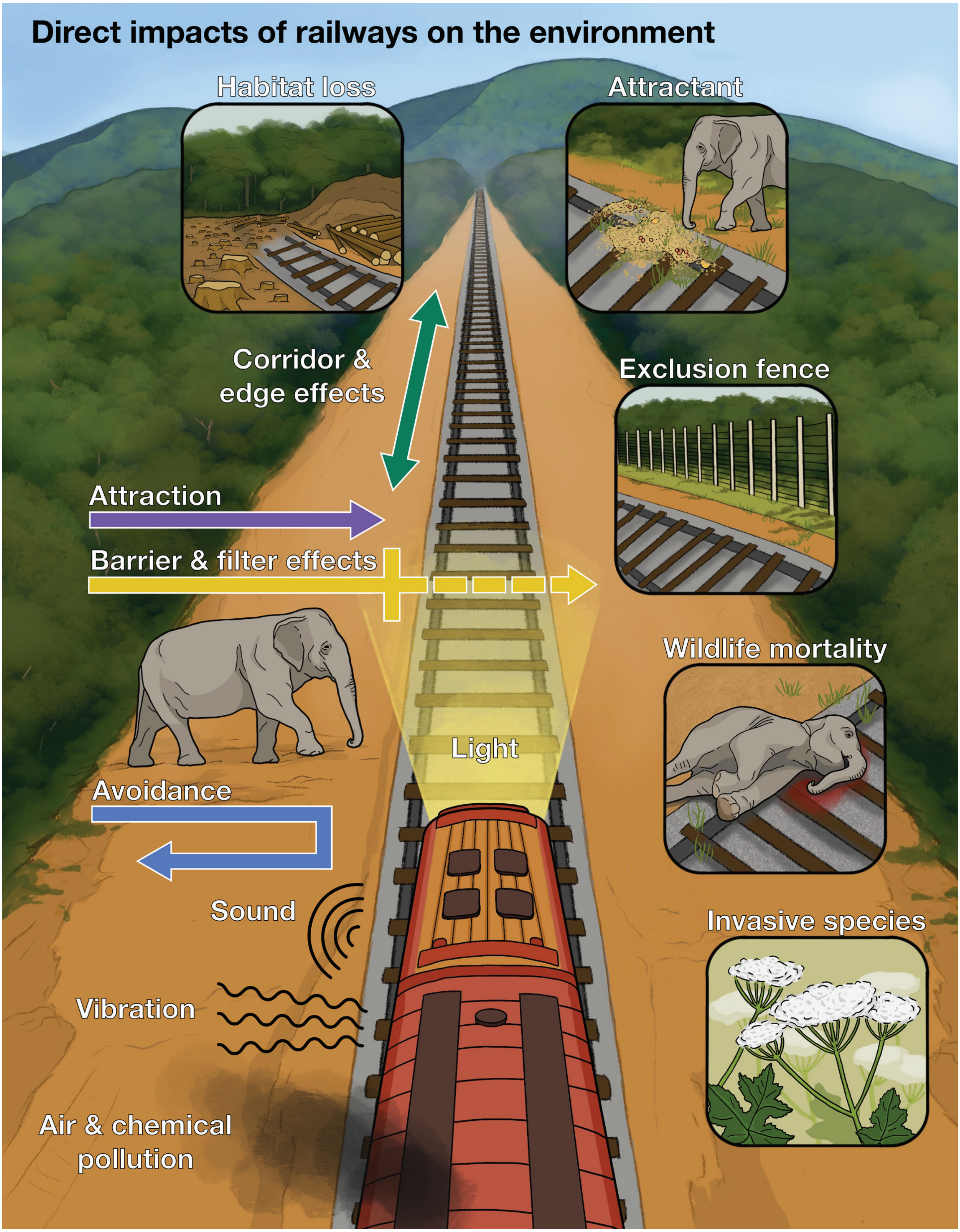

Figure 3. The direct impact of railways on Asian elephants.
| JULIE JOHNSON AND MADISON MAYFIELD / CENTER FOR LARGE LANDSCAPE CONSERVATION

2.3. Highway Impacts

Direct impacts, such as mortality and barrier effects from LTI, are recognised as a serious and growing threat to wildlife populations across the globe. Wildlife-vehicle collisions, while often deadly for wildlife, can also contribute to human injuries, deaths, and property loss (Cserkész & Farkas, 2015; Dorsey et al., 2015; Silva et al., 2021). Highway traffic and associated noise can contribute to wildlife avoidance zones (Forman & Alexander, 1998). For each kilometre of road in a national park in India, road-related habitat loss and degradation affected at least 10 hectares (ha) of habitat (Raman, 2011).

Highways with moderate traffic volume (less than 8,000 vehicles per day) were near-total barriers to wildlife passage (Paquet & Callaghan, 1996; Olsson, 2007; Dodd & Gagnon, 2011; Gagnon et al., 2012). Theoretical models (Seiler, 2003; Iuell et al., 2003) infer that highways with 4,000–10,000 average annual daily traffic present substantial barriers to wildlife passage that repel animals away from highways; at 10,000 average annual daily traffic and above, highways become impermeable barriers (Seiler, 2003).

2.4. Railway Impacts

Train collisions with Asian elephants are a significant and well-documented source of mortality, especially in India and Sri Lanka (Joshi & Singh, 2011; Menon et al., 2017; Rangarajan et al., 2010; Sarma et al., 2006; Singh & Sharma, 2001). Various factors contribute to this mortality, including ecological factors, railway physical factors (steep embankments and curves), technical factors (train speed, frequency, and time of travel), elephant behaviour, and lack of awareness among operators and planners (Singh & Sharma, 2001; Sarma et al., 2006). In India, train-related elephant mortalities were higher near curves and areas adjacent to heavy forest cover that reduces visibility. Dasgupta and Ghosh (2015) reported increased elephant-train collisions attributable to increased traffic and speed, low visibility, and the lack of effective warning systems for approaching trains.

In India, 355 elephants died in train collisions between 1987 and April 2023; two-thirds occurred in the states of Assam and West Bengal (Joshi et al., 2019; Government of India, 2023). Train-elephant collisions were found to occur more often at night and involved more male elephants when accounted for in terms of ratio in the population, as males may cross the tracks more often to embark on crop raiding behaviour during crop harvest season (Roy & Sukumar, 2017; Sukumar, 2003). In Sri Lanka, 122 elephant deaths were reported from train collisions between 2005 and 2018 (Ament et al., 2021). In addition, elephant deaths from vehicular collisions are a concern in Peninsular Malaysia, Thailand, and other range states.

Figure 4. An Asian elephant waits with her herd to cross a busy road at Kota Tinggi, Johor, Malaysia.
| GUKAANESWARAN KALIYAPPAN / MANAGEMENT & ECOLOGY OF MALAYSIAN ELEPHANTS

2.5. Barrier Effects

Indirect LTI barrier impacts can be even more pervasive than direct impacts. For many species, barrier and fragmentation effects contribute to diminished landscape connectivity and LTI permeability, or the ability of animals to cross highways and other LTI (Forman et al., 2003; Bissonette & Adair, 2008). LTI creates barriers to wildlife movement that fragment populations and habitats, limit juvenile dispersal and genetic interchange, threaten population viability, and increase population susceptibility to stochastic events (Epps et al., 2005; Ng et al., 2020; Singh & Sharma, 2001; Wang et al., 2022). The degree of barrier effect varies by wildlife species, highway type and standard, and traffic volume (Fahrig & Rytwinski, 2009; Jacobson et al., 2016). Mega-herbivores like elephants, with large home ranges and food requirements, have been among the species most affected by habitat alteration, fragmentation, and the loss of ecological connectivity (Leimgruber et al., 2003; Menon et al., 2017; Suksavate et al., 2019; Neupane et al., 2019). Within a protected area in China, initial elephant use of established travel corridors crossing a new road diminished by 82% after construction, though crossings at underpasses have increased over time (Pan et al., 2009). In a study from north Peninsular Malaysia, Wadey et al. (2018) reported that a Malaysian highway was a strong and consistent barrier to Asian elephants, reducing permeability by 80%.

2.6. Behavioural Impacts of LTI

Asian elephants display various behavioural reactions to LTI, depending on locality and individual experiences. A study in Mudumalai, a tiger reserve in India, found that wild elephants responded negatively to drivers who are more intrusive in their behaviour (e.g., yelling or taunting) and reacted differently towards varying vehicle sizes. However, a significant proportion of elephants became agitated or displayed extreme responses when motorists simply drove past, indicating that driver behaviour, vehicle type, and traffic volume are all compounding factors (Vidya & Thuppil, 2010). When elephant groups cross roads, the mature elephants often cross first, and they tend to stay on the road longer, possibly to look out for the group (Mizuno et al., 2017). Additionally, wider roads (regardless of major or secondary roads) elicit stress behaviour (i.e., straightening of the tail) from a larger proportion of elephants in the group, resulting in longer road crossing duration (Mizuno et al., 2017). Wadey et al. (2018) discovered that elephants in northern Peninsular Malaysia are drawn to the open, grassy areas along highways, including both hidden and exposed slopes, where forage is more abundant compared to adjacent forests, leading to increased time spent near roadways and elevating risks of vehicle collisions and poaching. The elephants were found to be primarily consuming grasses and other pioneer plants (Yamamoto-Ebina et al., 2016).

Additionally, recent observations by a WWF-India team through a complementary GPS collaring and camera trapping exercise indicate that elephants take longer to cross railway tracks that are elevated with steep inclines on either side, increasing the risk of collisions. Camera trap evidence has revealed that elephants cross such tracks one at a time, with each individual at the top waiting on the track until the one ahead has fully descended.

2.7. Canals

Canals rely on local topography for optimal water flow, often independent of paved roads and railways. Few studies have explored the impacts of canals on wildlife versus other forms of LTI, but canals have been noted as a significant cause of mortality. The rate of wildlife mortality due to drowning in canals is likely related to the speed of water flow; the height, gradient, and surface of canal embankments; and species-specific traits (Ament et al., 2021). Less is known about the impacts of canals versus roads; however, there is a clear overlap in many of the impacts and mitigation measures of roads and railways that can also be applied to canals (Ament et al., 2021). The density of canal networks on the landscape is relatively low; however, when combined with other LTI on the landscape, canals create additional barriers to Asian elephant movement and further fragment habitat. Near India's Rajaji National Park, an irrigation and hydroelectric canal has restricted access to the river Ganges, which elephants visit for drinking, bathing, and cooling off in the hotter months (Singh and Sharma, 2001). The mitigation measures offered in this handbook are tailored more specifically to roads and railways; however, many lessons may apply to the mitigation of canals for conservation practitioners and development officials.

3. The Mitigating Role of Wildlife Crossing Structures

Projects designed to promote landscape connectivity and permeability for wildlife as well as to reduce LTI-related wildlife mortality, have increased internationally—including in Asia—in the past decade, (ADB, 2019; Ament et al., 2021; Rajvanshi & Mathur, 2015; Wang et al., 2015) especially those benefiting Asian elephants (Chogyel et al., 2017; Pan et al., 2009; PLANMalaysia, 2022; Wang et al., 2015). Growing experience and research underscore the technical and economic feasibility of mitigation measures and management activities to effectively reduce the impact of LTI on wildlife (Andrews et al., 2015; Barrueto et al., 2014; van der Ree et al., 2015).

Wildlife crossing structures are typically the cornerstone of successful strategies to minimise the impact of roads and railways on wildlife. Crossing structures have proven highly effective in promoting grade-separated passage for numerous wildlife species, where animals cross above or below LTI (Bissonette & Cramer, 2008; Clevenger & Waltho, 2003). When used together with wildlife fencing, wildlife crossing structures dramatically reduce the incidence of wildlife mortality by as much as 98% (Clevenger et al., 2001; Gagnon et al., 2015). Many studies point to the benefit of well-spaced wildlife crossing structures (Bissonette & Adair, 2008; van der Ree et al., 2015; Wang et al., 2017) in promoting highway permeability; permeability increased as much as 1,367% for wild desert bighorn sheep (*Ovis canadensis*) after crossing structures were constructed (Gangon et al., 2017). Improved permeability increases landscape connectivity, yielding benefits at the wildlife population level (van der Ree et al., 2015) and promoting genetic interchange within heretofore genetically isolated subpopulations (Sawaya et al., 2013).

The efficacy of crossing structures in promoting permeability across LTI relates in part to the fact that traffic volume has a minimal effect when animals move through below- and above-grade crossing structures, especially compared to when animals attempt to cross the roadway at grade and are repelled or killed by traffic (Gagnon et al., 2007, 2017). Researchers have quantified the economic cost of wildlife-vehicle collisions (WVCs) and found that, in general, when crash rates exceed relatively low levels, the installation and maintenance of mitigation measures can be economically justifiable (Ament et al., 2022).

Elephants crossing a road in Thailand with spectators looking on.
| SUPHISIT JITVIJAK

4. Handbook Objectives

While the AsETWG's first publication (Ament et al., 2021) provided an overview of available LTI mitigation measures, this handbook provides specific recommendations and design criteria for Asian elephant-specific crossing structures and additional mitigation measures, as well as guidance for data-driven determination of locations for such mitigations to address LTI impacts to elephants. This handbook benefits from the growing experience with elephant mitigation applications in Asia that have accelerated in the past decade. The handbook's recommendations and guidelines thus reflect current best practices, recognising that they are continuously evolving, driven by technological advancements and lessons learned from post-construction monitoring.

This handbook's specific objectives include detailing the following:

1. wildlife crossing structure types and applications,
2. best-practice design criteria for effective elephant crossing structures,
3. elephant crossing structure site selection methodologies,
4. role of fencing in promoting effective elephant crossing structures,
5. mitigations appropriate for low-traffic and low-speed roads, and
6. new/emerging technologies as LTI mitigations.

The earliest and most comprehensive wildlife crossing planning and guidance documents were the COST 341 European Manual for Designing Solutions to Wildlife Habitat Fragmentation (Bekker et al., 2003) and North America's Wildlife Crossing Structure Handbook (Clevenger & Huijser, 2011). While these documents and their guidance remain pertinent today for all wildlife, neither provided guidance specifically related to Asian elephants.

The first comprehensive efforts at Asian wildlife crossing guidance were the Wildlife Institute of India's environmental guidelines for India and South Asia (Rajvanshi et al., 2001) and Eco-friendly Measures to Mitigate Impacts of Linear Infrastructure on Wildlife (WII, 2016). These were followed by the Asian Development Bank's green infrastructure design report (ADB, 2019) and Nepal's Wildlife-friendly Infrastructure Construction Directives (Government of Nepal, 2022). Though all provided Asian elephant crossing structure guidance and design recommendations, they largely preceded the growing body of empirical examples of wildlife crossings, especially underpasses, specific to elephants. The refinement of Asian elephant crossing structure design guidelines relies on sound monitoring of completed projects (Wang et al., 2015, 2022; Chogyel et al., 2018; Chogyel, 2022) and the understanding that Asian elephant passage best practices will continue to evolve as more projects are implemented and monitored for success. The AsETWG has drawn heavily on expertise from the IUCN SCC Asian Elephant Specialist Group and available post-construction mitigation measure monitoring reports to present best practices for siting and designing Asian elephant measures to address LTI impacts.

A bull crosses a roadway.
| NACHIKETHA SHARMA

5. Asian Elephant Crossing Structure Types and Design Considerations

The AsETWG's first publication (Ament et al., 2021) established a consistent nomenclature for Asian elephant wildlife crossing structures, especially with the diversity of design types and applications. Wildlife crossing structures are classified as underpasses providing below-LTI-grade passage or overpasses that provide above-LTI-grade passage (Clevenger & Huijser, 2011; Smith et al., 2015). Each passage type has a range of applications, design variations, and preferences in use by various wildlife taxa (Clevenger & Huijser, 2011; Van der Ree et al., 2015).

Underpasses encompass four broad subcategories that mirror generally accepted engineering design types:

- **Minor bridge underpasses** (Figure 5) are girder bridges typically less than 30 m wide and include arch structures and large reinforced concrete box culverts (RCBC). Though they are often designed for wildlife passage, they may also function as dual-use drainage structures. They are most effective when constructed along established travel corridors within drainages (Pan et al., 2009).

Figure 5. Minor bridge arch underpass in Bhutan.
| NORRIS DODD

- **Major bridge underpasses** (Figure 6) are wider, often multi-span bridges with spans exceeding 30 m but less than 120 m. They are often designed explicitly for elephant and other wildlife passage but may also span rivers, streams, and wetland areas. Their large size makes them especially effective as crossing structures for Asian elephants and other wildlife.

Figure 6. Major bridge underpass in China.
| YUN WANG

- **Long-span bridges** (Figure 7) are structures with spans exceeding 120 m that typically span rivers. Typically, they are not designed for wildlife passage. However, their size allows them to accommodate elephant use alongside river and stream areas, especially where dense vegetation exists, and passage is not blocked by steep terrain or obstructions.

Figure 7. Long-span bridge in Nepal.
| NORRIS DODD

Viaducts and flyovers are elevated roadways and railways, sometimes for extended lengths, under which animals can freely cross. Though the distinction between the two can be subtle, viaducts typically are designed to protect sensitive habitats such as wetlands, while flyovers are often extended above ground to accommodate unrestricted wildlife passage.

- **Viaducts** (Figure 8) typically are not designed specifically for wildlife passage (Clevenger & Huijser, 2011), but the sensitive habitats they protect allow for the maintenance of wildlife movement and adjacent habitats. As such, they are highly effective wildlife passages due to their large size, high clearance, and the degree of openness they afford for approaching and crossing animals.

- **Flyovers** (Figure 9) are extended (up to 10 km), elevated roadways passing over a variety of habitats. Increasingly used in India and now proposed in Nepal, these structures are specifically designed and constructed for elephant and tiger passage within protected areas. Flyovers and viaducts provide animals with many crossing options and do not require costly wildlife funnel fencing to be effective.

Figure 8. Viaduct for elephants in China.
| YUN WANG

Figure 9. Flyover on National Highway 54E in India.
| ROB AMENT

Overpasses fall within one of two subcategories:

- **Bridged (engineered) overpasses** (Figure 10) include girder, arch, and RCBC structures designed for wildlife passage and linking ridgeline travel corridors at cut slopes and embankment areas. Asia's first multi-species overpass within elephant range is a pair of extended arch structures spanning Highway 304 in Thailand, linking two national parks. The first overpass specifically designed for elephants was just completed in Bangladesh, a 50-metre-wide, 10-metre-long RCBC for trains to pass through.

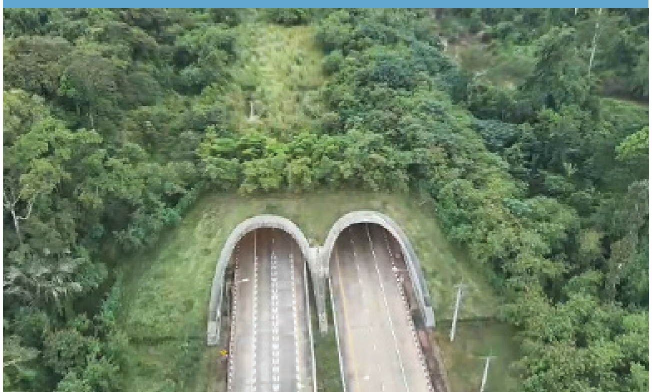

Figure 10. Engineered overpass in Thailand.
| WWF-THAILAND

- **Natural overpasses** (Figure 11) are tunnels through mountainsides and ridges through which vehicles or trains pass. In China, natural overpasses (up to 765 m long) have been created by tunnelling, allowing elephants to pass over highways through undisturbed habitats. Preliminary monitoring indicates that elephants frequently use these natural overpasses in addition to underpasses (Guan et al., 2020).

Figure 11. Natural overpass examples from China.
| YUN WANG

6. Criteria for Designing Effective Elephant Crossing Structures

Several criteria must be considered when designing effective crossing structures for Asian elephants, for which an overview is provided here with detailed information in the following sections. The siting of crossing structures is equally crucial as structure selection and will be discussed in a subsequent section. Criteria for selecting an effective crossing structure design include:

1. Structure type,
2. Structure size and openness,
3. Approaches to structure, and
4. Structure spacing and site selection.

6.1. Structure Type

Of the many factors influencing the selection of structure type for wildlife species, two are particularly important in determining whether an overpass or underpass may be better suited for providing Asian elephant passage across LTI: (1) terrain and (2) species preference. In the past, the cost differential between overpasses and underpasses was also a primary determinant. However, with the application of increasingly cost-effective overpass designs (Brennan et al., 2022), including transportable prefabricated concrete and metal-plate arches, this is no longer a consideration that rules out overpasses.

The terrain at a crossing or corridor/linkage site where an elephant crossing structure is warranted is a vital consideration for the best-suited structure type. For example, canyon and drainage situations where elephants often travel (Pan et al., 2009; Chogyel et al., 2017) are well suited to underpass applications that accommodate below-grade passage. Conversely, situations where LTI traverse deep-cut slopes or lie between continuous ridgelines upon which elephants regularly travel, are potentially suited for an overpass; in such situations, the need for fill material to create suitable approaches is minimised. Even in selected passage sites where flatter terrain does not support a drainage-related underpass or a ridge-to-ridge overpass, the option exists to consider either a flyover underpass or an overpass with backfilled approach slopes; this points to the utility of having a range of potential applications available to fit any particular site.

Whereas some wildlife species strongly prefer overpasses over underpasses (Barrueto et al., 2014; Gagnon et al., 2017), no such preference has been registered for Asian elephants. Singh and Chalisgaonkar (2006), Rajvanshi and Mathur (2015), and the Wildlife Institute of India (2016) all recommended and supported the application of both underpasses and overpasses for Asian elephants. The fact that Asian elephants will readily use well-designed and appropriately located (e.g., along established trails) underpasses is now well established (e.g., Wang et al., 2015; Chogyel et al., 2017), though there may be a multi-year “learning curve” associated with elephant use (Pan et al., 2009; Wang et al., 2015). While the first Asian overpass applications have only recently been implemented and success for elephants has yet to be established, Asian elephants have been documented crossing narrow bridges over canals in India (Joshi et al., 2008), suggesting they should readily use properly sized and vegetated overpasses.

6.2. Structure Size and Openness

Being the largest land mammal in Asia with a height of up to 3.5 m underscores the importance of designing appropriately sized crossing structures for Asian elephants. Their large body size and concerns that they are often hesitant to enter and cross through confining passages (Singh & Sharma, 2001) warrant large underpasses that are wider and higher than those for all other species. Though elephants have been recorded utilising underpasses less than 5 m in Bhutan, especially males (Chogyel, 2022), higher underpasses are warranted to ensure consistent use by all sexes, especially given the high investment cost with structures. A study from Tsavo, Kenya, also identifies higher structures with higher crossing rates of African elephants (Koskei et al., 2022). Additionally, underpasses designed for elephant use will accommodate passage for a wide variety of other species (Lala et al., 2022).

Bridged underpass width and length through structures are also important in determining their efficacy in facilitating elephant passage. The relationship between dimensions can be assessed using an openness index (Clevenger & Huijser, 2011) with the formula (metric units only):

$$\text{Openness Index} = \frac{\text{Height x Width}}{\text{Length}}$$

While acknowledging its limitations and the influence of other important underpass factors, such as acoustics (Jacobson, 2007; Clevenger & Huijser, 2011), this metric is a useful comparative design tool to evaluate underpass dimensions. Gordon and Anderson (2003) conducted a rigorous experimental evaluation of openness indices and found that mule deer (*Odocoileus hemionus*) use was influenced more by underpass width than height, given constant length. Underpass openness influences the amount of light penetrating the structure's interior and the corresponding view of the opposite side that elephants perceive. The cross-sectional area of the opening is greatly influenced by distance (length) through the structure (Clevenger & Huijser, 2011). Underpasses with inadequate openness can be confining to Asian elephants and limit effectiveness (Singh et al., 2011).

Longer underpasses may require wider and higher dimensions to maintain similar openness as shorter underpasses. For example, an elephant underpass (15 m wide × 6 m high) with a 15 m length under a narrow 2-lane road would have an openness index of 6.0. For a similar underpass crossing under a divided 4-lane highway with a 30 m length, the openness index would be 3.0; the underpass width would need to be increased to 30 m to maintain the same 6.0 openness index (see Figure 12). This points to the utility of the index in comparing underpass sizes under different LTI scenarios.

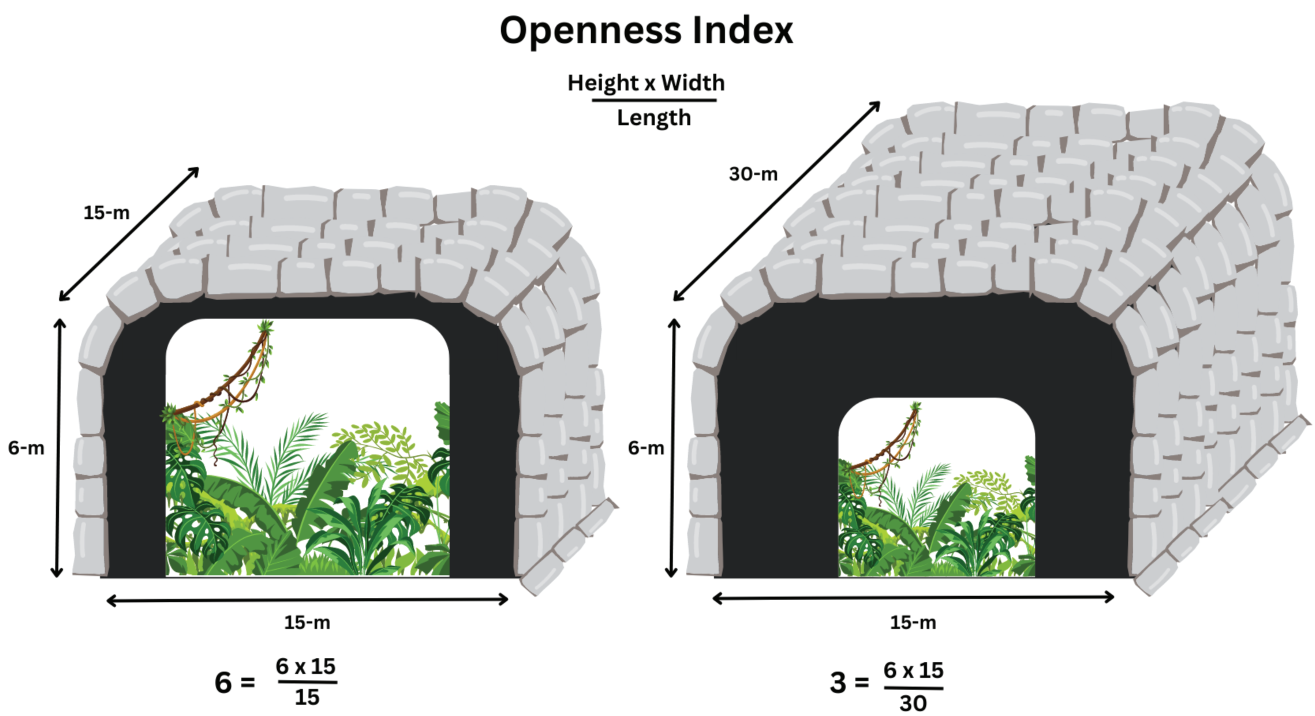

Figure 12. Openness Index visualisation illustrating the impact of length through underpasses with the similar height and width dimensions on perceived openness to elephants.
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For overpasses, the critical dimension is the width; like underpasses, the longer the span of the overpass, the wider it should be. Minimum width recommendations for Asian elephant overpasses have consistently been between 50 m (Singh & Sharma, 2001; Rajvanshi et al., 2001) and 60 m (Singh & Chalisgaonkar, 2006).

6.3. Crossing Structure Approaches

While often overlooked, elephants' approaches to travel to and through underpasses and across overpasses are critical in achieving effective crossing structure use. Elephant use of appropriately sized and well-designed structures can be diminished or even eliminated with approaches that block passage or do not offer clear line-of-sight visibility through or across structures. The view through underpasses should remain as unimpeded as possible, and elephants should be able to see daylight through underpasses from the opposite side when approaching during daytime. Preferably, bridge abutments and side walls, including excavated soil embankments, should flare outward from underpass openings at 45 degrees or greater angles. Creating enticing, wide, and open underpass approaches to structures that enhance visibility can minimise the perception of being confined. Extended viaducts and flyovers provide elephants with more options to approach and cross under the structures where they are comfortable. For overpasses, approaches refer to the typically filled areas on either side of the overpass structure, recognising that the soil atop overpasses is typically shallower and revegetated differently than the approaches. Nonetheless, even overpasses should maintain good line-of-sight visibility to create a seamless habitat conducive to elephant passage.

While long-span bridges are wide, the streams and rivers they span may limit passage opportunities for elephants; further, areas adjacent to bridge abutments often have steep side slopes that are not conducive to elephant passage. Creating flat passage lanes under bridges near abutments where elephants are afforded some protective cover can enhance passage under large bridges.

Approach and crossing structure substrates can affect passage effectiveness. Natural soil or earthen floor substrates are preferred over concrete within crossing structures. Extensive rock rip-rap should be avoided, especially larger boulders often used to address drainage and erosion issues; these can negate passage benefits for elephants associated with otherwise suitable structures.

Where overpasses are not situated between cut slopes or ridges and require backfilled approach slopes, the steepness of the slopes on each side of the overpass structure is a critical consideration. Ideal approach slopes are relatively gentle, though they impact habitat a greater distance outward from the structure and add cost to the structure. Gentle 8:1 (run to rise) slopes were recommended for Asian elephants by Rajvanshi et al. (2001), though somewhat steeper slopes (6:1) have proven effective for use by other wildlife species (see Figure 13).

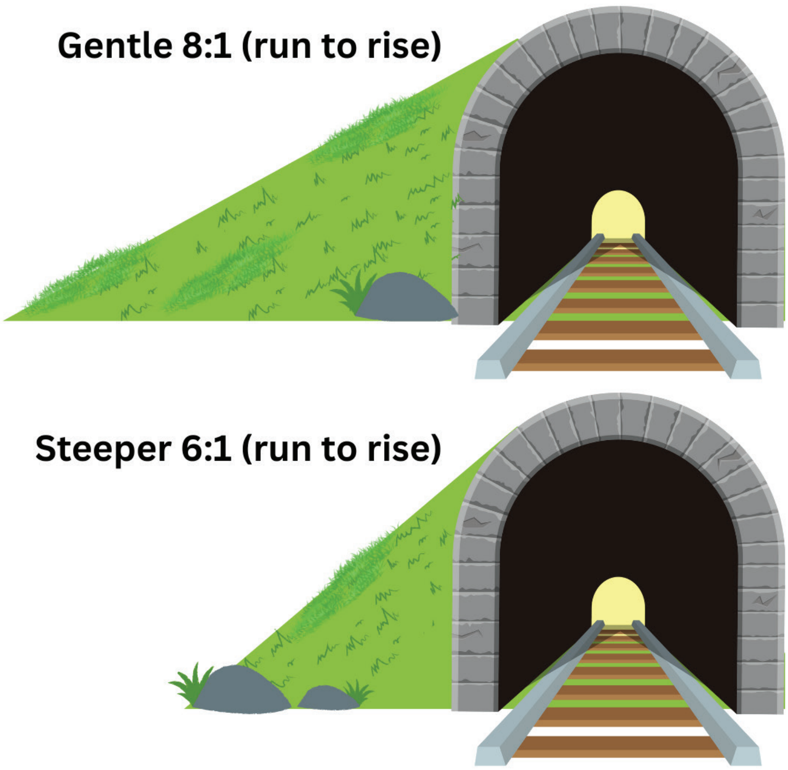

Figure 13. Approach slope visualisation of different backfill slopes approaching overpassess.
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6.4. Crossing Structure Spacing and Placement

The spacing and placement of crossing structures required to accommodate Asian elephant passage effectively is an important consideration for LTI projects, and several factors must be considered. First and foremost, wildlife species' size and relative mobility are primary factors. To guide the objective determination of crossing structure spacing along LTI, Bissonette and Adair (2008) recommended spacing based on allometric scaling of home ranges as a metric of their mobility. Allometric scaling references how different biological characteristics of organisms change at different rates as they grow. In the context of LTI projects, this concept is extended to understand how the size and mobility of wildlife species, like Asian elephants, influence their home ranges and, consequently, their movement patterns. While limited by the key assumption of homogeneous animal distributions across landscapes, their spacing guidance promotes adequate LTI permeability to maintain landscape connectivity.

In the case of Asian elephants, which have extensive home ranges (e.g., 184-500 km2; Baskaran et al., 2018, Williams et al., 2008, ADB, 2019), the spacing guidance between structures is 13.6 km (ADB, 2019). However, this spacing does not adequately reflect other factors resulting in non-homogeneous Asian elephant distribution adjacent to LTI projects, including proximity to important habitats, travel corridors, and other factors.

New and existing data should also be incorporated into planning decisions to ensure structures are being placed in frequently utilised crossing points or elephant movement corridors. This is discussed further in the Methodologies for Asian Elephant Crossing Structure Site Selection section. Underscoring how the above factors can influence actual elephant crossing structure spacing, Dodd and Imran (2018) recommended two underpasses and an overpass within a 2 km section of the total 5.3 km of wildlife sanctuary core zone habitat through which a new railway crosses in southeast Bangladesh. This 1.0-km spacing reflects intensive seasonal sign surveys and camera trapping conducted along the alignment that documented consistent heavy yearlong use. Likewise, in South Yunnan, China, two expressways crossing Asian elephant critical habitats exhibit spacing < 1 km between wildlife crossing structures based on documented elephant corridors: 0.95 km spacing between 17 structures on the Silan Expressway and 0.53 km spacing between 25 structures on the Sixiao Expressway (Wang et al., 2015).

A wild male Asian elephant captured for translocation was eventually collared with a GPS satellite tracker to monitor his movement in Peninsular Malaysia. | MANAGEMENT & ECOLOGY OF MALAYSIAN ELEPHANTS (MEME)

7. Best Practice Design Guidelines for Elephant Crossing Structures

This section details the AsETWG's best-practice design criteria and recommendations for measures to mitigate the impact of LTI on Asian elephants and other wildlife. Recommendations are presented as minimums to ensure effectiveness, recognising that the minimum dimensions may be challenging enough to achieve in many cases. However, the larger the structure, the more likely it is to be readily and successfully used by elephants. Recommendations below are a starting point for LTI mitigation; structures should be context-sensitive and will require the consultation of experts.

For consistency, we employ terminology for design criteria dimensions mirroring that used in calculating openness indices (Figure 14): height (vertical head space below structure), width (distance across structure parallel to LTI), and length (distance for animals to cross through structure perpendicular to LTI). Separate guidelines and recommendations are provided for each crossing structure type and other considerations for ensuring the effectiveness of crossing structures.

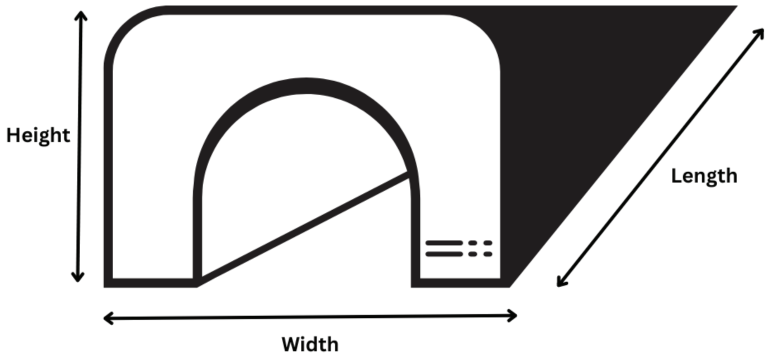

Figure 14. Crossing structure terminology illustrating structure dimensions.
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7.1. Underpasses

7.1.1. Minor Bridge Underpasses (< 30 m width)

While other below-grade passage designs, such as larger major bridge underpasses, viaducts, and flyovers, can be more effective at promoting Asian elephant passage, minor bridged underpasses have been and will continue to be a vital option used in LTI across Asia. Minor bridged underpasses often have a dual-use function in addressing drainage needs associated with streams and wildlife passage, making them cost-effective. Bridged underpasses can reflect a wide array and diversity of designs and applications. Single-span girder bridges (Figure 15) can serve as highly effective elephant passages along stream courses that elephants use as movement corridors. However, adequate accommodation for elephant passage must be provided with abutment treatments (e.g., side slopes) that can otherwise force elephants into streams or limit openness; in these situations, vertical abutments are preferred.

Figure 15. Single-span girder minor bridges that serve as Asian elephant underpasses, including a highway bridge in Nepal (left) and a railway bridge in Bangladesh (right), both under construction.
| NORRIS DODD

Divided highways with separate bridges for directional vehicular travel can increase the length that elephants must negotiate through structures, reduce openness, and contribute to a tunnel effect that deters successful passage. In addition to enlarging bridges, open atria between bridges (right) can reduce the tunnel effect and increase perceived openness for elephants. If bridges can be separated adequately (e.g., >30 m), each can be considered separately in evaluating openness and affording better passage accommodation. Keeping the central area natural is vital to attract elephants to use this kind of crossing structure. Suggested protective measures can be used here, such as noise walls, vegetation restoration, design of water system, and closure to human activity, etc.

Figure 16. Example of open atria between bridges.
| NORRIS DODD

Despite underpass width often being considered more important than height in influencing use by some species (Gordon & Anderson, 2003; Brennan et al., 2022), underpass height is an especially critical consideration for elephants due to their large body size that can exceed 3.5 m at the shoulder. Existing Asian guidelines call for a minimum height for elephant underpasses associated with narrow transport infrastructure (<20 m length) of 5.5 m (ADB, 2019) to 6.5 m (Government of Nepal,2022), and 6.5 m for wider transport infrastructure (ADB, 2019; Government of Nepal, 2022). Recent monitoring of underpasses along a narrow 9.9 m wide road in southern Bhutan (Chogyel, 2022) found comparable Asian elephant use of a 4.7 m high underpass (Figure 17) to use of two underpasses just over 6 m in height. In Bangladesh, the design height and width of a 10 m wide × 5 m high concrete box culvert elephant underpass along a new railway were limited by the fixed railway grade (Figure 17). Yet elephants used the underpass soon after completion without fencing (under construction); the narrow width of the railway and thus underpass length of 6.9 m appear to help offset the height and width limitation. These examples illustrate that for narrow transport infrastructure (<10 m wide), underpasses with heights less than 6.5 m, while not ideal, can be effective where conditions do not permit greater heights.

Figure 17. A 6.2 m wide x 4.7 m high underpass on Bhutan NH2 used by Asian elephants (left); reinforced concrete box culvert Asian elephant underpass (10 m wide × 5 m high × 6.9 m long) along a railway in southeast Bangladesh (right).
| NORRIS DODD

Some of the best information to support higher wildlife crossing heights is provided for African savannah elephants (*Loxodonta africana*) from a 133 km Kenyan railway with 41 crossings that included large bridges, wide wildlife underpasses (average width 67.5 m), and culverts averaging just 5.6 m in width (Koskei et al., 2022). They found that higher elephant crossing rates were associated with higher structure heights, and that height had its greatest influence on crossing at underpasses and culverts; few elephant crossings occurred at structures less than 5 m high. Their modeling found that each additional 1 m in height increased predicted elephant crossings 168% for culverts and 364% for underpasses.

It is important to stress that the recommendations in this handbook represent minimums, and increased dimensions are recommended where possible.

AsETWG Minor Bridge Underpass Guidelines

While the adage “bigger is better” certainly applies to Asian elephant underpasses, real-world limitations, including budget and design limitations, can influence underpass design. Our guidelines provide a sliding scale of minimum underpass dimensions based on three classes of LTI design length (Table III-1). For narrow 2-lane highways or railways less than 10 m in length and where higher underpasses are impossible due to design constraints, 6.0 m heights and 12.0 m (unobstructed) width is recommended. Increasingly greater heights are recommended for increasingly wider LTI (Table 1).

Table 1. AsETWG sliding-scale guidelines for minor bridge underpasses up to 30 m in width by underpass length across transport infrastructure.

Underpass length across LTI (m)	Minimum underpass dimensions		
	Width (m)	Height (m)	Openness index
≤10	12.0	6.0	7.2
11-20	15.0	6.5	4.9 – 8.9
>20	20.0	7.0	4.7 – 6.7

Prefabricated metal plates and concrete arches (Figure 18) present rapid construction options and are especially well suited to retrofit applications on existing LTI. Up to 13.5 m wide metal-plate arches are transportable to remote locations for assembly and are a cost-effective option; construction costs for three metal-plate arch underpasses in Bhutan (average dimensions 10 m wide × 6.4 m high × 9.9 m long) averaged USD 490,000 (Chogyel, 2022).

Figure 18. Metal-plate arch underpass in southern Bhutan (left); underpass being erected (right).
| LEFT: NORRIS DODD | RIGHT: CONTECH ENGINEERED SOLUTIONS

7.1.2. Major Bridge Underpasses (>30 m and <120 m width)

Major bridge underpasses are between 30 and 120 m in width, typically associated with multi-span structures. Major bridge applications accommodating Asian elephant passage have been made where passage is the primary purpose or as cost-effective dual-use structures associated with streams and smaller rivers (Figure 19). Koskei et al. (2022) found that of the 41 African elephant crossings they evaluated, bridges provided the most effective crossings compared to underpasses and culverts and were used disproportionately by elephants for crossing a railway.

The most intensive project where elephant passage guided a major bridge underpass design is the Sixiao Expressway in South Yunnan, China, which passes through a biodiversity-rich national nature reserve. Seventeen major bridge underpasses were constructed in 2003-2006 (Figure 19). These underpasses average 66.6 m in width (range = 40-120 m) and 11.9 m high (range = 5-30 m). All underpasses were located where historical elephant movement corridors intersect the expressway; as such, the elephant passage rate has steadily increased since construction and now averages 84% (Wang et al., 2015).

Figure 19. Major bridge underpass designed specifically for Asian elephant passage along the Sixiao Expressway in South Yunnan, China (left); dual-use structure spanning a river in southern Nepal (right).
| LEFT: YUN WANG | RIGHT: NORRIS DODD

AsETWG Major Bridge Underpass Guidelines

As all major bridge underpasses are sufficiently wide to promote Asian elephant passage, the AsETWG guidelines only cover underpass height. And because it is unlikely that such bridges will be associated with narrow LTI <10 m across often associated with minor bridge underpasses, we offer guidelines for two LTI length classes; <20 m and >20 m (Table 2).

Table 2. AsETWG sliding-scale guidelines for bridged underpasses up to 30 m in width by underpass length across transport infrastructure.

Underpass length across LTI (m)	Minimum underpass dimensions	
	Width (m)	Height (m)
<20	30	6.5
>20	30	7.0

7.1.3. Long-Span Bridges (>120 m width)

Long-span bridges exceeding 120 m in width generally are associated with rivers, though their large size does accommodate Asian elephants and other wildlife passage (Koskei et al., 2022). Often, such bridges' open floodplain portions are unsuitable for elephant conveyance, with elephants using the relatively narrow vegetated area between the bridge abutments and the riverbanks for crossing (Figure 20). As such, such areas must remain free of obstructions, roads, and human trails. Further, vegetated and relatively flat passage pathways for elephants can facilitate conveyance. Wildlife mitigations planned for an upgraded road in southern Nepal include creating flat, obstruction-free passage lanes (terraces) 10-12 m wide under either side of 12 existing long-span bridges (12) to enhance elephant passage (Dodd et al., 2022).

In some cases, elephant passage has been a design consideration for long-span bridges. According to Kasmuri et al. (2020), 11 long-span bridge underpasses were constructed in 2014 along the Malaysian Central Spine highway project. These underpasses range in width from 150 to 350 m, averaging 227 m.

Figure 20. Long-span bridge in southern Nepal where obstructions and human impacts limit Asian elephant passage under the bridge. | NORRIS DODD

AsETWG Long-Span Bridged Guidelines

In addition to creating 10-12 m wide flat, obstruction-free passage lanes adjacent to bridge abutments, minimum bridge heights should follow those in Table 2.

7.2. Viaducts and Flyovers

Extended sections of elevated roadways are increasingly being constructed to promote Asian elephant passage, with major projects completed in China, India, and Malaysia. On China's Silan Expressway, 15 viaducts were built expressly for Asian elephants (Figure 21) ranging in roadway length of 100 to 620 m (average = 317.0 m) and 5 to 48 m in height (average 30.0 m). Viaducts (3 each) on two of Malaysia's highways ranged in roadway length from 80 to 900 m (figure 22), averaging 310.0 m (Kasmuri et al., 2020). Some of India's first three flyovers constructed in Rajaji Tiger Reserve and designed for both tigers and elephants, range in roadway length from 400 to 736 m and average 545.0 m (WII, 2016).

WII (2016) characterised elevated LTI on pillars as "the best solution in elephant landscapes". Though flyovers/viaducts are relatively costly, the cost becomes more acceptable when considering a flyover can span the length of LTI where bridged underpasses have been spaced as close as 0.5 km apart (Wang et al., 2015). Further, elevated LTI eliminates the need for costly fencing and associated long-term maintenance.

AsETWG Viaduct/Flyover Guidelines

As with bridge underpasses, flyover/viaduct height is a critical design consideration. WII (2016) recommended a minimum 8 m height below elevated LTI. While 8 m height may be adequate for elephant passage, with the high cost associated with flyovers and viaducts, the ASETWG recommends 10 m clearance height to ensure effectiveness for passing elephants.

Figure 21. Viaduct constructed in China.
| YUN WANG

Figure 22. An elephant at the viaduct in Malaysia.
| ASTRO MALAYSIA

7.3. Overpasses

7.3.1. Engineered Overpasses

The application of engineered wildlife overpasses has increased considerably elsewhere in the world in the past two decades. However, outside of South Korea, where many small wildlife overpasses have been constructed (half of their 56 overpasses had widths <7 m, and just 14% were >50 m wide (Woo et al., 2018), the rest of Asia has just recently begun to construct overpasses. The first overpass in Southeast Asia was constructed in Singapore (50 m width) primarily for small animal passage. In northwest China, several overpasses have been built for ungulate crossings of LTI, with their widths all exceeding 50 m; preliminary monitoring indicates ungulates are using the overpasses frequently (Wang et al., 2022; Zhang et al., 2019).

Asia's first overpass constructed within elephant range includes a pair of extended precast arch structures, one 0.17 km long and the other 0.25 km long, spanning Highway 304 in Thailand, with revegetation atop the structures (Figure 23). Twin 16 m arches span the four-lane highway to create tunnels for vehicle conveyance. This multi-species overpass, linking two national parks, was completed in 2019, and subsequent monitoring has not reported Asian elephant usage. Camera trapping at the site before construction also did not detect elephants which appear to reside further into the national park cores (Sukmasuang et al., 2020). The overpass structures have relatively steep (3:1) approach slopes that are not considered ideal for elephant passage.

In southeastern Bangladesh, a 7 m long × 9.5 m high x 50 m wide RCBC serves as tunnel for trains with backfilling to restore the ridgeline elephant travel corridor (Figure 24). Construction lasted 2.5 years, disrupting elephant use of the corridor, though elephants began using the completed overpass within a month, dispelling concerns over permanent disruption. Integration of concrete elephant fence and revegetation of the backfilled approaches is now complete.

Figure 23. Highway 304 wildlife overpass in Thailand comprised of two twin 16 m precast arches extending 0.17 and 0.25 km spanning the highway.
| ITALIAN-THAI DEVELOPMENT PLC

Figure 24. Newly constructed elephant overpass spanning a new railway line in southeastern Bangladesh (top left); with backfilling around the structure (top right); to reconnect the excavated elephant travel corridor along the ridgeline (bottom).
| TOP: NORRIS DODD | BOTTOM: BANGLADESH RAILWAY

Historically, overpasses have been considered more costly than underpasses. However, recent engineering developments and new design options have dramatically reduced their costs, making them more comparable to underpasses (McGuire et al., 2020), especially with their utility in accommodating passage for a wider array of species (Brennan et al., 2022). Engineered overpass structures can be positioned between large cut slopes or tied into terrain features to reduce costs and improve effectiveness by providing continuity along preferred ridgeline animal travel routes. They can also be constructed on flat terrain with gentle approach slopes. Overpass designs can accommodate a range of sizes and include girder bridges, arches, and even large RCBCs. Like underpasses, overpasses are increasingly being constructed with prefabricated concrete and metal-plate arch "buried" structure designs (Figure 25) that further reduce cost and increase transportability (McGuire et al., 2021, Brennan et al., 2022).

Figure 25. Overpass design types, including girder bridge (top left); concrete arch (top right); retrofit metal-plate arch on an existing highway (bottom). All examples from the USA.
| TOP LEFT, TOP RIGHT: NORRIS DODD | BOTTOM: CONTECH ENGINEERED SOLUTIONS

Clevenger and Huijser (2011) recommended 50–70 m wide overpasses to accommodate large, high mobility mammal species such as elephants; the longer the overpass span and length with approach slopes, the wider it should be. Luell et al. (2003) recommended that overpass width-to-length ratios (W:L) should be 0.8 or higher, reflecting the notion that wider widths should accompany longer lengths. Singh and Sharma (2001) and Rajvanshi et al. (2001) made recommendations for Asian elephant-specific overpass dimensions, both with 50 m widths, while Singh and Chalisgaonkar (2006) recommend 60 m widths. The arch overpass structures constructed in Thailand are 0.17 and 0.25 km wide though approach slopes are quite steep. The elephant overpass in Bangladesh is 50 m in width over the narrow railway tunnel created by the RCBC, with near-level backfilled approach slopes extending outward 30 m (60 m total length). Singh and Chalisgaonkar (2006) recommended side walls 2.5–2.75 m in height to guide crossing elephants and buffer them from disturbance, light, and noise from below.

Brennan et al. (2022) conducted a comprehensive structural assessment of 120 overpasses worldwide, excluding European land bridges or eco-bridges with widths > 80 m. They also compared wildlife passage effectiveness to width dimensions and W:L ratios. They stressed the importance of using consistent measurement of overpasses to make such comparisons. They recommend using inner widths between side walls at overpass centres (especially for hourglass-shaped decks) and lengths that encompass landscaped approach ramps extending outward from structures. Brennan et al. (2022) found that overpass widths averaged 34 m, lengths 103 m, and W:L ratios 0.58. Overpass width and W:L ratio were positively associated with wildlife crossing rates though not significantly so, and wider (40-60 m) overpasses in North America exhibited twice the crossing rates and greater diversity of wildlife species than smaller overpasses. They concluded that overpasses >50 m wide represent a cost-effective approach to addressing LTI impacts and promoting effective passage for wildlife.

AsETWG Engineered Overpass Guidelines

Overpass Width: Recognising that overpass widths should reflect the span length over which they cross LTI, the AsETWG guidelines provide a sliding scale of minimum overpass widths based on three classes of total overpass length, including landscaped approach slopes (Table 3). For narrow 2-lane highways or railways with total overpass lengths less than 60 m, a minimum 50 m width is acceptable; wider overpasses are recommended for longer lengths over LTI (Table 3).

Table 3. AsETWG sliding-scale guidelines for engineered overpasses by total overpass length across transport infrastructure, including landscaped approach slopes.

Overpass length including approach slopes (m)	Minimum overpass width (m)	Width: Length Ratio
≤60	50	≥0.83
61-80	60	≥0.75
>80	70	≥0.88

Side Walls and Other Treatments: While the 2.5-2.75 m overpass side wall heights recommended by Singh and Chalisgaonkar (2006) are ideal for funneling and buffering crossing elephants from traffic disturbance from below, the AsETWG feels that 1 m high side walls with durable fencing/barrier above are adequate to guide elephants across sufficiently wide overpasses. Other treatments, including earthen berms, trees or similar vegetation (e.g., bamboo) established along overpass edges, can provide more cost-effective and environmentally sensitive options to limit noise and light disturbance from LTI below. Sołowczuk (2020) provided comprehensive strategies for implementing overpass sound and light treatments, including the design and shape of sound walls, vegetation, and earthen berms to maximise effectiveness under various terrain and topographic conditions on adjacent approaches. The full revegetation of overpasses with native vegetation is strongly recommended, and thus sufficient (1 metre or deeper) soil depth is needed atop structures to establish vegetation effectively.

7.3.2 Natural Overpasses (Tunnels)

China has implemented multiple natural overpasses, of which three have been constructed along two expressways since 2006; natural overpasses are also under construction in India. Natural overpasses do not disrupt elephant travel corridors during construction and maintain natural vegetation. Three natural overpasses were constructed within established elephant corridors by tunneling along the Sixiao and Silan expressways in South Yunnan, China, completed in 2006 and 2020, respectively. On the Sixiao Expressway, the 765 m Elephant Valley Tunnel overpass received considerably higher use by elephants than the shorter 115 m Baihuashan Tunnel overpass (Figure 26) due to its sevenfold greater width and absence of nearby homes and other human disturbances. Key takeaways from monitoring include: 1) natural overpasses effectively promote elephant passage, 2) the longer the tunnel, the better, and 3) minimising human disturbances and maintaining natural habitats above tunnels underpin overpass success.

Figure 26. Aerial view of the 115 m wide Baihuashan Tunnel overpass, South Yunnan, China, with homes and buildings in the vicinity that limit effective elephant use of the overpass. | GOOGLE MAPS

AsETWG Natural Overpass Guidelines

Though costly to excavate, natural overpasses can provide superior (Wang et al., 2015) passage for Asian elephants as they maintain natural ecological corridors and vegetation without impact or disruption. Based on China's experience, natural overpasses should be constructed in areas not subject to human disturbances (homes and other buildings) that limit effective use.

8. Methodologies for Asian Elephant Crossing Structure Site Selection

A wide variety of methodologies can be utilised for optimal site selection of crossing structures. In addition to those mentioned below, Table 4 provides references for additional methodologies that may be useful for site selection as well as pre- and post-construction monitoring.

Table 4. Methods of measuring effectiveness of mitigating impacts of LTI from Ament et al., 2023.

Metric	Methods	Selected References
Roadkill rates	• Surveys • Encounter surveys • Citizen science • Review of existing databases	Gerow, et al., 2010 Guinard, et al., 2012 Lee et al., 2006
Wildlife use of crossing structures	• Sign surveys • Tracking beds (e.g., sand, snow, sooted track plates) • Camera traps (with or without individual identification) • Video cameras • Passive integrated transponder (PIT) tags and automated readers	Gonzales-Gallina, 2018 Clevenger & Waltho, 2005 Clements, 2013 Soanes et al., 2013 Mateus et al., 2011 Wang et al., 2017
Animal movements and dispersal	• Animal tracking (e.g., radio, satellite, GPS, etc.) • Species encounter rates (camera trapping without individual identification) • Camera trapping with individual identification (dispersal) • Movement/behavioural observation	Shephard et al., 2008 Colchero et al., 2011 Bautista et al., 2004
Genetic and demographic connectivity	• Non-invasive sampling (hair snaring) • Invasive samping to collect DNA	Sawaya et al., 2014 Balkenhol & Waits, 2009 Soanes et al., 2018
Species occurrence and distribution (plants, animals)	• Camera trapping, trapping, active searches • Vegetation plots	Goosem, 2002 Herrmann et al., 2016
Animal population demographic parameters	• Capture-mark-recapture	Garland & Bradley, 1984 McCall et al., 2010

Asian elephants exhibit extensive ranging behaviour, occupying vast home ranges. Despite their far-ranging nature, they form social units that undergo dynamic fission and fusion processes. Consequently, their distribution often overlaps with other groups, and they tend to concentrate in regions abundant in critical resources. Yang et al. (2022) identified that 75.2% of Asian elephant core habitat exists outside designated protected areas. As such, the spacing of crossing structures must reflect non-homogeneous Asian elephant distribution adjacent to LTI projects influenced by these and other factors:

- seasonal and traditional congregation areas;
- proximity to critical resources such as wetlands, salt licks, and springs;
- travel corridors, trails, and seasonal migration routes; and
- impact of habitat fragmentation that concentrates elephants into residual suitable habitats.

In such areas with concentrations of elephant distribution, crossing structure spacing along LTI has ranged from 0.53 km (Wang et al., 2015) to 1.0 km in China and 1.0 km in Bangladesh (Dodd and Imran, 2018). Such spacing was predicated on data-driven determination and prioritisation of where crossings structures are warranted using a variety of methodologies described below.

8.1. Asian Elephant Connectivity and Corridor Plans

Where they exist, national or regional Asian elephant connectivity and corridor assessments can be invaluable in identifying priority sites for considering crossing structures to promote connectivity with existing LTI or in new LTI development where fragmentation avoidance is not possible. These assessments are beneficial when combined with other field-based data (e.g., sign and camera trapping). Large-scale corridor assessments typically link blocks of relatively intact habitat and protected areas (core areas) via corridors. These corridors are intended to maintain connectivity between the core areas or blocks to support wildlife movement and dispersal.

Crossing structures may be warranted where existing or planned LTI crosses identified corridors. India (Menon et al., 2017) and Bangladesh (Motaleb et al., 2016) have completed comprehensive corridor assessments, while Malaysia has identified and updated ecological corridors to preserve connectivity in the peninsular region (PlanMalaysia, 2022). The elephant corridors mapped in southeastern Bangladesh (Figure 27) were instrumental in considering crossing structures associated with a new railway. They were validated with seasonal sign surveys and camera trapping (Dodd and Imran, 2018).

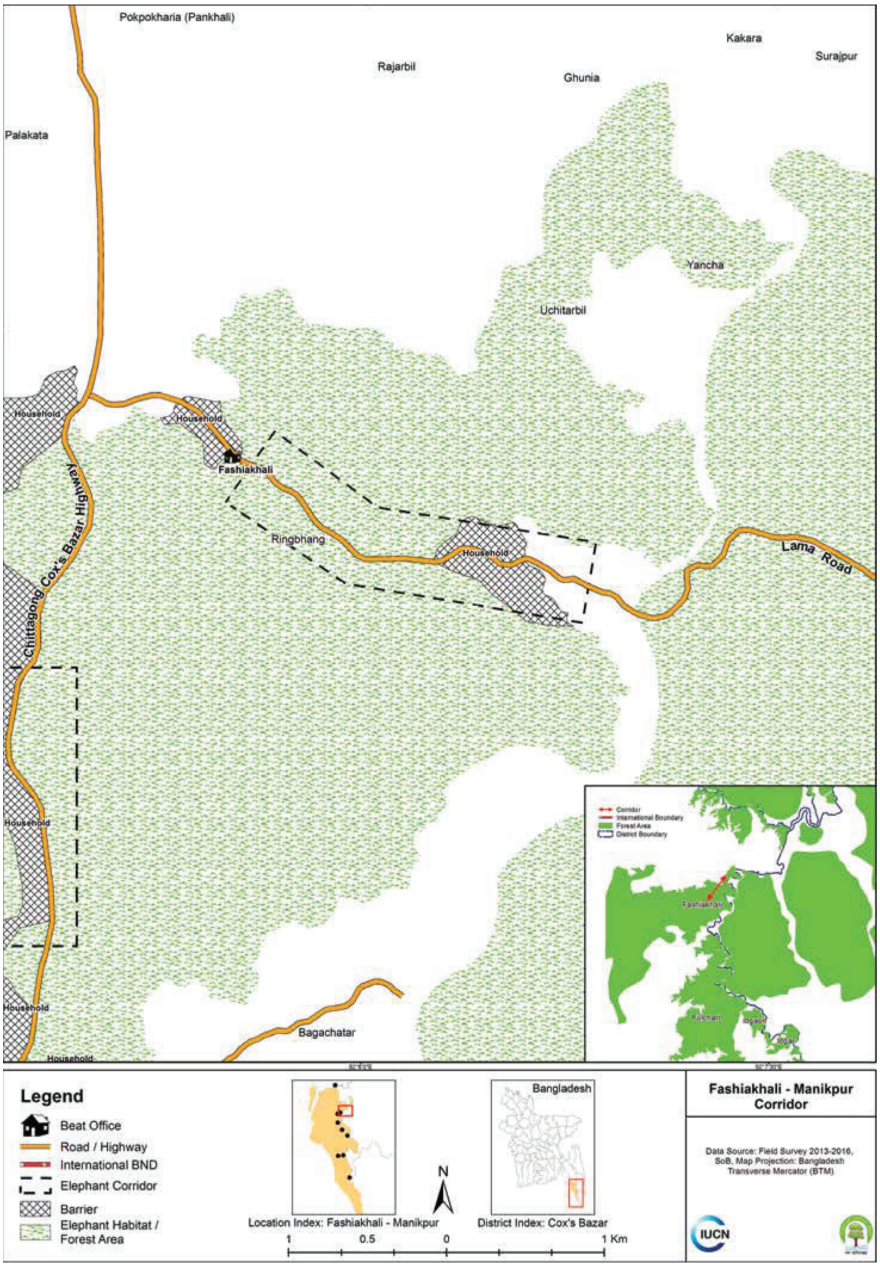

Figure 27. Elephant linkage associated with the core zone of a Bangladesh wildlife sanctuary where corridors intersect two existing highways (dashed boxes).

MOTALEB ET AL. (2016)

8.2. Sign Surveys

Asian elephant signs, including tracks, dung, trails, plant feeding, and crop damage, are apparent, unmistakable, and often abundant in high-use elephant concentration areas. Quantifying elephant signs constitutes a relatively quick and inexpensive approach to assessing and monitoring elephant presence and relative abundance. Sign surveys have been used to monitor elephant movements in Yunnan Province, China, to determine relative abundance (high/moderate/low/absent), locate 42 crossing structures along two expressways, and monitor elephant use of the crossing structures. Due to the ease and straightforward process for conducting surveys, transport maintenance workers and volunteers have carried out dung counts with minimal labour requirements (1-2 people) and at low cost. Intensive and repeatable track and other sign count transects can provide excellent comparative information on elephant distribution and relative abundance (Dodd and Imran, 2018).

In Bangladesh, Dodd and Imran (2018) employed seasonal sign transect surveys along a proposed new railway corridor and qualified sign along transects using 0.25-ha circular plots. To estimate the relative age of elephant dung, piles were counted and classified by stages of decay (e.g., S1–S5; Hedges, 2012) to estimate freshness. This classification was intended to assist in the determination of how recently elephants had been in the area and to provide an indicator of resident versus seasonal elephant occupation. Tracks were estimated on plots with categories of sets of elephant tracks (e.g., 1, 2–5. 6–10, and >10). Established year-long movement corridors and trails were differentiated from seasonal trails used only for the raiding of crops. Elephant signs can persist for extended periods, especially during the dry season. However, tracks may become obliterated during the monsoon season, and seasonal and age-specific variation may affect the dung decay rate (Mohanarangan et al., 2022).

Figure 28. Asian elephant sign types, including slightly decayed dung pile (left); tracks through a new elephant underpass (centre); established elephant movement corridor/trail (right).
| LEFT: YUN WANG | CENTRE, RIGHT: NORRIS DODD

8.3. Camera Trapping

An increasingly popular approach for conducting wildlife studies involves the use of relatively affordable but high-quality infrared remote-triggered cameras (Meek et al., 2012; Si et al., 2014). These cameras have become the preferred method due to their cost-effectiveness and ability to capture excellent images. Camera trapping can be used to determine Asian elephant occupancy, relative abundance, animal behaviour, temporal activity patterns, and even identification of individual animals. Unlike sign counts or surveys, cameras can accurately estimate the number of elephants in groups. Camera batteries can last extended periods before needing to be switched out; SD storage cards can also be switched out simultaneously, though more frequent downloading is recommended to preserve data should camera theft occur. Cameras with uplink capabilities to remotely obtain data where cellular coverage is adequate are also becoming more widely available and affordable.

Dodd and Inram (2018) conducted camera trapping at all elephant trails and corridors along a proposed railway in Bangladesh to quantify elephant abundance and seasonal use to prioritise corridors for crossing structures. Presence and seasonal abundance of elephants and other wildlife were assessed with camera trapping at randomised locations across a wildlife sanctuary in southern Bhutan where a new road was proposed; sampling was stratified by habitat type (ADB, 2018).

Figure 29. Image of an Asian elephant recorded along an established corridor in Bangladesh where an overpass is being constructed.
NORRIS DODD

8.4. Global Positioning System Telemetry

The application of satellite-based global positioning system (GPS) telemetry has increased steadily over the past two decades, becoming more prevalent and enabling ecologists to track and map out locations and movement of animals across time and space dimensions. The field of movement ecology is dedicated to examining how wildlife (individual or population) moves and interacts with environmental variables and their surrounding ecosystems, which may include the impact of anthropogenic activities, disturbances, and threats. Telemetry studies have helped interpret the size of wildlife's home ranges, migration patterns, and other information that contributes to understanding their spatial needs, social behaviour, and population ecology.

GPS telemetry can facilitate locating wildlife crossing structures in association with LTI projects (Dodd et al., 2007) and thus is considered the "gold standard" for informing data-driven recommendations. Data from GPS location fix can be mapped on top of existing or proposed LTI to determine spatial crossing patterns and peaks (Dodd et al., 2007), or in the case of species for which existing LTI are a severe barrier to the passage, patterns of approaches to within 0.25 km of LTI can be mapped (Dodd et al., 2011). The development of more powerful statistical tools has helped advance the analysis of wildlife movement ecology with the use of modelling approaches such as Resource Selection Functions (RSFs) and Step Selection Functions (SSFs) that examine environmental variables influencing the wildlife movement by comparing actual habitat use with unused area or random steps (Thurfjell et al., 2014). Furthermore, analysis of landscape connectivity employing least-cost path or circuit theory can help identify corridors important for connecting habitat patches and supporting safe passage for wildlife (de la Torre et al., 2019). GPS telemetry is effective for examining wild Asian elephant road or rail crossing behaviours by identifying road sections frequently used temporally by elephants for crossing and areas where roads are a barrier to passage (Wadey et al., 2018; Bastille-Rousseau et al., 2018).

GPS telemetry can be costly and requires considerable initial effort from various stakeholders to capture animals. However, once installed, GPS location fixes are collected frequently over two to five years (or longer), yielding thousands of fixes for individual animals. Data can be uploaded regularly to satellites and posted online for retrieval and analysis. Collars can be programmed to drop off from the animals for recovery and subsequent cost-effective collar refurbishing and reuse. Furthermore, using GPS telemetry minimises potential human disturbances that can bias animal behaviour and avoids the intensive effort of manually collecting VHF-based location data on tracked individuals (Cagnacci et al., 2010; Hebblewhite and Haydon, 2010).

The capture of elephants can require a team of five to eight people to handle them after safe tranquilising under set procedures (Daim, 1995). Several considerations ensure that the risks associated with capture are minimised, though accidental injury or death of elephant or staff can still occur.

Figure 30. Team handling and fitting of a male Asian elephant that was tranquilised with a GPS telemetry collar in Peninsular Malaysia.
| MANAGEMENT & ECOLOGY OF MALAYSIAN ELEPHANTS (MEME)

Most Asian countries have cautiously embraced Asian elephant GPS telemetry. In Malaysia, more than 100 wild Asian elephants have been collared with Inmarsat or Iridium satellite GPS collars (Africa Wildlife Tracking, Pretoria, South Africa) programmed to record GPS locations at fixed intervals. GPS telemetry is especially useful in Malaysia as the terrain and dense tropical forest make direct observation of far-ranging elephants difficult.

In Assam, India, elephant telemetry (Figure 31) efforts have been ongoing since 2021 in an area north of the Brahmaputra River, where elephants travel between Nameri National Park and the Sonai Rupai Wildlife Sanctuary and use the cultivated spaces in between during harvest season. In tandem with camera trapping, telemetry has provided insights into how elephants move across railway tracks in the area. Further, GPS telemetry is helping to make a case for corridor designation for the Nameri-Sonai Rupai-Arimora Chapori (NSA) Corridor, which elephants have traditionally used to seasonally traverse between the Brahmaputra and the Himalayan foothills region of Assam (Figure 31). Where LTI intersects this corridor, crossing structures may be warranted as LTI is upgraded in the future.

Figure 31. Elephant fitted with GPS telemetry collar in Assam, India.
| WWF-INDIA

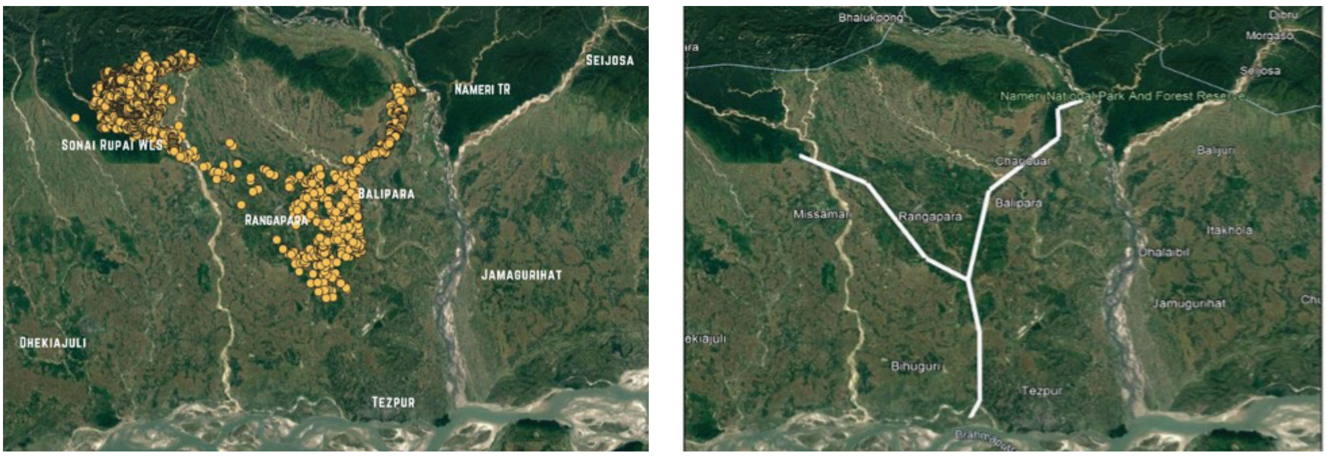

Figure 32. Asian elephant GPS fixes for one elephant north of the Brahmaputra River in Assam, India (left); the proposed Nameri-Sonai Rupai-Arimora Chapori (NSA) Corridor supported by the telemetry data (right).
| WWF-INDIA

8.5. Elephant Collision Hotspots on LTI

Compiling information on locations of Asian elephant collisions with vehicles and trains along LTI can be invaluable in identifying where crossing structures and fencing may be warranted to prevent future collisions and ensure protection of Asian elephants and the safety of people travelling through these areas. Identifying locations where the animals turned back from crossing or managed to successfully cross the road is equally important, as these locations must also be considered when planning the location of mitigation measures (Zeller et al., 2020). A combination of camera trapping and GPS collaring can be employed to gain a comprehensive understanding of these critical crossing areas and elephant behaviour, especially as it relates to the speed and behavior exhibited when crossing roads and railways. By integrating data from these two methods, conservationists can pinpoint the most vulnerable locations and behaviours, allowing for the implementation of targeted interventions to reduce the likelihood of collisions and facilitate elephant movement across LTI.

8.6. Enhancing Habitat Near Crossing Structures

Habitat enhancements near wildlife crossing structures can help attract animals to the structures, thus helping establish and maintain use by elephants and other animals. Such enhancements include elephant forage and fodder planting, ensuring availability of water and artificial salt licks. When done at a sufficient scale, planting native vegetation can improve the quality and quantity of preferred forage species for elephants. Water developments and tank improvements can improve water availability and should ideally be sited near forage enhancements and salt licks. Mineral or salt licks are essential to various wildlife to supplement nutrients and salt deficiencies in their diet. Often with the ongoing expansion of roads, plantations and urban land development, some crucial natural salt licks are lost.

Habitat enhancements can be undertaken as LTI-project mitigation and compensation offsets as has been done on the Chittagong-Cox's Bazar Railway project in Bangladesh where they added 287 ha of forage plantings, six water developments, and six salt licks (Dodd and Imran 2017). These enhancements have proven effective in dramatically reducing human-elephant conflict in neighbouring villages. Similarly, to attract wildlife towards the viaducts and facilitate safe movement across roads, the Department of Wildlife and National Parks (PERHILITAN) in Peninsular Malaysia has created artificial salt licks near wildlife viaducts. Locating crossing structures or habitat enhancements, or both, near human settlement areas must be done carefully so as not to create or exacerbate human-elephant conflicts. Habitat enhancements may be appropriate following LTI projects when desired use of passage structures has not occurred, or conflicts with neighboring human settlement occur.

Figure 33. Asian elephant habitat enhancements accomplished in Bangladesh as railway construction compensation offsets, including water developments (top left); artificial salt licks (top right); preferred elephant forage and fodder enhancement plantings (bottom).
NORRIS DODD

Artificial salt licks are created in various manners, ranging from recessed or raised concrete cribs to hold salt, molasses, and water as done in Bangladesh (Figure 34), or by digging pits 2-3 m long, 1.5-2 m wide, and 30-50 cm deep, as done in Malaysia. The pits are often saturated in water, forming wet-lick pools. Unlike "dry" licks, where wildlife consumes the mineral-rich soil, "wet" licks are typically small pools of salty water that wildlife drink (Simpson et al., 2020).

Figure 34. A male elephant using an artificial salt lick created near the Gerik Viaduct in Perak, Malaysia.
| SALMAN SAABAN

8.7. Other Considerations When Locating and Designing Crossing Structures

Land Tenure Control

When making a substantial financial investment in constructing crossing structures, it is vital to consider a site's long-term land tenure, ownership, and control to maintain the structure's effectiveness over its design life. The most secure locations for structures are within protected areas (where avoidance of LTI development was not possible), which often coincide with high biodiversity. In many cases, human activity is minimal or not allowed within these areas, which enables safe and free movement of wildlife through structures, and authorities mandated with managing these areas are able to oversee their use. Outside of protected areas, the risk of land use changes (e.g., human development or forest clearing) occurring could diminish the effectiveness of crossing structures (depending on who has jurisdiction over the area and the ability to reduce disturbances) and must be evaluated.

In southern Bhutan, a once well-used elephant underpass located just outside a protected area experienced increased human presence and activities; elephants subsequently abandoned the use of the underpass and began crossing the highway, at grade, some distance away (Chogyel et al., 2018).

Illegal Resource Extraction and Poaching

In some cases, wildlife crossings may present opportunities for illegal harvesting of wildlife and other resources due to a combination of human access and concentrations of animals at crossings. A study to assess the effectiveness of the viaducts for wildlife passage was conducted by Clements (2013) in Peninsular Malaysia. Aside from detecting wildlife, the cameras captured almost ten times more detection of human activities at the viaduct underpasses compared to the surrounding forest, and a similar detection rate of human encroachers (i.e., illegal hunters and forest resource gatherers) at the viaducts and surrounding forests. In the surrounding forests, researchers found 125 encroachment camps and 131 snares for capturing wildlife predominantly near the road and 43 access trails emanating from the road (Clements et al., 2014).

The four-lane Aring-Kenyir Road (Federal Route 185) in Terengganu, Malaysia, was completed in 2008 and incorporated ten viaduct crossings and bridges spanning rivers and streams, with three viaducts designed explicitly for wildlife passage. The bridges have become popular fishing spots among locals. Established dirt roads provide access from the highway to beneath the viaducts (Figure 35). Despite the presence of humans, elephants utilise these viaducts. On a visit to the viaducts in October 2022, relatively fresh evidence of a recreational camp at one of the viaducts (Figure 35) with a burnt shell of a Malayan box turtle (*Cuora amboinensis*), listed as Vulnerable by the IUCN, in a campfire was noted.

Figure 35. Human activities under a wildlife viaduct in Tasik Kenyir off the Aring-Kenyir Road, Malaysia, including locals fishing under the viaduct (left); an established dirt road leading from the highway to the viaduct (right).
| MANAGEMENT & ECOLOGY OF MALAYSIAN ELEPHANTS (MEME)

Figure 36. Remnants of a recreational camp under a wildlife viaduct on the Aring-Kenyir Road, Malaysia.
| MANAGEMENT & ECOLOGY OF MALAYSIAN ELEPHANTS (MEME)

The presence of humans at the viaducts and crossing structures is concerning as it potentially deters wildlife from approaching the structures, thus undermining the investment to safeguard and promote wildlife connectivity in the area. There is evidence of wildlife sensitivity to human presence that temporarily alters their use of these areas to avoid humans (Lam, 2017). This potential impact reinforces the need for effective wildlife enforcement and measures to control or limit access off the highway to wildlife crossings. Incorporating the complexities of human encroachment is crucial for effective wildlife management. Recognizing the socio-economic realities and community needs is essential, as these factors often drive human presence near wildlife corridors. Therefore, while planning and implementing wildlife corridors, it is imperative that managers not only focus on ecological aspects but also engage empathetically with local communities, fostering coexistence and understanding of the shared landscape.

9. Role of Fencing in Promoting Effective Elephant Crossing Structures

Fencing is essential in promoting permeability across LTI, funneling animals to crossing structures where traffic has minimal impact (Gagnon et al., 2007; 2017). The importance of wildlife fencing when used in conjunction with crossing structures to reduce wildlife-vehicle collisions has been stressed by experts for decades (Forman et al., 2003; Rytwinski et al., 2016; van der Ree et al., 2015). However, Asian elephants pose a challenge as fencing can have limited deterrent effects and require substantial maintenance. Yet, as stressed by Pan et al. (2009), Chogyel et al. (2017) and Clevenger and Huijser (2011), locating crossing structures in established, natural elephant movement corridors can reduce the amount of fencing needed to funnel animals to passages.

Many barrier measures have been used in Asia with varying success, ranging from electrified fences to concrete ditches. Effectiveness is often a tradeoff between efficacy, cost, and maintenance requirements; effectiveness and durability (minimising maintenance) should be primary considerations in fence applications.

Low-cost electrified fence applications have been effective in preventing elephant access to crops but require constant maintenance to remain effective; an electric fence is most suited for limited crop-protection applications. One of the most prevalent barriers used in Asia to prevent elephant entry is rubble walls constructed of local stone from streams and rivers, with or without plaster. A comprehensive assessment found that elephants could breach most walls, with only 12% of walls retaining their integrity (Natarajan et al., 2021). Natarajan et al. (2021) recommended rail track fences as a more durable and impenetrable elephant barrier.

Figure 37. A rubble wall in southern Bhutan.
| NORRIS DODD

A rail track fence is constructed from a retired, welded railway track. These fences have been used in central and southern India and have proven effective—it is one of the most durable designs used for African *(Loxodonta spp.)* and Asian elephants. Railway track fencing has been configured with two, three, or four horizontal track bars attached to vertical track posts (Figure 38). As described by Saklani et al. (2018), applications using just two horizontal track bars have been fraught with issues related to elephants either trying to jump over the 1.7-metre-high fence or attempting to cross through the two bars separated by 0.8 m and becoming stuck. As such, fencing with just two horizontal bars is not considered a sufficient barrier for practical use. Conversely, fence applications with four track bars, such as those employed in central India, have been shown to effectively funnel the elephants to the nearest wildlife crossing or natural habitats over a short distance.

Figure 38. Applications of railway track elephant barrier fencing with two horizontal track bars (left) and four horizontal track bars in Posita, Jharkhand, India (right).
| LEFT: SAKLANI ET AL., (2018) | RIGHT: WILDLIFE TRUST OF INDIA

A reinforced-concrete bridge guardrail design is being constructed in Bangladesh on a new railway as an alternative to a rail track fence (Figure 39). This fence has three horizontal rails spaced similarly to track rail fences with a 2.2 m height. Its cost is comparable to a rail track fence and is anticipated to provide an acceptable alternative, especially when track rail is unavailable.

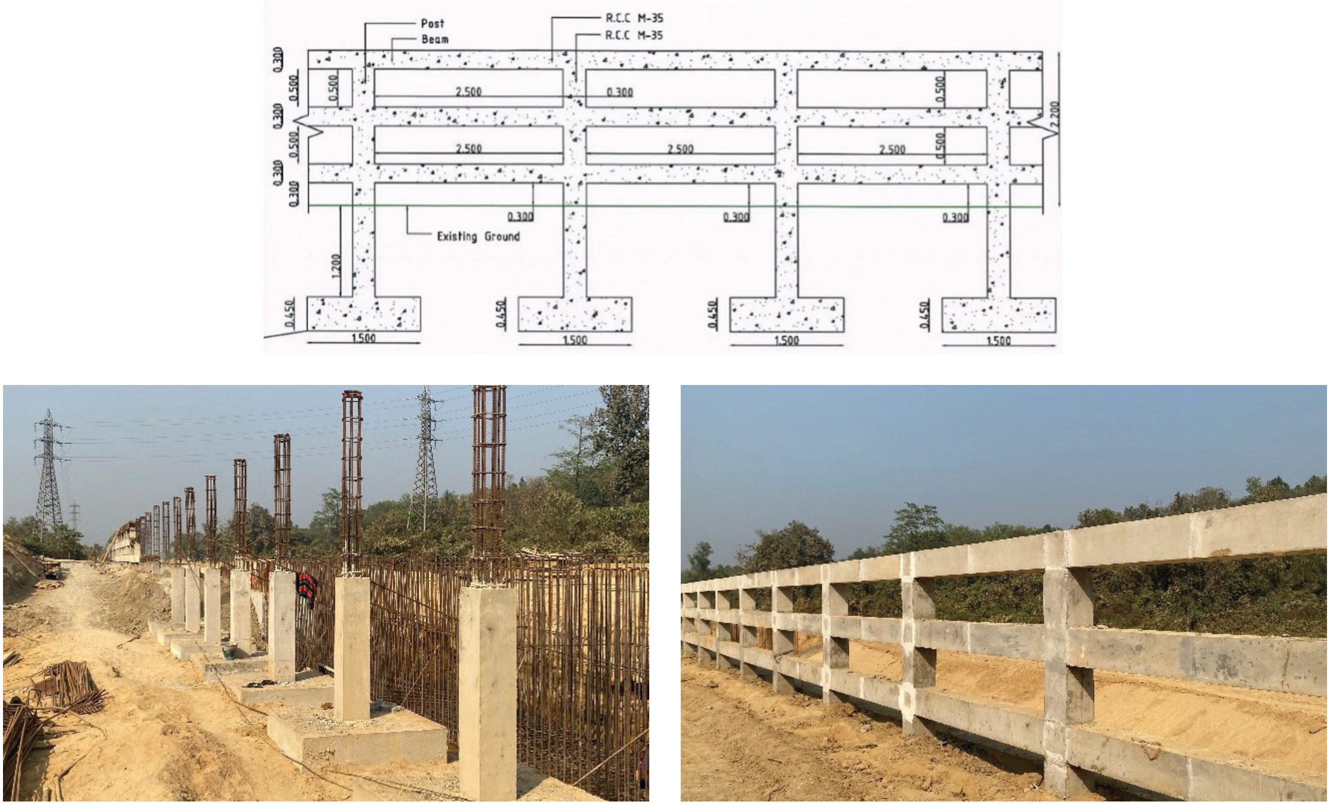

Figure 39. Schematic of reinforced concrete elephant fence for railway project in Bangladesh (top); ongoing construction of fence (lower left); completed fence (lower right).
| NORRIS DODD

China has recently employed a welded metal tube (20 cm in diameter) fence (Figure 40) along 2.6 km of the Silan Expressway at 17 elephant hotspots associated with crossing structures to prevent elephants from entering the highway. Preliminary monitoring suggests that the fencing is holding up well; if proven durable, this design may present a more cost-efficient option than the track-rail or reinforced concrete options.

Figure 40. Welded tube metal fence along the Silan Expressway near 17 crossing structures to prevent elephants from reaching the highway.
| YUN WANG

In Peninsular Malaysia, an innovation called ELEfence was developed through the collaboration of three agencies: the Department of Irrigation and Drainage Malaysia (JPS), the Department of Wildlife and National Parks Peninsular Malaysia (PERHILITAN) and the University of Technology PETRONAS (UTP). It consists of prefabricated concrete columns installed using screw piles and interlinked with prestressed cables (Figure 41). The use of Industrialized Building System (IBS) components helps ensure quality control, reduce environmental impact, and save installation time required on-site compared to in-situ construction. The screw pile system provides quick installation, high load capacity, and minimal site disruption. The ELEfence system has advantages over traditional electric fence systems due to its high lateral durability and low maintenance cost. Currently, ELEfence is constructed along one of the PERHILITAN projects in Kota Tinggi, Johor, the state with some of the highest HEC cases recorded nationally. Some mega-LTI projects in Malaysia, such as the East-Coast Railway Link (ECRL) network and the Gemas-Johor Bahru Electrified Double Tracking Project, have already shown interest in applying ELEfence.

Figure 41. The Malaysian ELEfence prototype was successfully tested at the National Elephant Conservation Centre, Lanchang, Pahang.
| SALMAN SAABAN

Elephant barrier designs that are high-cost, and nearly maintenance-free include concrete ditches and reinforced concrete walls (Figure 42). To date, extensive applications of these measures have been limited as they can be cost-prohibitive. In addition, these structures may not be friendly for small to mid-sized wildlife, as they may create a barrier or become a deadly trap and escape passageways may be needed at intervals.

Figure 42. A dual-purpose reinforced concrete sound and elephant barrier wall in India.
| ROB AMENT

Various vegetative or “biofence” treatments can deter or block Asian elephant passage. Biofences range from chilli peppers planted as a deterrent to the use of thick, spiny or thorny vegetation planted in dense rows to create a barrier. Thorny bamboo (*Bambusa bambos*; Figure 43), native to southern Asia, has been used successfully to block elephant passage (Kumar et al., 2022) and can be combined with electric fencing to increase its effectiveness. It reduces the potential impact of elephants pushing against fencing and causing damage. Thorny bamboo and other plants can be planted to create a buffer beyond fencing to limit elephant access to the fence, thus prolonging its functional life and reducing long-term maintenance.

Figure 43. Thorny bamboo to deter elephant movement and minimise fence damage.
| iSTOCK.COM MANSUM008

Steep slopes can also assist in deterring elephant passage. Steep uphill slopes can increase the effectiveness of fencing as animals have a more difficult time pushing/leveraging against fences. It also increases the “effective barrier height” of fencing. Effective height is predicated upon the concept of barrier height as a function of increasing slope, as described by Payne and Bryant (1994), where functional fence barrier height increases with slope steepness. For instance, a 2-metre-high fence on flat ground has an effective barrier height of 2.3 m when placed on a gentle (10%) slope. But the same fence has an effective barrier height of 3.2 m on a 30% slope. With proper erosion control, fencing installed on embankment slopes can increase fence effectiveness at minimal additional cost.

Lastly, Thouless and Sakwa (1995) and Natarajan et al. (2021) stress the benefit of combining elephant barrier treatments to improve barrier effectiveness; for instance, highway applications in China have combined electric fences and trenches.

10. Non-Structural Mitigation Approaches

Relatively low-cost, non-structural mitigations are available for low-traffic/low-speed roads that traverse Asian elephant habitats, particularly within protected areas. Such non-structural strategies are intended to modify driver behaviour through reduced vehicular speed and increased alertness. Increased motorist alertness can reduce vehicle stopping distances by as much as 21 m at 88 km per hour vehicle speed, enough to avoid or reduce the severity of collisions with animals (Huijser et al., 2008). The risk of collision increases exponentially with increasing vehicular speed (Kloden et al., 1997). Thus, increasing motorist alertness and decreasing vehicular speed can significantly reduce wildlife-vehicle collision incidence (Huijser et al., 2008), especially where massive Asian elephants are involved.

10.1. Motorist Alert Signage

An important function of highway warning signage is to elicit modified motorist behaviour (e.g., slowing down) in response to anticipated hazards, most of which motorists encounter after passing signage (e.g., sharp curves). In the case of wildlife crossing alert signage, motorists often do not encounter animals when passing signs. This contributes to motorist habituation to the signage, which can often render signage relatively ineffective in helping to lessen wildlife-vehicle collisions (Sullivan et al., 2004, Huijser et al., 2015). Regardless, signage to alert motorists to the potential of encountering elephants is an important step toward promoting motorist safety and reducing collisions (Figure 44).

Figure 44. Asian elephant alert signage. Motorist alert sign erected along the Silan Expressway, Yunnan Province, China (left); caution sign within Rajaji National Park, India (right).
| LEFT: YUN WANG | RIGHT: ROB AMENT

However, Found and Boyce (2011) did find that warning signage effectiveness was increased when signage was erected at limited, place-specific “hotspots,” and proper siting was also stressed as important by Huijser et al. (2015). Wildlife warning signage integrated with flashing lights and variable message boards can be more effective than static warning signs (Gagnon et al., 2017; Huijser et al., 2015). However, signs with flashing lights may elicit motorist habituation if they operate continuously (Lehnert and Bissonette, 1997). Flashing signs are most effective when utilised during peak wildlife crossing periods (e.g., migrations). Solar-powered flashing lights (with batteries for nighttime operation) can be attached to static alert signs during key periods such as elephant migration (right). Installation of large, billboard-sized signage can also effectively alert motorists, especially when driving through elephant concentration areas (Figure 45).

Figure 45. Example of a flashing sign.
| CENTER FOR LARGE LANDSCAPE CONSERVATION

Figure 46. The installation of billboard-sized signage within elephant linkages, such as this one intersecting the Aring-Kenyir Road in Terengganu, Peninsular Malaysia or other concentration areas, is effective in alerting motorists to potential elephant presence.
SALMAN SAABAN

The most effective signage is fully integrated with animal-activated detection systems that trigger flashing and message signs only when animals are present (Huijser et al., 2015). When designated place-specific crossings, or crosswalks, were created by fencing and integrated with an animal detection system that triggered time-specific alert signage, large mammal collisions were reduced by 98% without motorist habituation (Gagnon et al., 2019). However, animal detection systems are expensive and maintenance-intensive and may not be well suited for remote applications.

Additionally, the dark colour of the Asian elephant bodies increases the risk of elephant-vehicle collisions along highways during night time. Apart from the installation of signage to increase motorist awareness (Figure 46), the installation of streetlighting may be encouraged at locations where elephants often cross to make it easier for motorists to detect elephants from a further distance so they may slow down and take evasive action to avoid collisions.

10.2. Traffic Calming Measures

Traffic calming is a strategy to slow vehicle speeds and increase driver alertness. Traffic calming measures allow drivers more reaction time and shorter braking distances, thus, decreasing the likelihood of a collision with animals on or approaching the road. There are two categories of traffic calming measures, physical and psychological. Physical measures include rumble strips, narrow lanes, sharp curves/shorter curve radii, speed bumps, humps or tables. These measures can be designed to make it difficult for a vehicle to be controlled at various speeds so that the driver must slow down to maintain control.

A series of signs, striping, and rumble strips slows vehicles on NH 37 in Assam, India (Figure 47). The highway follows the southern border of Kaziranga National Park, where many large animals, such as Asian elephants, tigers and greater one-horned rhinoceros, cross back and forth from the park and the adjacent Karbi Anglong Hills throughout the year (this movement occurs most frequently during the annual monsoon season when a large part of the park floods and wildlife move to higher ground).

Figure 47. Rumble strips from Lumding in Assam.
NILANGA JAYASINGHE / WWF-US

Figure 48. An example of high financial penalties for speed violations in India.
| NILANGA JAYASINGHE / WWF-US

Measures that seek to affect driver experience so that they slow down include enforcement of speed limits that are sometimes associated with penalties for speeding and enforced using speed-detection cameras and patrolling by law enforcement agencies (Figure 48); painting narrower lane striping so drivers slow down to decrease their lane departures; groove asphalt so that it is noisier inside the vehicle at higher speeds; use of fixed objects such as curbing, called chicanes (Figure 49); or painting lanes to make a straight road more serpentine. Many of these techniques are more appropriate for roads and highways in protected areas or other non-thoroughfare types of roads. They are not commonly deployed on controlled access, multi-lane, high traffic volume, and high-speed roads.

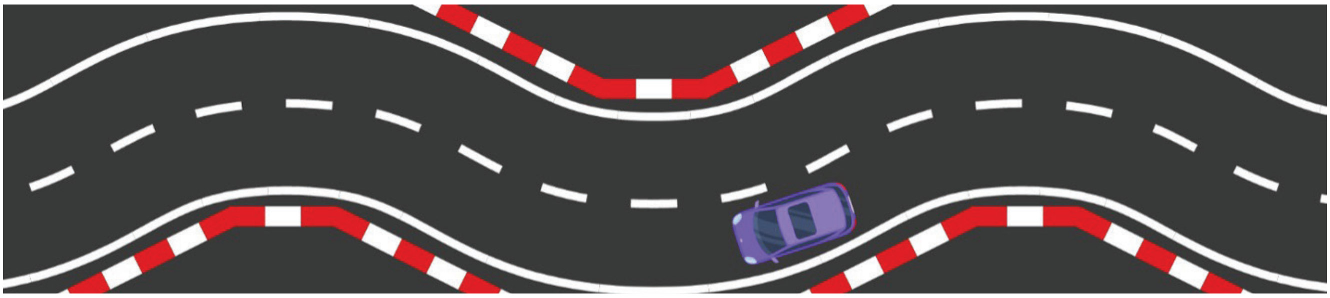

Figure 49. A chicane where curbs are placed in a straight road to make it more sinuous.
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When traffic calming measures are integrated with effective signage within designated (place-specific) high-incidence elephant crossing zones, they have the potential to be quite effective. However, more research is needed on the efficacy of the various traffic calming measures in reducing wildlife-vehicle collisions or whether they increase wildlife movement across the road, especially in Asia. One study of the use of rumble strips on the road in Tasmania, Australia, indicated a decrease in the mortality of mammals by 59% (Lester, 2015). A summary of the effectiveness of traffic calming measures and their cost is available from North America (Huijser et al., 2021). A literature review on Google Scholar™ using “traffic calming” AND “wildlife-vehicle collisions” AND “Asia” returned no scientific papers.

10.3. Railway Mitigation

Raising awareness among locomotive drivers is a vital railway mitigation strategy, particularly increasing their knowledge of key wildlife crossing areas. Enhanced training and information dissemination can significantly increase driver vigilance, enabling them to identify and respond appropriately to sensitive zones. By being more alert and consciously reducing speed in these areas, the likelihood of collisions with wildlife can be substantially reduced, making this an essential component of comprehensive wildlife protection measures.

Early warning systems are a promising measure to reduce Asian elephant mortalities from train collisions. By alerting train drivers to the presence of elephants on or near the tracks so that they may slow down or even stop to prevent collisions with crossing elephants. Two general approaches to sensor technology are being developed in Asia: locomotive- and ground-based systems. Locomotive-based sensor systems (Figure 50) typically employ optical and/or thermal/infrared (Forward Looking Infrared; FLIR) cameras that can detect elephants 750 m or more in advance of trains. Ground-based detection systems can be installed at frequent crossing locations, such as the end of elephant fencing. Such systems typically use a combination of technologies in addition to optical or thermal cameras, including acoustic and/or seismic sensors and radar, to detect the presence of elephants and alert train engineers in real-time via messaging from a base station, train signalling, or by an onboard alarm. Some systems also use GPS to track the location of elephants in relation to railway tracks and provide more detailed information to train drivers. Early locomotive-based systems often required train engineers to monitor cameras to detect elephants. However, machine learning and artificial intelligence (AI) facilitated computer monitoring, which can now detect elephants on or near railways in sufficient time for engineers to take appropriate action.

In a pioneering initiative, the Northeast Frontier Railway (NFR) in India has utilised AI to proactively observe and safeguard wild elephants from train collisions, which have been frequent occurrences in Assam. Through the implementation of AI-based software integrated with optical fibre cable (OFC), the NFR has established a reliable and advanced system to monitor elephant movements and avert potential accidents on railway tracks (Deccan Herald, 2023). This innovative approach marks a significant step forward in mitigating the human-elephant conflict and underscores the promising application of AI technology in wildlife conservation and railway safety management.

A recent sensor technology pilot study in Bangladesh evaluated a range of off-the-shelf detection technologies (Schwarz et al., 2023) for both locomotive- and ground-based systems. They found that combining optical and thermal imaging (FLIR) cameras provided the most reliable detection for both applications (Figure 50). FLIR cameras zoomed out with narrow fields of view (15 degrees), performed best for locomotive-based applications and reliably detected elephants up to 800 m. The main limitation was difficulty discerning elephants from their surroundings on hot days. FLIR cameras with wider fields of view (35 degrees) were reliable in detecting elephants out to 120-200 m and thus were more suited to ground-based systems. An independent train signaling system integrated with the detection systems was developed to provide advanced alerts to approaching trains.

Figure 50. Locomotive in Bangladesh equipped with a thermal imaging camera (top) as part of a sensor technology pilot study, and daytime (bottom left) and nighttime (bottom right) thermal camera images of testing elephants.
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In India, the Central Scientific Instruments Organisation (CSIO) has developed reliable and cost-effective elephant detection based on AI-integrated seismic sensors at crossing locations along railways. Their ground-based systems can be integrated with railway signaling or messaging alerts to advise approach trains of crossing elephants.

In addition to traditional early warning systems, new and emerging technologies have the potential to make these detection systems even better at reducing train collisions with Asian elephants. For example, machine learning algorithms can process large amounts of data from cameras and other sensors to accurately detect elephants and other wildlife in real-time (Gunasekara et al., 2021). It should be noted that sensor technologies require constant maintenance to ensure effectiveness and reliability, which can be costly and prove difficult in remote areas. In addition, using unmanned aerial vehicles (UAVs) could provide a more comprehensive view of the area surrounding railway tracks and help detect elephants at a greater distance, allowing more time for train drivers to respond (Yang et al., 2023).

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A herd of elephants crosses a road at Anamalai Hills, India.
| SREEDHAR VIJAYAKRISHNAN

Asian Elephant Transport Working Group (AsETWG):
Building a Network of Experts to Address Elephant-LTI Conflicts

The Asian Elephant Transport Working Group (AsETWG) was formed in 2018 as a collaboration between the IUCN World Commission on Protected Areas' Connectivity Conservation Specialist Group (CCSG) and the IUCN Species Survival Commission's Asian Elephant Specialist Group (AsESG). AsETWG currently has a growing membership of more than 30 volunteers working to deliver practical, flexible, and science-based solutions that avoid and mitigate threats of LTI to Asian elephants across all 13 range states. Interested participants are encouraged to volunteer their time and contribute their energy and knowledge to ongoing activities.

To learn more about AsETWG, visit: http://conservationcorridor.org/ccsg/working-groups/asetwg/
To apply for membership, visit: https://conservationcorridor.org/ccsg/membership/
For more information, contact: connectivity@largelandscapes.org