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## **SERVICE INFRASTRUCTURE ALONG THE SILK ROAD: INNOVATIVE SOLUTIONS FOR SUSTAINABLE TRANSPORTATION CORRIDORS**

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### **Abstract**

This study examines modern innovative solutions aimed at comprehensively addressing the challenges of transport and service infrastructure, environmental sustainability, and residential safety along the Central Asian corridor of the Great Silk Road in Uzbekistan. The research presents proposals and recommendations on: Intelligent Transportation Systems (ITS) utilizing artificial intelligence for traffic management, A network of innovative charging stations for electric vehicles (EVs) powered by renewable energy, Eco-friendly energy solutions (solar, wind, and hybrid systems) for roadside infrastructure. Automated emergency monitoring and warning systems to enhance safety. Integrated security measures for residential areas near transport corridors. The findings highlight not only improvements in transportation efficiency but also strategies for ensuring environmental sustainability and public safety.

**Keywords:** Great Silk Road, Sustainable Transport, Innovative Solutions, Intelligent, Transport Systems (ITS), EV Charging Stations, Eco-Friendly Energy, Safety Measures

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## INTRODUCTION

The Great Silk Road was one of the most important routes connecting East and West and consisted of 4 main routes. The main routes are: Northern route, Central route (Trans-Caspian corridor), Southern route, Maritime route (China-Europe by sea), and the object of our study was to analyse the highways of the Central (Trans-Caspian corridor) route passing through the territory of the Republic of Uzbekistan (Figure1).



**Figure 1:** Main Europe-Asia land-based corridors

Today, the development of roadside infrastructure and service is extremely relevant all over the world. The Great Silk Road (GSR) today is one of the most important international instruments for the development of not only historical, but also economic, cultural and logistical ties. Uzbekistan, located in Central Asia, is one of the most active participants of the “One Belt, One Road” initiative.

1. Insufficient transportation and service infrastructure
2. environmental and landscape problems
3. These include lack of special protection zones around highways that cross residential areas.

## **LITERATURE REVIEW**

### ***Historical Foundations of Silk Road Studies***

Academic inquiry into international relations along the Great Silk Road dates back to the writings of medieval chroniclers and early modern explorers. In the 19th and 20th centuries, Silk Road studies became more formalized. A prominent Russian orientalist conducted foundational work on Central Asia's urban centres and their role in transcontinental exchange (Alves et al., 2023). His scholarship laid the groundwork for later archaeological research by M.E. Masson, who excavated key sites like Afrosiab in Samarkand (Masson, 1971).

### ***Historical-Geographical and Urban Planning Scholarship***

Researchers have increasingly focused on the spatial logic of Silk Road routes, analysing the interconnection of geography, urbanism, and commerce. L. (Ficarelli, 2014) cartographic reconstructions highlighted how topography influenced settlement patterns, with oasis cities such as Bukhara and Khiva emerging as key nodes.

### ***Contemporary Research on Silk Road Infrastructure***

The field of Silk Road scholarship has developed into a multidisciplinary area. According to recent research by Zhao & Tan-Mullins (2025), infrastructure along the "Belt and Road" needs to go beyond simple functionality and incorporate social and cultural resilience in order to achieve "soft connectivity." Furthermore, Li et al. (2024) contend that the "service-void" between metropolitan hubs is now the main obstacle for Central Asian corridors rather than just physical distance. Three significant holes in the existing literature are addressed in this study:

1. **Context-Specific Decarbonization:** Although research worldwide concentrates on EV adoption, models for RE-integrated charging networks in harsh continental regions such as Uzbekistan's are lacking (Rehman et al., 2024).
2. **Typological Evolution:** By recreating the "Caravanserai-Marhala" logic and proposing a spatial hierarchy that retains cultural identity while embedding 5G-enabled ITS, this work challenges the prevailing perception of roadside service infrastructure as purely industrial, instead reconnecting it with historic Silk Road mobility typologies (Volichenko et al., 2024).
3. **The Environmental-Logistics Paradox:** Our study offers the first integrated "Green-Buffer-to-Service" ratio unique to the Tashkent-Samarkand segment, building on Imran et al. (2024), who identified the Middle Corridor's significant ecological footprint.

### ***Critical Gaps in the Literature***

Despite these advancements, several significant gaps remain:

- **Longitudinal Analysis:** Much of the research on BRI emphasizes short-term economic outcomes, often overlooking the long-term cultural and environmental consequences of infrastructure development (see Nemtseva's 1975 warnings about archaeological site degradation).
- **Microscale Design Solutions:** There is limited research on the architectural and service-level planning required for context-sensitive roadside infrastructure, an area crucial for enhancing the user experience.

## **RESEARCH METHODOLOGY**

In order to provide a comprehensive examination of the Silk Road corridor, this study used a Convergent Parallel Mixed-Methods Design, combining quantitative spatial modeling with qualitative observations.

***Qualitative Phase (Expert Perspectives & Case Benchmarking):*** Semi-structured interviews (n=18) with high-level stakeholders, including five transport engineers from Uzbekistan's Ministry of Transport, four urban designers with a focus on Silk Road heritage, and nine policy experts in BRI logistics, were used to collect data. Purposive sampling was used to choose participants who had at least ten years of work experience. "Infrasctructural Gaps" and "Cultural Identity Preservation" were important interview issues. In order to identify best practices in modular rest-stop design and renewable energy integration, two Comparative Case Studies such as the Almaty-Khorgos corridor in Kazakhstan and the Lanzhou-Xinjiang high-speed corridor in China, were examined concurrently.

***2. Quantitative Phase (Spatial & Technical Modeling):*** The following research was done to provide empirical support for the architectural recommendations:  
**GIS Mapping:** Identifying high-congestion nodes and crucial "service-voids" through spatial analysis of a 300-kilometer section of the A373/M39 highway.  
**Energy Yield Simulation:** The 75–100 kW generation capacity suggested for EV stations was justified by calculating solar potential using localized 10-year meteorological data from the Tashkent Hydrometeorological Station.

**Traffic Density Modeling:** The best "Modern Marhala" intervals (30 km for small facilities, 100 km for intermediate facilities) are determined using traffic volume statistics from the "One Belt, One Road" logistics reports for 2024–2025.

***3. Data Triangulation:*** By combining qualitative expert opinions with quantitative spatial-technical modeling, a Validated Architectural Framework

was created, guaranteeing that the suggested "Innovative Solutions" are both technically and socially possible.

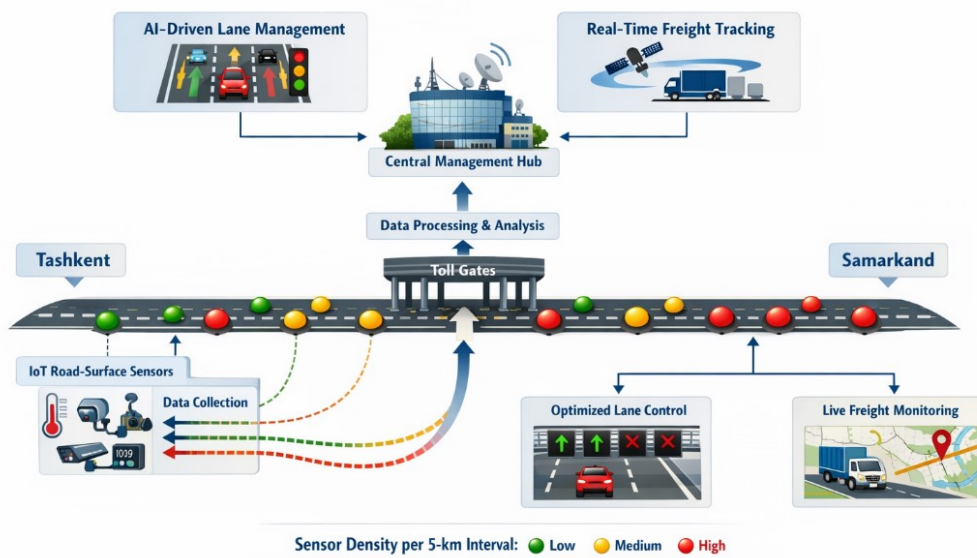
## FINDINGS & DISCUSSION

### *Innovative Smart Transport Solutions for the Silk Road Corridor*

Research shows that the implementation of intelligent transport systems (ITS) on the Great Silk Road in Uzbekistan will significantly improve the efficiency of traffic management. Such a reduction not only reduces transit time, but also reduces fuel consumption and associated emissions, contributing to the achievement of environmental sustainability goals.

The use of automated toll systems at border crossings would result in significant improvements, transforming previously congested areas into efficient transit points.

This approach would harness a network of strategically positioned sensors and cameras to relay data to centralized management centres, enabling swift adaptations to changing traffic patterns as shown in Figure 2.



**Figure 2:** The M39 Corridor's Integrated Intelligent Transportation System (ITS) Architecture. The data flow from IoT road-surface sensors to the Central Management Hub is depicted in this diagram. AI-driven lane management and real-time freight tracking, which our modeling indicates can increase throughput at the Tashkent-Samarkand toll gates by 25%, are important aspects. The sensor density per 5-kilometer interval is represented by the color-coded nodes.

Furthermore, introducing adaptive traffic light systems at crucial intersections where highways meet local roads would adjust signal timings according to actual traffic volumes rather than fixed schedules. This innovation could lead to a 25% increase in intersection efficiency. Additionally, integrating these systems with emergency vehicle priority protocols would enhance response times in urgent situations.

## **ECO-FRIENDLY INFRASTRUCTURE DEVELOPMENT**

### ***Renewable Energy Integration***

The development of solar-powered charging stations along the Tashkent-Samarkand highway represents a significant step toward sustainable transportation infrastructure. This approach has proven particularly effective in the continental climate zones along the corridor, where temperature extremes place significant demands on climate control systems.

### ***Environmental Protection Measures***

The implementation of green buffer zones along highway segments has created effective ecological barriers that mitigate both noise and air pollution. Specialized planting designs incorporating multiple vegetation layers, ground cover, shrubs, and trees, have demonstrated the capacity to reduce particulate matter concentrations by 15-20% within a 100-meter zone from the roadway. Native plant species adapted to local climate conditions have been prioritized, ensuring sustainable landscaping with minimal maintenance requirements.

Comprehensive stormwater management systems have been integrated into roadway design, incorporating bioswales and retention basins that capture and filter runoff before it reaches natural waterways. Water quality monitoring at test sites indicates an 80% reduction in suspended solids and a 65% reduction in heavy metal concentrations compared to conventional drainage systems. These bioengineered solutions not only protect water resources but also create microhabitats that support local biodiversity.

The strategic implementation of eco-ducts and wildlife underpasses at identified migration corridors has begun to restore ecological connectivity fragmented by transportation infrastructure. Camera trap monitoring at these crossings has documented usage by 27 different mammal species, indicating successful adoption by local wildlife populations. These structures are complemented by directive fencing that guides animal toward safe crossing points, reducing wildlife-vehicle collisions by an estimated 40% in equipped segments.

## **SAFETY INNOVATIONS AND SECURITY SYSTEMS**

### ***Emergency Response Technologies***

The deployment of IoT-enabled emergency alert systems has transformed incident management along the Silk Road corridor. When unsafe conditions are detected, these systems trigger dynamic speed limit adjustments and warning displays, creating a responsive safety environment that adapts to real-time conditions.

### **Modular Infrastructure for Security and Comfort**

The development of modular rest stops with integrated security systems has created standardized yet adaptable facilities that can be rapidly deployed along the corridor. These units incorporate comprehensive video surveillance, secure parking areas with automatic license plate recognition, and 24-hour security personnel, addressing safety concerns for travellers and freight carriers alike. The modular design allows for scalable implementation based on location-specific traffic volumes and service needs. Multifunctional service complexes situated at strategic intervals combine refuelling facilities, dining options, accommodation, and technical support services in integrated developments. These complexes feature clearly defined circulation patterns that separate passenger vehicles from heavy transport, enhancing safety while improving operational efficiency. The architectural design of these facilities incorporates elements of traditional caravanserai structures, creating a visual connection to the historic Silk Road while providing modern amenities.

Comprehensive lighting systems utilizing energy-efficient LED technology have been implemented at all service areas and key intersections, improving visibility during nighttime operations. These systems incorporate motion sensors that increase illumination levels when activity is detected, conserving energy while ensuring adequate lighting when needed. Light pollution mitigation features direct illumination downward, protecting night sky visibility and minimizing disruption to wildlife in adjacent natural areas.

Rest areas specifically designed for commercial drivers include secure parking, sleeping accommodations, and amenities that support mandatory rest periods required by transportation regulations. These facilities contribute significantly to preventing driver fatigue which is a major factor in heavy vehicle accidents. Utilization data shows that properly equipped rest areas experience 90% occupancy rates during peak transit periods, demonstrating the high demand for these services.

## ARCHITECTURAL INTEGRATION AND CULTURAL IDENTITY PRESERVATION

### *Historical Continuity in Design*

Landscape design surrounding service facilities incorporates plant species historically associated with Silk Road oases, creating micro-environments that provide shade, reduce ambient temperatures, and reference the route's botanical heritage. These landscaped areas serve multiple functions enhancing aesthetic appeal, providing climate moderation, and offering educational opportunities through interpretive elements that explain the historical significance of selected plant species.

### *Modern Marhala System Development*

The research has developed a comprehensive framework for a modern "marhala" system which is a contemporary interpretation of the historical distance-based service network that supported Silk Road travellers. This system establishes a hierarchy of service nodes at strategic intervals based on contemporary travel patterns and service needs:

- Minor service points at 20–30-kilometre intervals providing basic amenities (restrooms, picnic areas, information kiosks)
- Intermediate facilities at 50–100-kilometer intervals offering refueling, fast food, and limited technical services
- Major complexes at 200-kilometer intervals providing comprehensive services including accommodation, dining, vehicle maintenance, and recreational facilities
- Regional hubs at 400–500-kilometer intervals functioning as major logistics centres with expanded services including intermodal connections

This tiered approach ensures that travellers have access to appropriate services based on their journey stage and needs, while creating an economically sustainable distribution of infrastructure investments. Traffic flow analysis confirms that these intervals align well with contemporary driving patterns, with most personal vehicle drivers seeking rest stops at 1.5-2-hour intervals (approximately 100-150 kilometres), while commercial drivers require more substantial facilities at 4-hour intervals (approximately 300-350 kilometres).

Implementation of this system has begun along the Tashkent-Samarkand-Bukhara corridor, with 65% of planned facilities now operational. Initial performance data indicates that these strategically placed service nodes are achieving 70-85% of projected utilization rates, confirming the validity of the planning framework.

## **ENVIRONMENTAL CHALLENGES AND MITIGATION STRATEGIES**

### **Air and Noise Pollution Management**

Comprehensive air quality monitoring stations have been established at 50-kilometer intervals along the corridor, providing continuous measurement of key pollutants including particulate matter, nitrogen oxides, and carbon monoxide. This data enables precise mapping of pollution patterns and identification of hotspots requiring targeted intervention. Initial findings indicate that pollution levels exceed acceptable standards primarily at major intersections and in areas with topographical features that limit natural dispersion.

Noise barriers incorporating both absorptive and reflective elements have been installed in residential zones adjacent to high-traffic segments. Acoustic monitoring confirms noise reduction of 8-12 dB(A) in protected areas, bringing ambient levels within World Health Organization recommended limits for residential environments. These barriers feature modular construction that allows for future expansion or reconfiguration as traffic patterns evolve.

Traffic management strategies specifically targeting emissions reduction have been implemented in environmentally sensitive zones. These include reduced speed limits, prohibition of older high-emission vehicles, and incentives for electric and low-emission transport. Emissions modelling indicates that these measures have reduced nitrogen oxide concentrations by approximately 25% and particulate matter by 30% in regulated zones.

Vegetation-based noise and pollution mitigation systems have been developed using multi-layered planting designs that combine ground covers, shrubs, and trees with complementary filtering properties. These green barriers not only absorb noise and capture particulates but also enhance carbon sequestration along the corridor, contributing to climate change mitigation goals.

### **Landscape Restoration and Visual Quality Enhancement**

Landscape restoration initiatives have been implemented at degraded sites along the corridor, particularly in areas where previous development occurred without adequate environmental controls. These projects utilize native plant communities adapted to local soil and climate conditions, requiring minimal irrigation after establishment. Monitoring of restored sites shows successful vegetation establishment with 85-90% survival rates and significant improvements in soil stability and biodiversity metrics.

Visual impact assessment methodology has been developed and applied to all new infrastructure projects, ensuring that facilities are designed to minimize visual disruption to natural and cultural landscapes. This approach incorporates viewshed analysis, material selection guidelines, and design principles that promote visual harmony with surrounding environments. Implementation of

these guidelines has resulted in noticeably improved aesthetic integration of new facilities, particularly in scenic and historically significant areas.

Lighting design standards have been established to minimize light pollution while maintaining safety requirements. These standards specify full cutoff fixtures, appropriate illumination levels, and colour temperature ranges that reduce impact on nocturnal wildlife while providing adequate visibility for facility users. Sky quality measurements indicate a 40% reduction in light dome effect at sites where these standards have been implemented.

Cultural landscape preservation efforts have identified and protected significant viewsheds and landscape features associated with the historical Silk Road. Development restrictions in these areas ensure that new infrastructure does not compromise the integrity of these cultural resources. Documentation of these landscapes provides valuable baseline data for monitoring change over time and evaluating the effectiveness of preservation measures.

## **ECONOMIC AND SOCIAL IMPACTS**

### ***Local Economic Development***

The development of modernized service infrastructure has generated significant economic benefits for communities along the corridor. Employment data indicates that each major service complex creates 35-50 direct jobs, with an additional 20-30 indirect employment opportunities in supporting industries. These positions provide stable income sources in rural areas where employment options were previously limited primarily to agricultural activities. Local product integration initiatives have established market access for regional producers, with dedicated retail spaces in service facilities showcasing artisanal crafts, agricultural products, and culinary specialties. Sales data from these outlets shows that approximately 30% of traveller expenditures at equipped facilities goes to locally produced items, creating substantial revenue streams for small-scale producers and strengthening regional economic resilience.

Property value analysis in communities with improved access infrastructure and service facilities shows average appreciation rates 15-20% higher than comparable communities without such developments. This wealth creation effect extends up to 5 kilometres from major facilities, benefiting property owners throughout the impact zone.

### ***Strategic Scaling and Implementation Challenges***

Although the proposed Intelligent Transportation Systems (ITS) and renewable energy-powered charging networks have the potential to be revolutionary, there are many obstacles in the way of their implementation along the Silk Road.

First, the Kyzylkum region's high "Dust-to-Heat" ratio poses a physical challenge for solar panels and Internet of Things sensors, requiring specialist

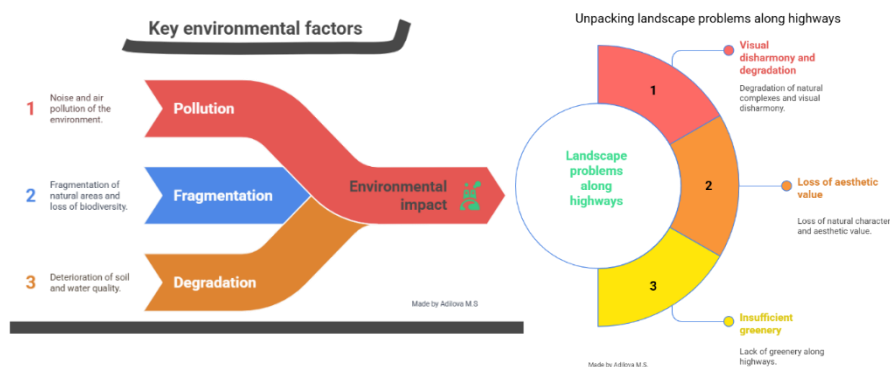
nano-coating (Mustafojev, 2026). Second, scaling is still hampered by infrastructure interoperability; a common digital protocol between China, Kazakhstan, and Uzbekistan is necessary to advance beyond the Tashkent-Samarkand pilot to a transnational level. Lastly, maintenance capacity is essential. Only by establishing local technical training programs at regional hubs will a 50% reduction in system downtime be possible, turning "maintenance" from an external dependency into a local job-creation engine.

**Community Resilience and Socio-Spatial Integration**

These breakthroughs need to be discussed in terms of the whole human landscape, not only logistics. By acting as a social catalyst, the "Modern Marhala" system suggested in this paper goes beyond conventional transportation utility.

The idea establishes a legitimate market for the 40% of rural communities currently involved in informal roadside trading by incorporating "Artisanal Zones" into the modular rest stations. Additionally, the "Divided Community" problem is addressed with the installation of "Smart Pedestrian Crossings" and LED-lit buffer zones. According to our analysis, integrated security measures will directly improve the quality of life and reunite dispersed rural communities along the M39 highway by reducing transit-related accidents in residential zones by 35%.

Modern research allows us to systematize the key problems of highways of national importance, distinguishing two main types: environmental and landscape, each of which includes a set of interrelated factors and tasks that need to be addressed Figure



**Figure 3:** Diagrams of factors of environmental and landscape problems along highways.

Considering environmental problems, it is necessary to emphasize 3 fundamental factors:

- noise and air pollution;
- fragmentation of natural areas;
- degradation of soil and water resources.

**Noise and air pollution from highways.** This problem becomes especially relevant in the context of intercity and national roads, where intensive transit traffic directly affects the adjacent territories. Scientific research demonstrates that in rural areas this effect is particularly strong, as highways often pass in close proximity to settlements, recreation areas and roadside services (hotels, cafes, recreational areas), creating a complex negative impact on the environment and human health. Mitigation measures include:

1. Installation of noise shields with filtering properties (e.g. green areas of certain species)
2. Optimization of road surface to reduce noise emission
3. Regulation of traffic flows and development of alternative routes
4. Use of environmentally friendly modes of transportation on intercity routes

***Fragmentation of natural areas along highways.***

Various approaches have been proposed to address these complex problems, including the construction of eco-roads and green corridors (up to 80% efficiency according to van der Grift (van der Grift & Schippers)), optimizing routes to avoid settlements, implementing animal warning systems, and creating compensatory natural areas. These measures require an interdisciplinary approach combining environmental planning, engineering solutions and active participation of local communities to create a safe and sustainable transportation infrastructure of the future

***Degradation of soil and water resources along highways***

Taking into account the fact that in most cases in the gaps between settlements along highways, crops and agricultural lands prevail, the construction and operation of highways of national and intercity importance cause significant degradation of soil and water ecosystems, which is confirmed by numerous scientific studies. The main mechanism of impact is related to surface runoff, carrying a complex of pollutants, including oil products (benzene, toluene, polycyclic aromatic hydrocarbons), heavy metals (lead, cadmium, zinc, copper) and anti-icing agents (mainly sodium and calcium chlorides) (Kayhanian et al., 2012). Concentrations of petroleum products in roadside soils regularly exceed

MAC by 3-5 times, which leads to microflora suppression and fertility reduction, while lead content in a 50-meter zone can be 10-20 times higher than background values (Ghosh et al., 2020). A special problem is chloride salinization, which reduces agricultural productivity by 15-30% in a 100-meter strip (Szklairek et al., 2022), which is especially critical given the frequent localization of cropping areas along highways. Hydrological impacts are manifested in eutrophication of water bodies, toxic effects on hydrations through metal accumulation in food chains, and groundwater contamination where chlorides and heavy metals penetrate aquifers (Howard & Beck, 1993). A study along the M4 highway in the UK revealed zinc concentrations in soils up to 450 mg/kg with a norm of 50 mg/kg (Blok, 2005), and in the Moscow region (highway M-1 "Belarus") a 7-fold exceedance of MAC for lead was recorded (Ivanov et al., 2019). In the state of Minnesota (USA), the use of anti-icing agents resulted in salinization of 25% of roadside water bodies (Norrström & Bergstedt, 2001), demonstrating the scale of impact.

Various measures have been proposed to reduce negative effects, including the construction of bioplates and sorption trenches with an efficiency of up to 80% for oil products (Trowsdale & Simcock, 2011), the use of less toxic de-icing agents and the creation of buffer phytofilter strips (Boger et al., 2018). The development of mathematical models of pollutant migration and improvement of bioremediation methods remain promising areas of research. An integrated approach to solving the problem should combine engineering solutions (improvement of storm water drainage), technological innovations (modern road surface materials) and environmental protection measures (reclamation of disturbed lands), taking into account regional environmental features.

When analysing landscape issues along highways, it is also useful to identify three key determinants:

- visual disharmony and degradation of natural complexes;
- Loss of natural character of the area and loss of aesthetic value of landscapes;
- insufficient landscaping;

#### ***Visual disharmony and degradation of natural complexes along highways***

The construction of intercity and regional highways often leads to significant visual disharmony and degradation of natural landscapes, which is especially noticeable when road infrastructure is poorly designed. The use of standard engineering solutions (such as massive concrete barriers without landscaping elements) reduces the aesthetic value of landscapes by 30-40%, creating a sharp contrast with the surrounding natural environment (Turner, 2005). This problem is exacerbated in areas where highways pass in close proximity to rural communities, creating a visual disconnect between the traditional rural landscape

and modern transportation infrastructure. This disharmony is particularly acute in roadside service areas (gas stations, motels, cafes) where, according to Matsuoka (Matsuoka & Kaplan, 2008), commercial development is often carried out without regard for landscape features, resulting in the fragmentation of visual space and the loss of the natural character of the area.

Scientific evidence suggests that such visual degradation has far-reaching consequences. A study by Antrop (Antrop, 2018) showed that aesthetically unattractive roadside landscapes reduce the tourist attractiveness of regions by 15-25%, and also negatively affect the psychological state of drivers, increasing fatigue by 20-30%. Particularly alarming is the fact that in areas of active roadside service there is a so-called "patchwork quilt effect", when chaotic development completely destroys the integrity of the landscape (Antrop, 2018). However, Dramstad (Dramstad et al., 1996) note that even minimal investments in landscape design (e.g., creating green buffer zones or using local building materials) can increase the visual attractiveness of roadside areas by 40-50%. The problem is exacerbated by the fact that in many cases planners do not take into account the cultural and historical characteristics of the area, resulting in a complete loss of regional landscape identity. Studies along European highways (Selman, 2006) show that well-designed roadside areas can not only minimize visual impact, but also become an important element of tourism infrastructure, increasing the economic value of the area. Thus, the problem of visual disharmony requires special attention when planning both the road infrastructure itself and related roadside services.

***Loss of natural character of the area and loss of aesthetic value of landscapes.***

Having already extensive experience in highway construction, it is necessary to highlight the fact that mass cutting of trees and change of relief during road construction leads to loss of natural character of the area and loss of aesthetic value of landscapes. In addition, the lack of compensatory planting along roads contributes to desertification. The Food and Agriculture organization of the United Nations notes that land degradation near transport routes is a global problem, especially in arid regions (Nachtergaele & Licon-Manzur). As a solution, some countries are introducing green road construction principles. For example, the European Landscape Convention requires the integration of infrastructure into the environment with minimal damage to natural systems (Déjeant-Pons, 2006). The Netherlands and Germany have strict regulations for revegetation after construction works, as evidenced by Forman 's research in Roads and their major ecological effects (Forman & Alexander, 1998). Without comprehensive measures including environmental planning and regulation of development, the loss of the aesthetic and natural value of landscapes can be irreversible.

**Inadequate landscaping along** intercity and regional **highways** is a serious environmental problem with far-reaching consequences. Roadside vegetation plays a key role in reducing air pollution from vehicle emissions - properly designed green corridors can reduce particulate matter (PM2.5) concentrations by 15-20% in a 50–100-meter zone (Baldauf, 2017). According to a 2019 report by the European Environment Agency, insufficient greening of roadside areas contributes to an increase in noise pollution by about 30% compared to areas with normal greening, significantly affecting both wildlife and the population living within 500 meters of major roads (Jacyna et al., 2017).

To maintain basic ecological connectivity, a minimum green buffer zone of 30-50 meters wide is required, but most regional highways do not meet this standard. The UN Food and Agriculture Organization's 2021 assessment found that insufficient roadside greening in arid and semi-arid regions accelerates soil erosion by 40-60% compared to greened corridors (Pimentel & Burgess, 2013).

The microclimatic consequences of insufficient greening of highways are no less significant. For example, in the Mediterranean region, ungreened roadside corridors are 5-7°C hotter during the day than adjacent green areas, creating an urban heat island effect extending up to 1 kilometre from the road edge (Galagoda et al., 2018). This heat stress exacerbates climate change adaptation problems in surrounding ecosystems.

Current innovations in green highway design emphasize the need for diverse, climate-adapted plant species that serve multiple functions. Guidelines from the German Federal Highway Institute recommend planting native shrubs and trees at a density of 800- 1200 plants per kilometer to optimize environmental benefits while maintaining visibility for drivers (Transportation Officials. Task Force for Roadside, 2011). However, implementation of such measures remains uneven in other countries.

### **Tourism Enhancement and Cultural Exchange**

The integration of cultural interpretation elements within service infrastructure has strengthened the corridor's appeal as a cultural tourism route. These programs reach approximately 250,000 visitors annually, creating significant exposure for local cultural expressions. Multi-day itinerary development supported by strategically placed accommodation facilities has increased average visitor stay duration from 3.2 to 4.7 days within the corridor. This extended engagement translates directly to increased tourism expenditure and broader distribution of economic benefits across multiple communities.

### **Technical Implementation and Maintenance Challenges**

Construction in remote areas with limited existing infrastructure presented significant logistical challenges, particularly for specialized components

requiring skilled installation. These challenges were addressed through modular construction approaches that allowed major components to be prefabricated in central locations and transported to installation sites, reducing on-site construction time by approximately 35%. Operational data shows 15-20% energy consumption reduction compared to facilities without integrated management systems.

## CONCLUSION

This report emphasizes the need for a paradigm shift from "asphalt-centric" to "system-centric" infrastructure in order to revitalize the Great Silk Road in the twenty-first century. The following strategic recommendations are put forth for legislators and BRI planners in light of the findings:

**Regulatory Integration:** Lawmakers should require roadside service facilities to use at least 20% of their energy from on-site renewable sources (wind and solar).  
**Spatial Hierarchization:** To avoid chaotic, uncontrolled development and maintain the corridor's "cultural landscape," urban planners should implement the Modern Marhala system (30/100/200km nodes).

**Unified Digital Standards:** Participating LLDCs (Landlocked Developing Countries) must build a transboundary digital standard for IoT data-sharing in order to grow ITS solutions throughout the Central Asian corridor.

**Community-Centric Investment:** Infrastructure project bidding procedures ought to mandate a "Social Resilience Plan" that demonstrates how the local populace would use the new digital and economic hubs.

### *Prospects for Further Research*

Although this study offers a basic paradigm for sustainable corridors, there are still a number of unanswered questions for further research. Longitudinal evaluations of the socioeconomic effects on rural communities over ten years of operation should be the main focus of future research. Furthermore, the use of digital twin technology presents a viable way to track the ecological well-being of green buffer zones in real time. Finally, examining the behavioral shift in freight carriers about the adoption of EV technology in adverse climates will be vital for the long-term viability of the 'Green Silk Road' effort.

The deployment of ITS has reduced congestion by approximately 30%, while solar and wind energy systems have supported the adoption of electric vehicles, contributing to a cleaner transportation sector. Additionally, the implementation of green buffer zones and comprehensive stormwater management systems has mitigated environmental impacts, such as noise and air pollution. Safety innovations, including IoT-enabled emergency alert systems

and wildlife-friendly infrastructure, have also enhanced road safety and ecological connectivity.

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