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CARBON FOOTPRINT ASSESSMENT OF THE MARDAN–SWABI LINK ROAD CONSTRUCTION

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Abstract
This study assesses the carbon footprint linked to the development of a the Dualization of 42 km long Road from Mardan to Swabi roadway project in Khyber Pakhtunkhwa (KP), Pakistan. In addition to assessing carbon offset through tree plantation programs, the goal was to measure the greenhouse gas (GHG) emissions from material manufacture, construction activities, and post-construction vehicle traffic. Furthermore, traffic-derived emissions were evaluated using average daily traffic measurements combined with fuel-based emission coefficients. Investigations were also conducted into the potential for carbon sequestration provided by trees grown as part of the KP Billion Tree Tsunami campaign and other afforestation initiatives along the chosen road corridor. The findings indicated that the construction of the roadway resulted in significant carbon emissions, with approximately 5,803.9 tCO_2e attributable to construction materials. Additionally, an estimated 56,430.13 tCO_2e per year was associated with traffic-related emissions. In contrast, the total CO_2 offset through tree plantation was estimated at only 1,042.04 tCO_2e per year, highlighting a minimal mitigation effect relative to the overall emissions. Based on the results of the research, it is evident that road infrastructure considerably contributes to the escalation of carbon emissions, notwithstanding its essential role in fostering regional development. To facilitate environmental sustainability in forthcoming infrastructure enhancements, it advocates for the utilization of low-carbon materials, the adoption of advanced construction methodologies, and the amplification of afforestation initiatives.

INTRODUCTION

Background of Study

Carbon footprint measures the quantity of Carbon Dioxide (CO2) and other greenhouse gases that involved in a certain activity. Carbon foot printing refers to a calculation technique used by a firm or one can estimate his or her contribution towards greenhouse gas emission within project or time period (Goodier, 2010).

Global fossil fuel emission of carbon since 1900 has increased considerably. The operation of vehicles isn't the individual contributor to the carbon footprint related with road transportation. Road construction emits carbon even earlier to its operational phase. Activities involved in road construction, such as unearthing, transportation of materials and labor, result in substantial GHG emissions. Furthermore, the maintenance and rehabilitation of roadways also contribute to GHG, as road works are conducted to restore deteriorated infrastructure to acceptable quality standards (Albuquerque et al., 2020). Emissions from road infrastructure activities, including the production and transportation, construction, upkeep, and recycling of roads, contribute between 5% and 25% of the CO2 emissions associated with transportation, In addition to the CO2 emitted directly by vehicles (LIU et al., 2022).

31% of Pakistan's carbon emissions come from the transportation sector. This percentage is increasing every day because number of cars are increasing (KUMAR, 2024). Such evaluations are still scarce in KPK, Pakistan. In order to guarantee more sustainable practices, it is crucial to measure and analyze carbon emissions from road construction given the region's expanding infrastructure development. Assessing and reducing carbon emissions is vital. Without an assessment of these emissions, it is hard to create strategies to reduce them. In Khyber Pakhtunkhwa, a carbon footprint assessment will provide information to planners and engineers. Reducing carbon in highway construction requires a diversified strategy. This involves the use of environmental friendly materials such as recycled aggregates and asphalt, the adoption of warm mix asphalt technologies, and the implementation of energy-efficient construction techniques (Ilhan., 2024).

The road infrastructure domain is increasingly facing pressure to reassess existing strategies and investigate avenues for the reduction of carbon emissions. In order to mitigate GHG emissions, different strategies have been employed in the realms of road construction and maintenance. The immediate advantage of fabricating and applying asphalt mixtures at reduced temperatures is the consequent decrease in energy consumption, greenhouse gas emissions, as well as the fumes and odors produced at both the manufacturing facility and the paving site (Kar et al., 2015).

Problem Statement

The whole process—from the procurement and transportation of materials to the actual construction phase, as well as increase in traffic—release a considerable carbon footprint. There is lack of thorough, locally relevant studies that measure the carbon footprint connected to such infrastructure projects in KPK, Pakistan. Almost all of the existing data and emission factors are derived from research conducted in other countries, which may not accurately represent the specific construction practices prevalent in this region. Consequently, planners and policymakers frequently find themselves with limited reliable information to inform environmentally sustainable decision-making.

This research is centered on the Dualization of 42 km long Road from Mardan to Swabi roadway project in KPK and make an effort to evaluate its overall carbon footprint. It considers emissions arising from construction materials, transportation logistics, machinery operations, and traffic generated once the roadway is operational. Additionally, it investigates the potential of tree planting initiatives as a means to reduce some of these emissions. By anchoring the research in localized data and practices, this thesis aspires to facilitate more sustainable infrastructure development and assist Pakistan in progressing towards its climate objectives.

Objectives:

The primary objectives of this study are:

1. To identify and evaluate the major sources of carbon emissions in road construction in Khyber Pakhtunkhwa.
2. To examine the carbon footprint at different stages of road construction, including material production, transportation, and construction activities.
3. Assessing carbon offset through planation.

Significance of the Study

1. This study provides locally relevant carbon footprint data for road construction in Khyber Pakhtunkhwa, improving accuracy beyond reliance on international emission factors.
2. It offers a comprehensive assessment of emissions from construction, transportation, and traffic, supporting better understanding of lifecycle impacts.
3. The findings support sustainable infrastructure planning and policy development and highlight the role of tree plantation as a carbon offset strategy.

Literature Review

Road construction contributes significantly to the global carbon emissions of the construction industry, primarily due to its substantial energy, materials, and heavy machinery usage. Assessing the carbon footprint of this activity is essential for understanding its environmental impact and identifying strategies to reduce greenhouse gas emissions. Recently, interest in evaluating carbon footprints in road construction has surged, driven by the environmental consequences of infrastructure projects and growing concerns about climate change. The transportation sector, one of the largest consumers of energy and a source of both direct and indirect emissions, is responsible for approximately one-third of all carbon emissions, significantly affecting the environment (a et al., 2017).

The materials used in newly constructed roads accounted for 52.3% of the total carbon footprint (embodied impact), with maintenance accounting for the second-highest percentage at 24.3% (a et al., 2017)..

William Rees and Mathis Wackernagel, planners at the University of British Columbia, were the first who developed the term "footprint" to refer to the effects of human production or consuming activities. In this way, Wackernagel and Rees (1996) define an “ecological footprint” as an accounting tool used to measure the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area. The ecological footprint concept is still widely used today as a resource management tool (East, 2008). The total amount of greenhouse gases (GHGs), especially carbon dioxide (CO_2), emitted into the atmosphere due to human activities is referred to as a "carbon footprint." These emissions contribute to climate change and global warming. The increasing concerns regarding this phenomenon and the impact of carbon emissions as a contributing factor have led many companies and organizations to undertake "carbon footprint" projects aimed at assessing their own contributions to global climate change (Matthews et al., 2008). Increased public awareness of global warming has led to a heightened interest in "carbon footprints." To mitigate climate change, the global community now recognizes the necessity of reducing greenhouse gas emissions (Kumar et al., 2014). As a result, there exists a significant demand for the quantification of carbon footprints. A variety of methodologies for generating estimations have been proposed by researchers. These approaches extend from basic online calculators to more sophisticated life-cycle assessments, frequently referred to as input-output-based methodologies and instruments(Durojaye et al., 2020).

Carbon Footprints Of Construction Sites

The region's connection and economic growth depend on the roadways, which are essential pieces of infrastructure. The reliance on fossil fuel-based energy sources and the resulting greenhouse gas (GHG) emissions have grown significantly in recent years due to the expansion of economic activity(Kumar, 2018). Due to its activities, construction is a resource-intensive industry that regularly generates significant levels of greenhouse gas emissions. The road industry is under increasing pressure to review current practices and consider ways to reduce carbon emissions. The life cycle approach has been recognized as a trustworthy method for determining carbon footprint (Huang et al., 2013). Using sustainable materials, such as recycled aggregates and low-carbon concrete, installing energy-efficient equipment, and streamlining construction procedures can all help to lessen the carbon footprint of road construction. Carbon offset initiatives, such as planting trees, and eco-friendly designs that increase output and save maintenance are also beneficial. Reducing emissions and making road building more ecologically friendly also requires recycling resources and reducing garbage.

Impact of Carbon Footprint on Climate Change

Since the Industrial Revolution, the exploitation of natural resources has played a significant role in human economic activity and the overall development of society worldwide. The use of fossil fuels, deforestation, drainage of wetlands, modification of coastal marine ecosystems, unsustainable land use, and many other unbalanced processes of human activity have led to an increase in anthropogenic emissions of climate-active gases and their concentration in the atmosphere. These events are believed to have contributed to a about 1 °C increase in the global average temperature in the near-surface layer of the atmosphere over the past 150 years. The two most pressing concerns facing governments, as well as scientific and civil society organizations, at the moment are limiting the increase in global air temperatures and reducing human CO_2 emissions. In this sense, it is imperative to alter current production methods in order to lower and sequester greenhouse gas emissions (Lobus et al., 2023). A higher carbon footprint contributes directly to global warming and the negative impacts on our climate. Reducing it helps slow down these changes.

Global Carbon Footprint Trends

As scientists from all over the world aggressively publish their results about environmental issues including air quality, carbon footprint, and greenhouse gas emissions, they are keeping a close eye on the growing threat of global warming (Raza et al., 2021). The carbon footprint (CF), a key measure of greenhouse gas emissions, has grown in significance recently due to the combined consequences of global warming and international pledges to lessen its effects (Yue et al., 2020). A precise assessment of the carbon footprint is one of the most crucial elements in evaluating the progress of sustainable development. Although recent studies have looked closely at carbon footprint, further research is necessary to completely comprehend the scientific contribution made by universities and other higher education institutions (Lobus et al., 2023). The global carbon footprint is a result of rising energy consumption, transportation, and industrial activity, especially that which uses fossil fuels. The overall trend shows that emissions are still rising, even though some countries have decreased their emissions by utilizing renewable energy sources and efficiency improvements.

Carbon Footprint Offsetting

Given the current situation, it would seem that morality demands that we fundamentally change the way we live. We should, for instance, travel less, eat less meat, have fewer children, and purchase fewer new clothes and electronics. However, balancing our greenhouse gas (GHG) emissions seems to be a relatively inexpensive option for us to keep things as they are (Baras, 2024). Carbon footprint offsetting is the process of balancing off your emissions by reducing or eliminating carbon dioxide (CO2) emissions from the atmosphere. Carbon footprint offsetting is the process of balancing carbon dioxide (CO2) emissions by funding initiatives that remove or reduce CO2 from the atmosphere, such as using renewable energy sources or planting trees. This is accomplished by funding these initiatives, which aid in offsetting the carbon produced.

Strategies For Reducing Carbon Footprint

Anthropogenic greenhouse gas (GHG) emissions are largely to blame for the rapid changes in Earth's climate. Crop cultivation, food processing, and product marketing all result in the creation of greenhouse gases (GHGs), which fuel climate change. Farmers and the public are demanding that effective regulations be developed and put into place to reduce greenhouse gas emissions from all agricultural sectors and activities. Sadly, there is a dearth of quantitative information about the most effective methods and strategies for reducing agricultural emissions as well as how crop productivity may affect the severity of greenhouse gas emissions (Gan et al., 2011). According to the IPCC's mitigation assessment, stabilizing or reducing consumption, moving to a sharing economy, and implementing other behavioral changes have a high mitigation potential because behavior, lifestyle, and culture have a significant impact on energy use and associated emissions(Schanes et al., 2016). In conclusion, the growing issue of greenhouse gas emissions and climate change, particularly in the agriculture sector, requires a holistic approach. While effective strategies to reduce agricultural emissions are needed, more research is needed to determine the most effective approaches and how they impact crop yield.

Enhancing Green Investments

"Enhancing green investments" means increasing the amount of capital allocated to eco-friendly initiatives or businesses. Growing urbanization is putting pressure on land use. The urgent need to shift to a more sustainable and low-carbon economy has received significant attention in recent years. There is a global movement to address the causes and lower greenhouse gas emissions as the effects of climate change become more obvious (Tan & Solangi, 2024). Nowadays, housing, industry, community services, and other economic uses occupy an increasing amount of land in urbanized areas. Green spaces, on the other hand, have been shown to benefit those who live nearby as well as those who work or play in the urbanized region. several European nations have made investments in green infrastructure a top priority. The public and other stakeholders must be persuaded of the worth of these green investments by providing an accurate, comprehensible, and readily replicable way of valuing the investment.

Research Gap

A number of studies have used LCA frameworks to assess the environmental impact of infrastructure projects globally. The majority of current research overlook traffic patterns, material sourcing, and topographical features, or it relies on generalized emission factors. Furthermore, there hasn't been much focus on including carbon offset mechanisms like tree plantings and operational emissions (from traffic) in this assessment.

MATERIAL AND METHODS

Study Area:

The geographical region for this study around the 42 km segment of the Mardan–Swabi Link Road situated in Khyber Pakhtunkhwa (KPK), Pakistan, which constitutes a component of the Khyber Pakhtunkhwa Provincial Roads Improvement Project (KP PRIP). This roadway, essential for improving interconnectivity, interlinks rural and semi-urban locales, thereby facilitating the transit of commodities and individuals. Engineered as a dual-lane roadway featuring a 7.3-meter-wide carriageway along with variable shoulder dimensions, this route traverses agricultural land and small settlements.

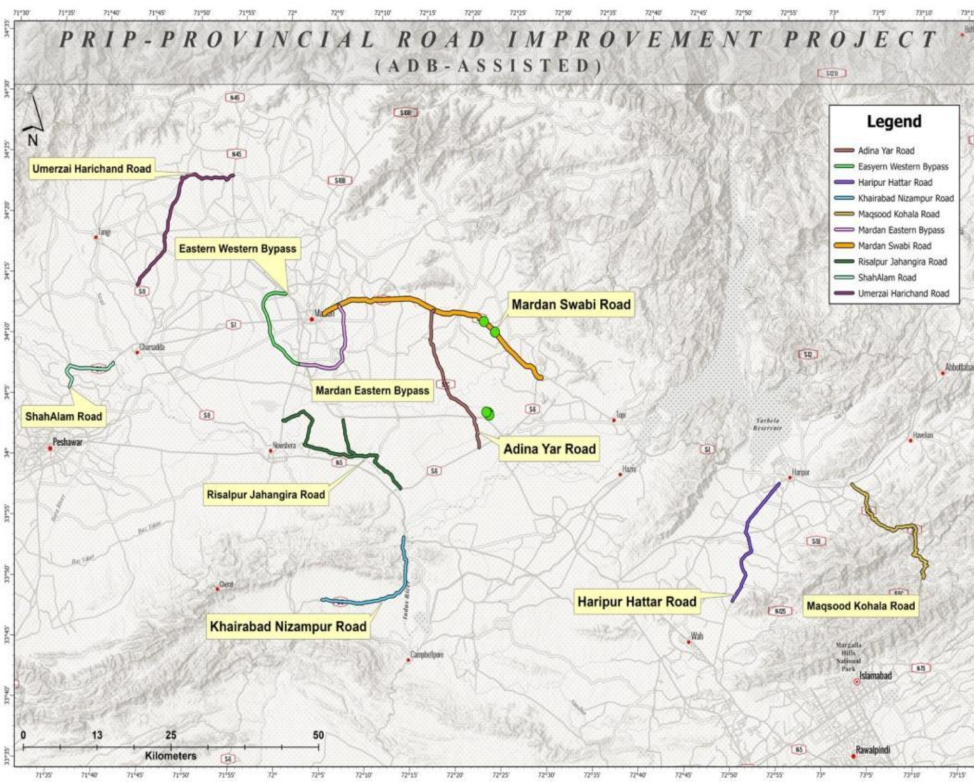

Figure 1: Location Map Shows Study Area

Research Design:

This paper estimates the carbon footprint of a 42-kilometer roadway construction project in Khyber Pakhtunkhwa, Pakistan, by employing a quantitative case study approach. Standard emission factorsare utilized to determine emissions. From the manufacturing of materials, their transpo rtation, construction activities, and traffic after construction. To evaluate the total environmental impact, the research also examines carbon storage resulting from plantation activities.

Data Acquisition

This section outlines how relevant data was obtained to support the study. Both primary and secondary data sources were utilized to ensure accuracy, reliability, and context. The data collected covers construction materials, project implementation practices, traffic patterns, and environmental aspects.

1. primary dataset Data were collected from validated project documents, o n-site observations, and confirmed technical reports pertaining to the road construction operations. The primary dataset included key parameters such as material quantities, traffic characteristic, and construction practices.
2. Secondary data were procured from academic literature, predominantly the studies conducted by(Hammond et al., 2008), to address deficiencies in emission data related to the construction materials.

Data Integration

The construction period of the Mardan–Swabi road has not been provided and as data regarding the construction and operation output (truck material emissions) being unreported, GHG emissions were calculated using project-specific data compiled with emission factors available in the literature. This level of detail enabled the calculation of the CO_2 emissions associated with the production and transport of the materials. The IPCC infrastructure emission criteria were followed in estimating the emissions in order to prevent underestimating the carbon footprint and to guarantee transparency and repeatability throughout the investigation.

Road Size and Material Type

Dimensions of the road and material composition were defined based on project data, total length of the road is 43 km, with a Total Road width (for computations) of 10.3 meters including width of carriageway and shoulders. The pavement structure comprised of several layers with specific materials, consisted of subgrade, sub-base, base course, and asphalt surface layer.

Materials Volume Estimation

(Length × Width × Thickness = Volume) this formula was used to determine the volumes of materials used in the road construction. For consistency, the measurements were converted to meters, and the volumes that resulted were given in cubic meters (m^3).

Emissions of Carbon

The carbon emissions linked to material production and transportation were measured using emission factors. The sources of these emission factors are (Hammond et al., 2008), are expressed in tons of carbon dioxide equivalent per cubic meter (tCO_2e/m^3). The volume of each material utilized was multiplied by its corresponding emission factor to determine the carbon emissions from each layer of road construction. The following formula was used to determine each layer's

total carbon emissions: Volume × Emission Factor equals total emissions.

Traffic data was gathered over the course of three days, from Thursday to Saturday. The collected data were used to determined traffic parameters such as, Average Daily Traffic (ADT), Annual Average Daily Traffic (AADT), and Peak Hour Count. Vehicles were classified into various types to determine the traffic composition. This classification, helped in estimating CO_2 emissions from vehicle movements on the road.

CO_2 Absorption by Trees

To assess the carbon offset through tree plantation, data on the number of trees planted and their CO_2 absorption rates were collected. Each tree is estimated to absorb 0.02 metric tons of CO_2 per year, equating to 1 metric ton of CO_2 over its lifetime of 100 years.

Results and Discussion

The results of this study show that the carbon emissions from the 42 km Mardan–Swabi road project are mostly caused by the construction materials. The asphalt and base course layers are responsible for the most emissions. Different types and amounts of materials in different layers of pavement cause the emissions to be different. moreover, emissions from transport and traffic operations were measured, as well as looked into tree planting as a way to capture some of the overall emissions.

Depending on the type and thickness of the materials used, the many layers that make up the road structure each contribute significantly to the overall carbon emissions.

The following table outlines the composition:

Table 1: *Road Layers and Estimated Thickness*

Layer	Material	Thickness
Subgrade	Compacted native soil	Existing (improved, not replaced)
Sub-base	Crushed stone / granular	150–200 mm
Base Course	WBM or crushed aggregate	100–150 mm
Surface Course	Bituminous Asphalt	50–75 mm
Shoulders	PCC or asphalt-treated gravel	1.5–2.0 m width

Volume Estimation of Materials

To calculate the carbon footprint, the volume of each material used is estimated using:

Volume = Length × Width × Thickness

All dimensions are converted to meters, and the final volumes are given in cubic meters.

Table 2: *Estimated Volumes of Materials Used*

Layer	Thickness (avg, m)	Width (m)	Length (m)	Volume (m^3)
Sub-base	0.175	7.3	42,000	53,655
Base Course	0.125	7.3	42,000	38,325
Surface Course	0.0625	7.3	42,000	19,253
Shoulders (PCC)	0.15	3	42,000	18,900

Shoulder width taken as 1.5 m on each side = 3.0 m total.

Figure 1: Volume Of Road Construction Layers

Carbon Emission Factors

The emission factors used in this study are derived from Hammond & Jones (2011) and represent embodied carbon per unit volume.

Table 3: *Emission Factors of Road Construction Materials*

Material	Emission Factor (tCO_2e/m^3)	Source
Sub-base (Granular)	0.005	Hammond & Jones (2011)
Base Course (WBM)	0.01	Hammond & Jones (2011)
Surface Course (Asphalt)	0.14	Hammond & Jones (2011)
Shoulders (PCC)	0.13	Hammond & Jones (2011)

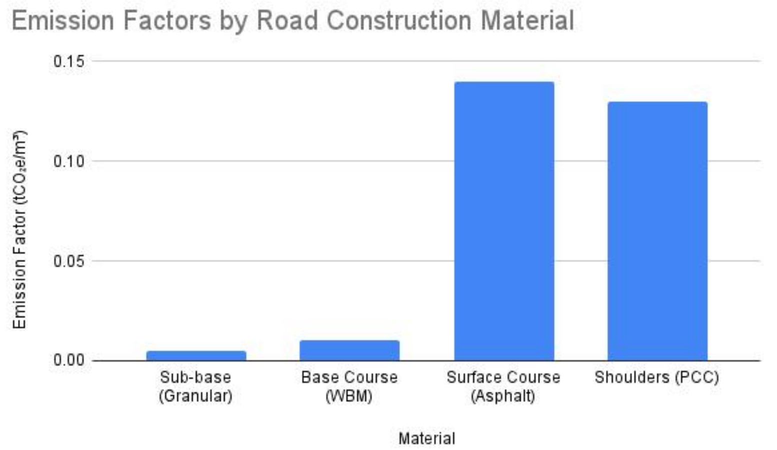

Figure 2: Emission Factor by Road Construction Material

Total Carbon Emissions by Layer

By multiplying material volume with respective emission factors, the total carbon emissions were determined.

Table 4: *Carbon Emissions from Road Construction Materials*

Layer	Volume (m^3)	Emission Factor (tCO_2e/m^3)	Emissions (tCO_2e)
Sub-base	53,655	0.005	268.3
Base Course	38,325	0.01	383.2
Asphalt Surface Course	19,253	0.14	2,695.4
Shoulders (PCC)	18,900	0.13	2,457
Total	–	–	**5,803.9**

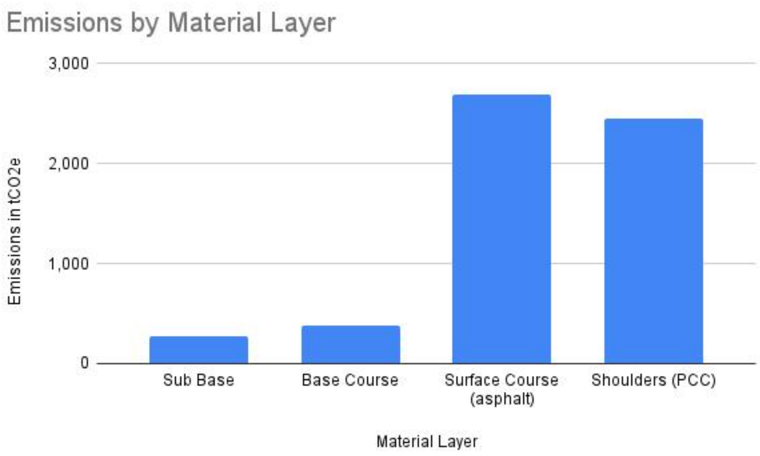

Figure 3: Emissions by Material Layer

This bar chart shows absolute CO_2 emissions, highlighting asphalt and PCC as the major sources.

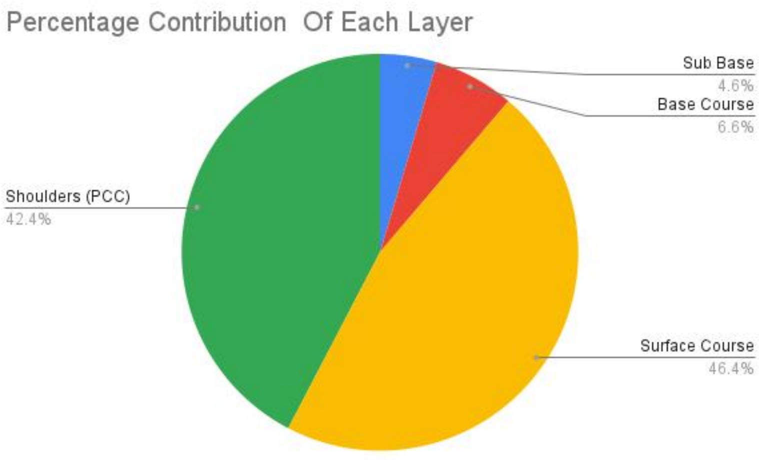

Figure 4: Percentage Contribution of Each Layer

This chart shows asphalt contributes ~46%, and PCC shoulders ~42% to total emissions.

Total Emissions: 5803.9 tCO_2e

The 42-kilometer road construction project's carbon footprint analysis provides several significant insights into how infrastructure development affects the environment, especially when it comes to material selection and design configurations.

Major Contributors to Emissions

From the results presented in Table 4 and Figure 3 and 4, it is evident that:

- The Asphaltic Surface Course contributes approximately 46.4% of total emissions, amounting to 2,695.42 tCO_2e.
- Although this layer is relatively thin (only 62.5 mm on average), asphalt has a very high emission factor (0.14 tCO_2e/m^3), largely due to its petroleum-based composition and energy-intensive production process.
- The Shoulders, constructed using Portland Cement Concrete (PCC) or gravel with treatment, account for around 42.3% of total emissions (2,457 tCO_2e).

These two components alone are responsible for nearly 89% of the total emissions, underscoring the significant impact of material choice.

Lower Emission Layers

The Sub-base layer, which is composed of granular materials with a relatively low emission factor (0.005 tCO_2e/m^3), accounts for just 268.28 tCO_2e (5%) of the total emissions.

The Base Course (WBM/crushed aggregate), although thicker than the surface course, produces 383.25 tCO_2e (7%).

This supports the idea that low-carbon resources, such unbound aggregates or recycled building materials, can successfully reduce the carbon footprint of infrastructure projects.

Traffic Counts and CO_2 Emissions

Traffic Volume Analysis

In order to determine the Average Daily Traffic (ADT) and the Annual Average Daily Traffic (AADT), traffic data was gathered over the course of three days: Thursday, Friday, and Saturday. The average traffic during the three days was between 11,457 and 12,910 cars, with a peak hour count of 47,887 vehicles.

Table 5: *Summary of Traffic Volume*

Day	Average Daily Traffic (ADT)
Thursday	11,457
Friday	12,430
Saturday	12,910
AADT	12,269

Vehicle Classification Distribution

A breakdown of vehicle types revealed that **Cars/Jeeps** dominate traffic composition with **47%**, followed by **Wagon/Pickup/Hiace** at **24.11%**, and **Bikes** at **19.07%**. The presence of heavy trucks and buses is relatively low, which is consistent with typical urban and inter-city corridors.

Table 6: *Percentage Share by Vehicle Type*

Vehicle Type	Percentage Share (%)
Bikes	19
Rickshaws	4

Cars/Jeep	47
Wagon/Pickup/Hiace	24
Mini-Buses	0.68
Large Buses	0.12
2-Axle Trucks	3.66
3-Axle Trucks	0.53
4-Axle Trucks	0.01
5-Axle Trucks	0
6-Axle Trucks	0.1
Tractor	0.25

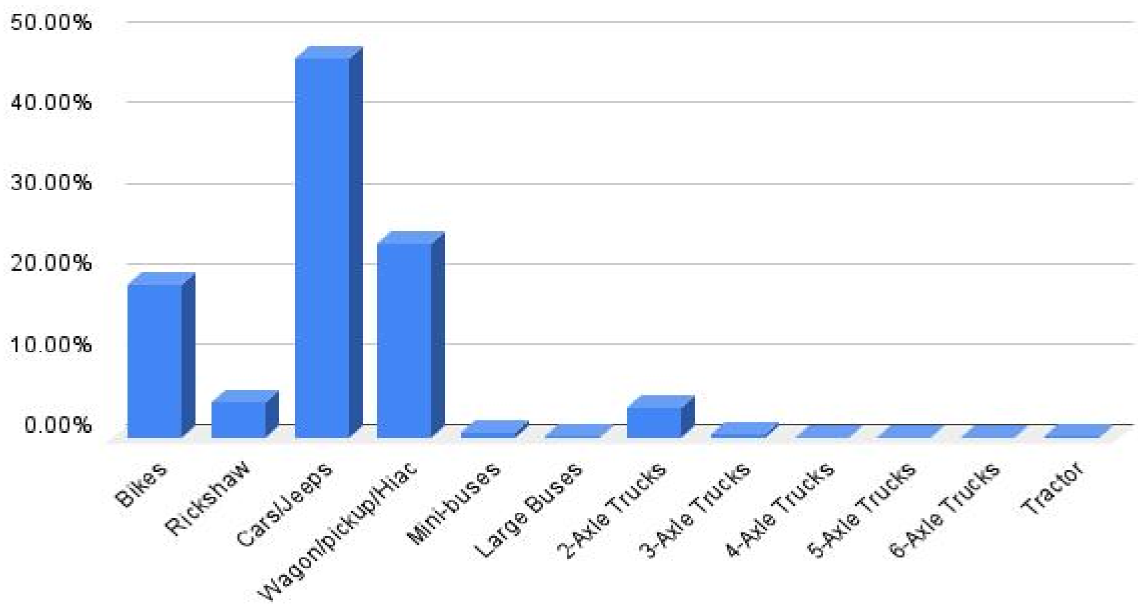

Figure 5: Percentage Share by Vehicle Type

CO_2 Emission Analysis

Emission Factors Used

Gasoline Vehicle CO_2 Emission: 8,887 g/gallon

- **Diesel Vehicle CO_2 Emission**: 10,180 g/gallon
- **Average CO_2 Emission per Mile (Gasoline Vehicle)**: 404 grams
- **Average Annual CO_2 Emission per Vehicle**: 4.6 metric tons
- **Daily CO_2 Emission per Vehicle**: 0.0126 metric tons (i.e., 4.6 ÷ 365)

Using the **AADT** as the traffic baseline, a more accurate estimation of **total annual CO_2 emissions** was conducted.

Table7: *CO_2 Emission Estimation Based on AADT*

Parameter	**Value**
AADT	12,269 vehicles/day

Total Vehicle Movements per Year	4,478,185
CO_2 Emission per Vehicle per Day	0.0126 metric tons
Estimated Total Emissions/Year	56,430.13 metric tons

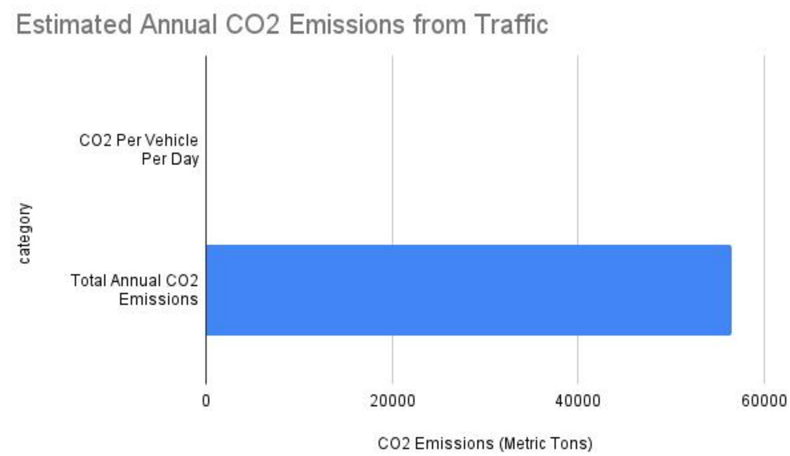

Figure 6: Estimated Annual CO2 Emissions from Traffic

The traffic count research reveals a significant number of cars, with an AADT of 12,269 vehicles, suggesting that this road stretch has heavy and constant traffic. Cars and Jeeps make up the majority of the traffic, indicating a reliance on private mobility. Light commercial vehicles follow this trend, while buses and large trucks contribute relatively little, in keeping with the expected vehicle mix on regional or peri-urban routes.

Using the number of vehicles (47,887) during peak hours to evaluate CO_2 emissions would result in a significant overestimation. Therefore, AADT was used to perform a more accurate calculation. This leads to an estimated 56,430 metric tons of CO_2 in emissions each year, which gives a more accurate picture of how traffic affects the environment along this corridor.

These findings underscore the importance of emissions control strategies such as:

- Encouraging the use of public transport.
- Promoting non-motorized travel modes (e.g., cycling, walking).
- Adoption of electric vehicles (EVs).
- Policy interventions for traffic demand management.

Such measures could significantly reduce transport-related emissions and contribute toward meeting regional climate targets.

CO_2 Absorption by Trees

To mitigate the carbon emissions from both construction and vehicle usage, a tree plantation initiative is proposed. The key data is as follows:

Table 8: *CO2 Absorption by Trees*

Parameter	Value
CO_2 Absorption per Tree	21 kg/year (0.02 metric tons/year)
Lifetime CO_2 Absorption (100 years)	1 metric ton
Number of Trees Planted	52,102

Total CO_2 Sink from Plantation	1,042.04 metric tons/year
Remaining CO_2 after Plantation	219,238.20 metric tons/year
Additional Trees Required	10,961,910
Total Cost for Additional Trees	12,688,630,063.20 PKR
Land Required	23,078 acres

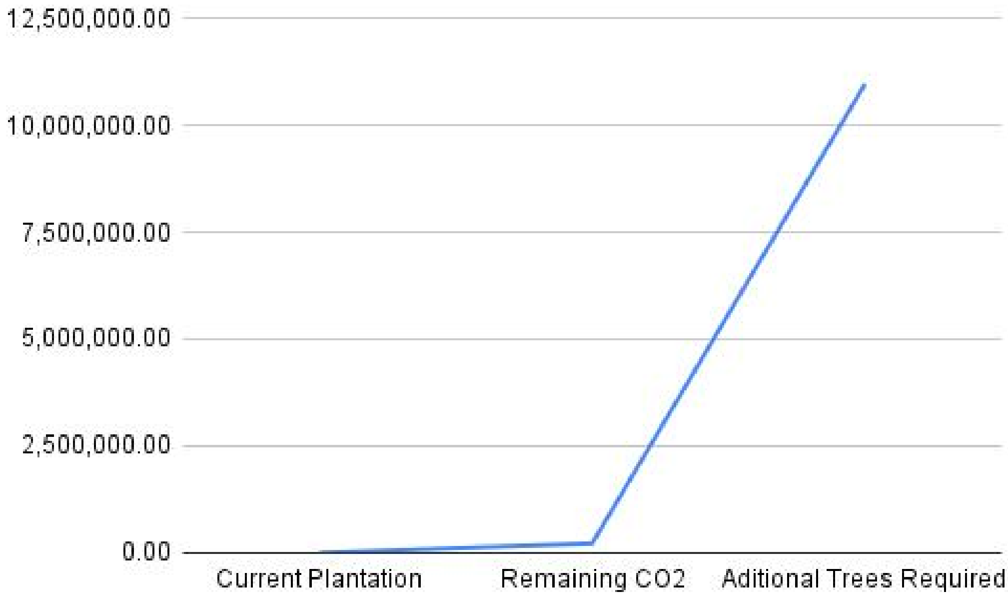

Figure: CO2 Absorption by Trees

CO_2 Absorption per Tree: Each tree can absorb **21 kg/year** of CO_2, which is equivalent to **0.02 metric tons/year**. Over a lifetime of 100 years, a single tree can absorb **1 metric ton** of CO_2.

- **Current Plantation**: The current plan to plant **52,102 trees** will result in a CO_2 sink of **1,042.04 metric tons/year**. While this is a positive step, it only offsets a small fraction of the total emissions from road construction and vehicle usage.
- **Remaining CO_2**: After accounting for the current plantation, **219,238.20 metric tons/year** of CO_2 will remain unabsorbed. This highlights the need for a much larger-scale tree plantation initiative to achieve carbon neutrality.
- **Additional Trees Required**: To fully offset the remaining emissions, an additional 10,961,910 trees would need to be planted. This would require 23,078 acres of land and cost approximately 12.69 billion PKR. The scale of this initiative is enormous, indicating that tree plantation alone may not be sufficient to achieve carbon neutrality.

Discussion:

The results of this analysis indicate that the 42-kilometer Mardan-Swabi roadway's carbon footprint is primarily caused by building materials. Due to their massive volumes and high emission intensities, base course and asphalt layers generate the most emissions. This is consistent with past research in Highway Engineering that shows the manufacture of materials, particularly asphalt, is a major source of embodied carbon in road infrastructure. The reduced emissions from the shoulder and sub-base layers demonstrate how the composition and type of material have an impact on the environment as a whole.

In addition to material-related emissions, transportation and construction activities also contribute to the total carbon footprint, emphasizing that emissions are not limited to material production alone. The results further show that traffic-related emissions during the operational phase add to the cumulative environmental burden, indicating that road infrastructure continues to generate emissions beyond the construction stage. Although tree plantation provides a measurable amount of carbon sequestration, its impact remains limited compared to total emissions, suggesting that offset strategies alone cannot achieve carbon neutrality.

Overall, the results demonstrate that reducing the carbon footprint of road infrastructure requires a comprehensive approach that addresses both material selection and construction practices, as well as operational emissions. The adoption of low-emission materials, improved construction technologies, and enhanced environmental mitigation measures can significantly contribute to reducing the overall environmental impact of such projects. These findings highlight the importance of integrating sustainability considerations into infrastructure planning and development in order to address the challenges of climate change.

Conclusion

This study assessed the carbon footprint associated with the construction and operation of a 42 km road project in Khyber Pakhtunkhwa, Pakistan, using data on construction materials, traffic emissions, and carbon offset through tree plantation. The findings reveal that the major sources of emissions stem from the use of construction materials—particularly asphalt, cement, and aggregates—followed by emissions from vehicle traffic post-construction. Although the analysis of the KP Plantation Program demonstrated that tree planting can sequester a significant portion of CO_2 over time, though not enough to fully offset emissions in the short term.

Despite some data limitations—such as reliance on emission factors from secondary sources and potential variations in traffic estimates—the research offers a comprehensive framework for carbon accounting in road infrastructure projects. It also emphasizes the importance of incorporating sustainability measures, such as improved material choices and reforestation, in future development.

In light of these findings, it is recommended that similar infrastructure projects adopt low-carbon technologies, enhance tree plantation drives, and integrate carbon footprint assessments into the planning and approval stages. This study contributes to the growing body of knowledge on sustainable infrastructure in Pakistan and underscores the urgent need for environmentally responsible construction practices in the context of climate change.

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