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Life Cycle Assessment and Life Cycle Cost Analysis of Pavement Design in Pakistan

Abdul Rafay Ali*, Muhammad Abdullah Haider [2], Syed Al Riyan Ahmad Zaidi [3] and Imran Hafeez[4]

[1]*Civil Engineering Department, University of Engineering and Technology Taxila, Pakistan*
[2] *Civil Engineering Department, University of Engineering and Technology Taxila, Pakistan*
[3] *Civil Engineering Department, University of Engineering and Technology Taxila, Pakistan*
[4] *Civil Engineering Department, University of Engineering and Technology Taxila, Pakistan*

(20-CE-119@students.uettaxila.edu.pk)

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Abstract **–** Roads are vital to societal development but require significant materials and energy, resulting in environmental and economic concerns. In Pakistan, road infrastructure planning often prioritizes cost while neglecting environmental impacts. This research integrates Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) to evaluate the dual effects of traffic on road infrastructure, focusing on greenhouse gas (GHG) emissions and pavement costs. Analysis of traffic volume and emissions monitoring highlights a significant rise in GHG emissions with increasing traffic, emphasizing the environmental burden of existing practices. LCCA results indicate that rigid pavements are more cost-effective over their life cycle compared to flexible pavements, considering construction, maintenance, and rehabilitation costs. By addressing the gap in Pakistan's road infrastructure policies, this work advocates for strategies that balance ecological sustainability with economic efficiency, offering insights into long-term, environmentally responsible development.

Keywords: GHGs, Traffic Volume, Sustainability, Cost Effective, LCA, LCCCA.

I. INTRODUCTION

The increasing environmental and economic pressures associated with infrastructure development necessitate sustainable solutions. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are pivotal tools for assessing the environmental and financial impacts of construction materials and methods throughout their lifecycle. LCA evaluates the environmental burdens across the phases of raw material extraction, processing, construction, maintenance, and disposal, identifying critical areas for improvement. In parallel, LCCA determines the economic feasibility of alternatives, incorporating costs from initial construction to eventual decommissioning.

Global urbanization has led to significant advancements in sustainable roadway construction, essential for reducing the transport sector's contribution to greenhouse gas (GHG) emissions, which account for 32% globally, with road traffic and construction making up 74% [1]. There is research performed life cycle inventory to study the eco-burden presented by using recycled materials to rehabilitate asphalt pavements which showed that the two main factors that account for a large amount of the environmental impact: the amount of asphalt binder used (39–48%) and the amount of energy used by heat sources to process paving materials (42–50%). This suggests that lowering the heat demand during the manufacturing process might be the most practical strategy for minimizing the environmental impact [2]. Evaluating road pavements using Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) is critical for enhancing sustainability in transportation networks. Key factors influencing life cycle costs and environmental impacts include traffic volume, road surface area, heavy-duty vehicle proportion, traffic speed, and design characteristics [3]. Various methods and tools help assess environmental impacts across a product's life cycle, providing insights into environmental performance and guiding sustainable decision-making.

Extensive literature highlights the relevance of LCA and LCCA in pavement design. Studies have underscored the environmental benefits of integrating recycled materials like Reclaimed Asphalt Pavement (RAP) into construction, significantly reducing greenhouse gas emissions and resource depletion. Specifically, adding 15% RAP to the asphalt mixtures reduced the environmental impacts by 14% to 16%. This demonstrates the possible advantages for the environment of using recycled materials, such RAP, in the procedures used to produce asphalt pavement [4]. Moreover, economic analyses reveal the long-term cost-effectiveness of rigid pavements compared to flexible ones, especially when considering maintenance and salvage values. However, gaps remain in standardizing methodologies, incorporating regional variations, and integrating social and economic dimensions into sustainability evaluations. [5]

The research addresses the gaps in pavement design assessments in Pakistan by integrating Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA). Focusing on key factors such as greenhouse gas emissions, pollutant quantification, and cost-effectiveness, it provides a comprehensive evaluation of pavement alternatives. For this analysis, the pavement along the Taxila Monument to Turnol (N-5) road was selected, offering a representative case for assessing the environmental and financial impacts of pavement designs. Through this dual analysis, the approach aims to offer a balanced perspective that considers both environmental impact and financial sustainability.

For the environmental analysis, traffic volume and emissions data were gathered and analyzed to establish correlations between traffic growth and the resulting environmental pollutants. Additionally, air and water quality tests were conducted to quantify emissions at various stages of the pavement life cycle, including construction, use, and eventual disposal. This rigorous testing ensures a thorough understanding of the ecological footprint of each pavement option.

Simultaneously, the financial viability of rigid and flexible pavements was evaluated through LCCA, considering factors such as initial construction costs, ongoing maintenance, and disposal costs. This methodology provides decision-makers with a comprehensive view of the long-term economic implications, allowing for the identification of cost-effective and sustainable pavement solutions for future infrastructure projects.

II. MATERIALS AND METHODS

A. Pavement Selection and Study Area

The pavement section selected for the Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) was the stretch of road between Taxila Monument and Turnol (N-5), a major segment of the National Highway Network in Pakistan. This section was chosen based on its representative nature in terms of traffic volume, geographical conditions, and the relevance of its maintenance and construction challenges. The selection allows for a comprehensive evaluation of the environmental and economic impacts of different pavement types in real-world conditions, ensuring that the findings can be applied to similar infrastructure projects in the region.

This research focuses on the environmental and economic evaluation of the pavement section from Taxila Monument to Turnol (N-5), specifically the southbound carriageway of the N-5, with a total length of 10.174 km. The study examines both rigid and flexible pavements constructed between 1st February 2003 and

30th June 2004. The pavement structure includes a 60 mm surface thickness, 300 mm base thickness, and a 250 mm subbase thickness, with a shoulder width of 1 meter for the inner shoulder and 2.5 meters for the outer shoulder. The lane configuration consists of three lanes, each 3.65 meters wide, with a design life ranging between 10 to 20 years. The subgrade comprises dense clayey soil at a depth of 21 meters. The analysis applies a Single Stand-Alone LCA methodology to assess the environmental impacts, while the Life Cycle Cost Analysis (LCCA) evaluates the financial implications, considering the initial construction, maintenance, and disposal costs of both pavement types. This research provides a comprehensive evaluation of the pavements' sustainability by integrating both environmental and economic factors.

The construction of both rigid and flexible pavements involved several key raw materials and machinery. For rigid pavements, the primary materials included cement, coarse aggregates, fine aggregates, and water. In the case of flexible pavements, materials such as bitumen, aggregates, and sand were utilized. The machinery employed during construction included asphalt pavers for the laying of bitumen layers, concrete mixers for rigid pavement material preparation, roller compactors for ensuring proper compaction, and graders for leveling the road surface. These materials and machines were selected to meet the design requirements of the pavement structure, ensuring durability, load-bearing capacity, and smoothness.

B. Traffic Volume Data

Traffic volume refers to the total quantity of vehicle traffic that uses transportation infrastructure, such as roads, highways, and bridges, during its entire life cycle. Increased traffic volume leads to higher emissions of air pollutants such carbon dioxide (CO2), nitrogen oxides (NOx), particulate matter (PM10 and PM2.5), and volatile organic compounds (VOCs). High traffic numbers drive up maintenance, repair, and replacement costs for transportation infrastructure owing to wear and tear. The traffic volume data at the project site (Taxila monument to Turnol N-5) was measured manually in 2023 is represented in the Table 1 as follows. PTPS (Pakistan Transport Plan Study) website document is used for traffic data of 2005 and then interpolated the traffic volume in between and observed 5.06% increase in traffic annually [6]. Table 2 shows the traffic data for the year 2005 which is taken from the PTSP (Pakistan Transport Plan Study)

Table 1. Traffic Volume (2023)

Traffic Volume	
Vehicle Type	**Passes Per Day**
Heavy Truck	1350
Medium Truck	1350
Small Truck	2142
Large Bus	510
Minibus	1326
Micro Bus	510
Utility	3570
Car	21420
Rickshaw	10710
Motor Bike	12240

Table 2. Volume (2005): Traffic

Traffic Volume	
Vehicle Type	**Passes Per Day**
Heavy Truck	704
Medium Truck	3681
Small Truck	1893
Large Bus	724
Minibus	3951
Micro Bus	724
Utility	269
Car	8577
Rickshaw	289
Motor Bike	1856

C. Analysis of Environmental Pollutants

Environmental pollutants are harmful substances that contaminate air, water, and soil, posing significant threats to ecosystems and human health. Environmental pollutants are released throughout a product's life cycle, including raw material extraction, manufacturing, transportation, usage, and disposal. These pollutants can include particulate matter, heavy metals, greenhouse gases, and chemicals. Because these pollutants have an effect on human health, the environment, and air quality, they are important factors to consider when doing a life cycle inventory study of building activities. PM10 and lead data were obtained from previous research, whereas data for the other pollutants was not available at the time of construction, so it was calculated by measuring air pollutants now and extrapolating the increase in trend of PM10 and traffic volume as will be described in the Life Cycle Impact Assessment [7].

D. Life Cycle Assessment

In Life Cycle Assessment (LCA), understanding the relationship between traffic volume and environmental pollutants is critical, particularly for transportation-related studies. The impact of traffic on air quality, noise pollution, and overall environmental health is often significant and varies depending on factors such as vehicle type, fuel consumption, and road conditions. The following Table 3 illustrate in detail the relationship between traffic volume and various environmental pollutants, such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and greenhouse gas emissions. By quantifying these emissions across different traffic scenarios, LCA helps assess the environmental burden of transportation systems and identifies opportunities for mitigation, such as traffic management strategies or alternative energy sources for vehicles.

Table 3. Relationship between Traffic Volume and Environmental Pollutants

Year	**Traffic Volume**	**PM_{10}**	**$PM_{2.5}$**	**O_3**	**SO_2**	**CO_2**	**NOx**	CO	**Lead**
	Passes Per Day	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**	**($\mu g/m^3$)**
2007	25021	108.13	162.23	49.14	8.73	822132	53384.4	480.96	0.15
2008	26287	110.47	165.75	50.21	8.92	839962	54532.7	491.39	0.15
2009	27617	112.87	169.34	51.29	9.11	858179	55705.8	502.05	0.16
2010	29015	115.31	173.02	52.41	9.31	876792	56904.1	512.94	0.16
2011	30484	117.81	176.77	53.54	9.51	895807	58128.2	524.06	0.16
2012	32026	120.37	180.6	54.71	9.72	915236	59378.5	535.43	0.17
2013	33647	122.98	184.52	55.89	9.93	935085	60655.8	547.04	0.17
2014	35350	125.65	188.52	57.1	10.15	955366	61960.6	558.9	0.17
2015	37139	128.37	192.61	58.34	10.37	976085	63293.4	571.03	0.18
2016	39019	131.16	196.79	59.61	10.59	997255	64654.9	583.41	0.18
2017	40994	134	201.06	60.9	10.82	1018883	66045.7	596.06	0.19
2018	43069	136.91	205.42	62.22	11.06	1040981	67466.4	608.99	0.19
2019	45248	139.88	209.87	63.57	11.3	1063558	68917.7	622.2	0.19
2020	47538	142.91	214.42	64.95	11.54	1086624	70400.2	635.69	0.2
2021	49944	146.01	219.07	66.36	11.79	1110191	71914.6	649.48	0.2
2022	52472	149.17	223.83	67.8	12.05	1134269	73461.5	663.56	0.21
2023	55128	152.41	228.68	69.27	12.31	1158869	75041.8	677.96	0.21

E. Life Cycle Cost Analysis

Pavement infrastructure in Pakistan is critical to establishing effective transportation networks, which are necessary for economic growth and societal progress. However, given the country's unique geography, climatic conditions, and resource limits, designing, building, and maintaining pavements is not without its obstacles. In this context, Life Cycle Cost Analysis (LCCA) provides a systematic methodology for assessing the economic feasibility, sustainability, and long-term performance of various pavement design options. The project data provided the initial expenses of construction materials, which are shown in Table 4 and Table 5 as follows

Table 4. Initial Cost of Flexible Pavement

Subbase and Base Course (Initial Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Quantity**	**Rates**	**Total Amount Rs.**
201	Granular Subbase	CM	16267.685	325.00	5286997.625
203b	Asphaltic Base Course Plant Mix (Class "B")	CM	6034.867	3,000.00	18104601
206b	Water Bound Macadam Base With Coarse Agg: Class B	CM	13897.07	450.00	6253681.5
206c	Water Bound Macadam Base With Coarse Agg: Class C	CM	9834.245	450.00	4425410.25
				Total	34,070,690.38
Surface Course and Pavement (Initial Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Quantity**	**Rates**	**Total Amount Rs.**
302a	Cut-Back Asphalt For Bituminous Prime	SM	62528.669	20	1250573.38
303a	Cut-Back Asphalt For Bituminous Tack Coat	SM	91655.969	15	1374839.535
305b	Asphaltic Concrete For Wearing Course (Class "B")	CM	5466.348	3,210.00	17546977.08
304b	Double Surface Treatment	CM	14888	64	952832
				Total	21,125,222.00
				Grand total	**55,195,912.37**

Table 5. Initial Cost of Rigid Pavement

Rigid Pavement (Initial Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Rates**	**Quantity**	**Total Amount Rs.**
106 a	Excavate Unsuitable Common Material	CM	30	974.25	29,227.50
108 c	Formation Of Embankment From Borrow Excavation In Common Material	CM	70	974.25	68,197.50
109a	Subgrade Preparation In Earth Cut	SM	20	25206	504,120.00
310 a	Jointed Plain Concrete Pavement (Jpcp) Using Minimum 5000 Psi Class Concrete Laid Through Concrete Paver Including Transverse And Longitudinal Joints Formation, Expansion Caps And Filling With Sealant Complete In All Respects Excluding Reinforcement (Dowel/Tie Bars)	CM	4,490.00	12516.4	56,198,523.75
401f	Lean Concrete	CM	2,000.00	4984.33	9,968,652.00
404b	REINFORCEMENT AS Per AASHTO M-31 GRADE 60	Ton	27,000.00	125.91	3,399,570.00
					70,168,290.75
	Previous Cost				**65,811,295.82**
				Grand Total	**135,979,586.57**

The cost of materials for construction nowadays is calculated using CSR (Composite Schedule of Rates)-NHA 2022 and is displayed in Table 6 and Table 7 as follows.

Table 6. Present Cost of Flexible Pavement

Subbase and Base Course (Present Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Quantity**	**Rates**	**Total Amount Rs.**
201	GRANULAR SUBBASE	CM	16267.685	2,097.10	34114962.21
203b	ASPHALTIC BASE COURSE PLANT MIX (CLASS "B")	CM	6034.867	19,937.59	120320704
206b	WATER BOUND MACADAM BASE WITH COARSE AGG: CLASS B	CM	13897.07	2,848.85	39590667.87
206c	WATER BOUND MACADAM BASE WITH COARSE AGG: CLASS C	CM	9834.245	2,848.85	28016288.87
				Total	**222,042,622.90**

Surface Course and Pavement (Present Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Quantity**	**Rates**	**Total Amount Rs.**
302a	CUT-BACK ASPHALT FOR BITUMINOUS PRIME	SM	62528.669	144.23	9018509.93
303a	CUT-BACK ASPHALT FOR BITUMINOUS TACK COAT	SM	91655.969	59.11	5417784.328
305b	ASPHALTIC CONCRETE FOR WEARING COURSE (CLASS "B")	CM	5466.348	21,138.28	115549194.6
304b	DOUBLE SURFACE TREATMENT	CM	14888	571.6	8509980.8
				Total	**138,495,469.66**

Grand total	**360,538,092.56**

Table 7. Present Cost of Rigid Pavement

Rigid Pavement (Present Cost)					
B.O.Q No.	**B.O.Q Description**	**Unit**	**Rates**	**Quantity**	**Total Amount Rs.**
106 a	EXCAVATE UNSUITABLE COMMON MATERIAL	CM	404.01	974.25	393,606.74
108 c	FORMATION OF EMBANKMENT FROM BORROW EXCAVATION IN COMMON MATERIAL	CM	489.25	974.25	476,651.81
109a	SUBGRADE PREPARATION IN EARTH CUT	SM	112.3	25206	2,830,633.80
310 b	JOINTED PLAIN CONCRETE PAVEMENT (JPCP) USING MINIMUM 5000 PSI CLASS CONCRETE LAID THROUGH CONCRETE PAVER INCLUDING TRANSVERSE AND LONGITUDINAL JOINTS FORMATION, EXPANSION CAPS AND FILLING WITH SEALANT COMPLETE IN ALL RESPECTS EXCLUDING REINFORCEMENT (DOWEL/TIE BARS)	CM	20,235.30	12516.4	253,272,603.04
401f	LEAN CONCRETE	CM	8,311.53	4984.33	41,427,375.08
404b	REINFORCEMENT AS per AASHTO M-31 GRADE 60	Ton	242,658.15	125.91	30,553,087.67
					328,953,958.14
	Previous Cost*Increase rate				**288,325,411.41**
				Grand Total	**617,279,369.55**

III.RESULTS AND DISCUSSION

A. Life Cycle Assessment Findings

The Life Cycle Assessment (LCA) findings highlight significant environmental impacts related to pavement infrastructure, particularly in relation to traffic volume and pollutant emissions. From 2006 to 2023, traffic volume increased annually by 5.06%, correlating with a rise in energy consumption, vehicle emissions, and pavement wear. This increase in traffic leads to higher air pollution, greenhouse gas emissions, and congestion. Gaseous emissions have risen at an annual rate of 2.25%, reflecting the direct relationship between traffic volume and pollutants such as CO_2, NO_x, and particulate matter (PM).

Data from air quality measurements, presented in graphical form (Fig. 1 to 5), shows a linear correlation between traffic volume and greenhouse gases, which is further supported by equations in Table 8. This relationship emphasizes the impact of traffic volume on environmental quality, suggesting that increased traffic contributes directly to air pollution and climate change, with the potential for more severe public health and ecological consequences.

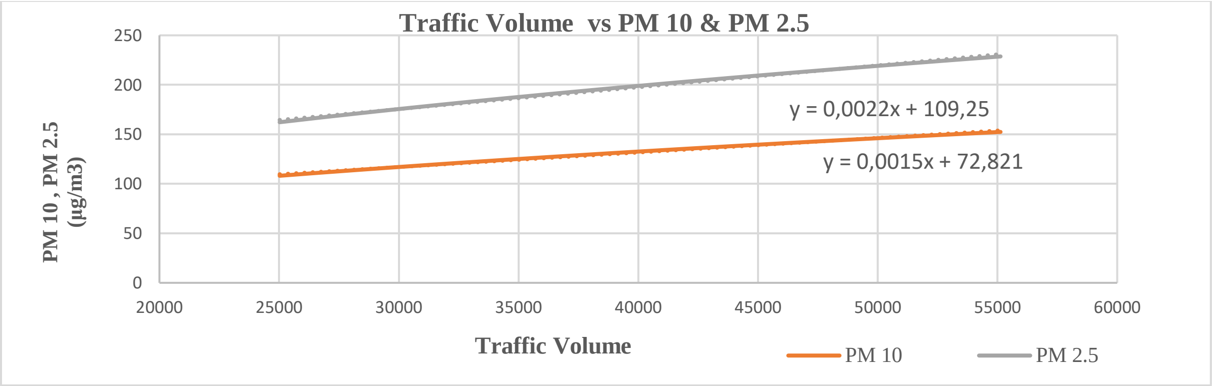

Fig. 1 Relationship b/w Traffic Volume & Environmental Pollutants (PM_{10} & $PM_{2.5}$)

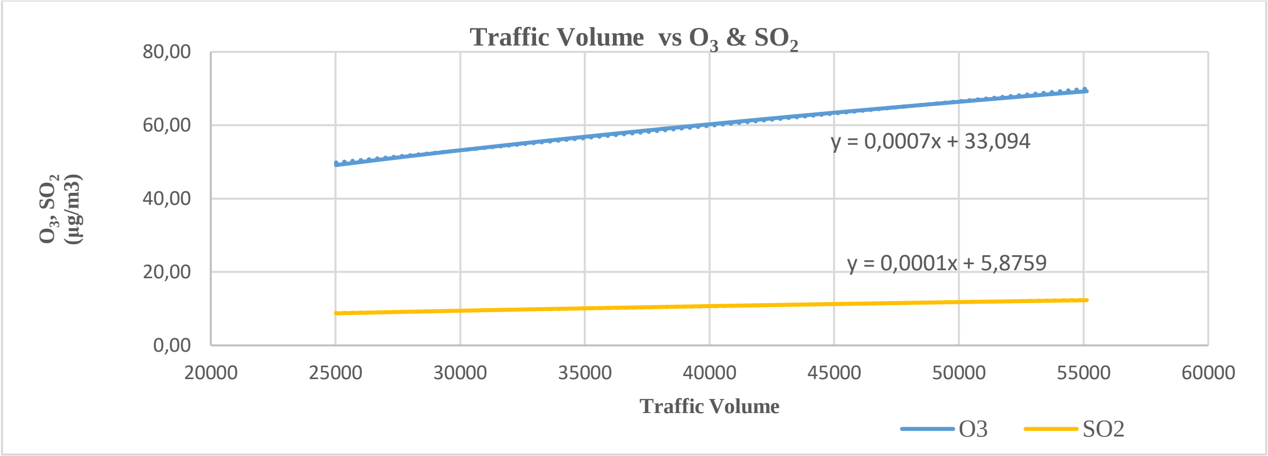

Fig .2 Relationship between Traffic Volume and Environmental Pollutants (O_3 & SO_2)

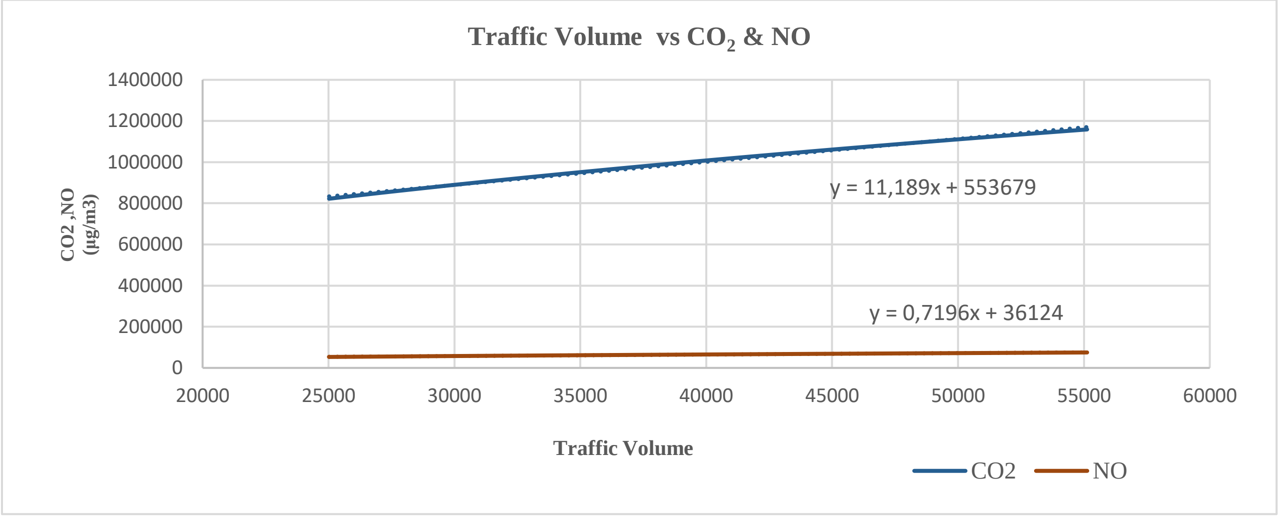

Fig .3 Relationship between Traffic Volume and Environmental Pollutants (CO_2 & NO_X)

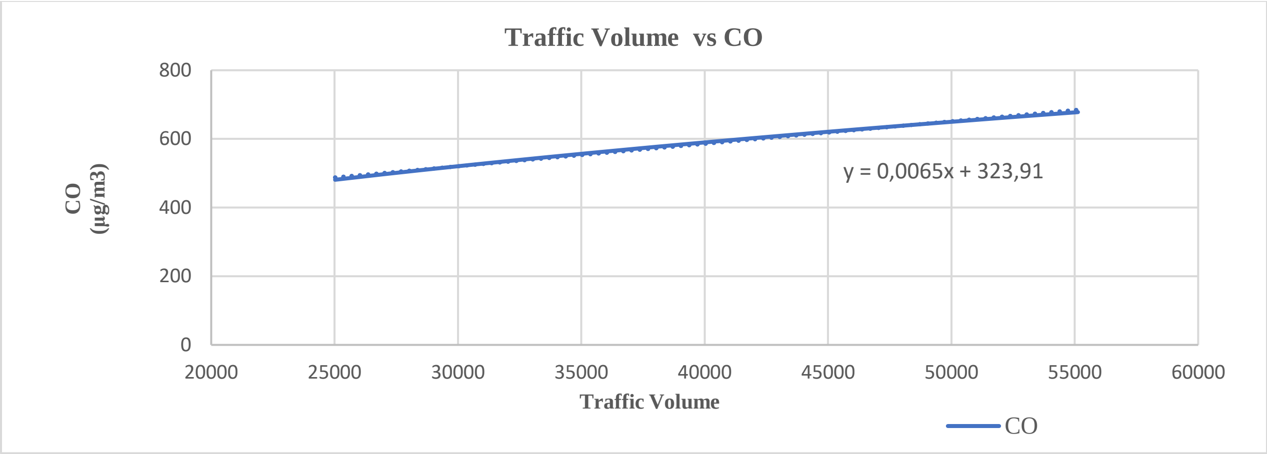

Fig .4 Relationship between Traffic Volume and Environmental Pollutants (CO)

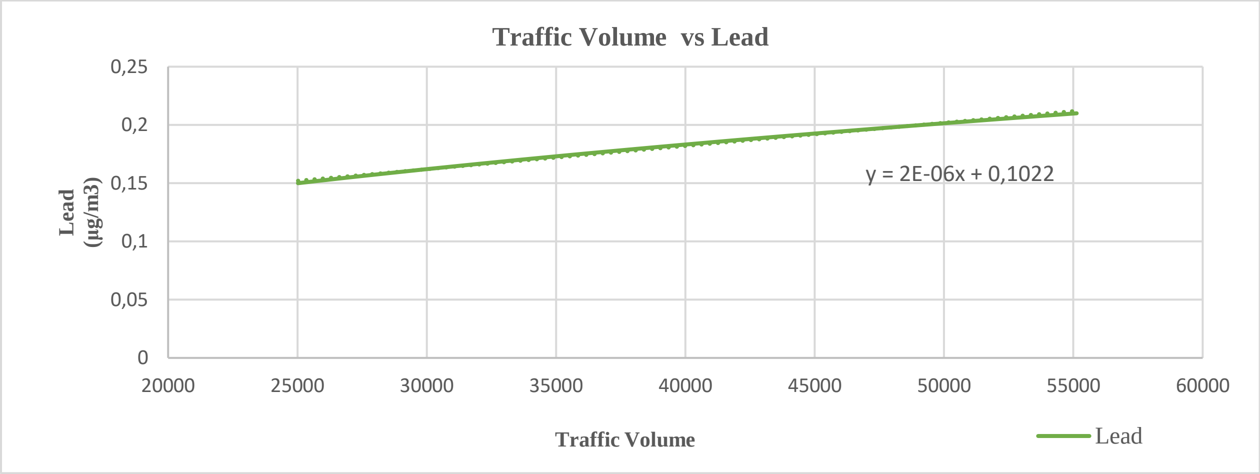

Fig .5 Relationship between Traffic Volume and Environmental Pollutants (Lead)

Table 8. Relationship between Pollutants and Traffic Volume

Sr No.	Pollutants	Equations shows relation with Traffic Volume
1.	PM_{10}	y = 0.0015x + 72.821
2.	$PM_{2.5}$	y = 0.0022x + 109.25
3.	O_3	y = 0.0007x + 33.094
4.	SO_2	y = 0.0001x + 5.8759
5.	CO_2	y = 11.189x + 553679
6.	CO	y = 0.0065x + 323.91
7.	NO_x	y = 0.7196x + 36124
8.	Lead	y = 2E-06x + 0.1022

Additionally, the construction phase's kerosene oil wastage and the rise in lead levels during the use period suggest increased water pollution risks. Kerosene oil and lead are hazardous substances that, if not properly managed, can contaminate soil and water sources. This indicates a need for improved construction practices and maintenance strategies to minimize environmental risks and protect water quality.

B. Life Cycle Cost Analysis (LCCA) Findings

The Life Cycle Cost Analysis (LCCA) findings indicate that rigid pavement is more cost-effective than flexible pavement over its entire life cycle, including initial expenses, maintenance, rehabilitation, and disposal. The final results are shown in Table 9 and Table 10 as follows:

Table 9. Life Cycle Cost of Flexible Pavement

FLEXIBLE PAVEMENT		
Initial Cost	Rs	55,195,912.37
Net Present Cost	Rs	47,859,915.64
Maintenance Cost (25% of Total Project Cost)	Rs	91,993,187.28
Overlay Cost (NHA CSR)	Rs	115,549,194.00
Miscellaneous Cost (5% of Overlay)	Rs	5,777,459.70
Engineer Over Head Cost (10% of Overlay)	Rs	11,554,919.40
Economic Loss (2% of Overlay)	Rs	2,310,983.88
Salvage Value ([RL/TL] *RTC)	-Rs	36,053,809.26
Life Cycle Cost	**Rs**	**294,187,763.02**

Table 10. Life Cycle Cost of Rigid Pavement

RIGID PAVEMENT		
Initial Cost	*Rs*	*135,969,034.07*
Net Present Cost	Rs	16,350,956.20
Maintenance Cost (10% less than Asphalt)	Rs	81,581,420.46
Salvage Value ([RL/TL]*RTC)	-Rs	61,727,936.95
Life Cycle Cost	**Rs**	**172,173,473.77**

Net present value (NPV) is a financial statistic used to determine the overall worth of an investment opportunity. The formula used to calculate the NPV is shown in equation I as follows.

$$\boldsymbol{NPV} = \sum_{t=0}^{T} \frac{c_t}{(I+r)} - \mathbf{I} \qquad \textbf{(I)}$$

- NPV is the net present value of the project.
- Ct represents the cash flows at time t.
- r is the discount rate (Difference between inflation rate and interest rate).
- T is the total number of time periods.
- I is the initial investment cost [8].

Salvage value is the projected residual worth of an item at the end of its useful life. The formula used to calculate the salvage value is shown in equation II as follows.

$$\textbf{Salvage Value} = ([RL/TL] * RTC) \quad \textbf{(II)}$$

Where,

- RL is Remaining Life
- TL is Total Life
- RTC is rehabilitation cost.

The analysis shows that flexible pavement is approximately 41% more expensive than rigid pavement when considering life cycle costs. Rigid pavement also requires less maintenance and fuel, saving money in the long run. Furthermore, rigid pavement has a higher salvage value, indicating better structural integrity and potential for recycling or reuse. These findings highlight the economic benefits of choosing rigid pavement for sustainable pavement infrastructure.

IV. CONCLUSION

This study provides a quantitative evaluation of pavement design through Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA), offering key insights into sustainability. Over a period from 2006 to 2023, traffic volume increased at an annual rate of 5.06%, driving a 2.25% yearly rise in pollutant emissions, including CO_2, NOx, and PM. The LCCA results show rigid pavement to be 41% more cost-effective than flexible pavement over its life cycle due to reduced maintenance costs, lower fuel consumption, and a higher salvage value. These findings underscore the importance of integrating life cycle considerations into pavement design. This study provides data-driven recommendations for developing infrastructure that optimally balances environmental sustainability with economic efficiency.

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