International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.4 (2025) pp. 4448-4462
http://www.ijcesen.com

ISSN: 2149-9144

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Research Article

Comparative Cost–Benefit Analysis of Elevated and Underground Metro Systems Using Life Cycle Cost Approach

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Article Info:

DOI: 10.22399/ijcesen.5151
Received : 01 November 2025
Revised : 25 December 2025
Accepted : 27 December 2025

Keywords

Cost–Benefit Analysis (CBA);
Elevated Metro System;
Underground Metro System;
Life Cycle Cost Analysis (LCCA);
Capital Expenditure (CAPEX);
Operation and Maintenance (O&M)

Abstract:

This study presents a comprehensive cost–benefit analysis (CBA) comparing elevated and underground metro systems based on their capital expenditure (CAPEX), operational and maintenance (O&M) costs, and life cycle cost components. Using financial indicators such as Net Present Value (NPV) and Benefit–Cost Ratio (BCR), the analysis assesses the long-term economic viability of both systems. The results reveal that while underground systems demand higher initial investments—primarily due to tunneling, waterproofing, and ventilation requirements—their operational costs also remain significantly higher, averaging ₹140 crore annually compared to ₹25 crore for elevated systems. The life-cycle NPV for underground systems was found to be nearly four times greater than that of elevated corridors, demonstrating the elevated system's superior economic efficiency. Despite offering spatial and environmental advantages, underground alignments incur heavy capital and maintenance burdens. The findings highlight the need for cost optimization, efficient project design, and innovative maintenance strategies in urban rail development. Overall, the study concludes that elevated metro systems are more financially sustainable for medium-density urban areas, while underground systems should be reserved for zones with extreme space constraints or high environmental sensitivity.

1. Introduction

The rapid pace of urbanization and industrial development has created an urgent need for innovative construction approaches that optimize space utilization, cost efficiency, and environmental sustainability (Li et al., 2024). As metropolitan areas become increasingly congested, the demand for structural solutions that maximize land use has risen significantly. In this context, the choice between underground and above-ground construction has emerged as a critical consideration in civil engineering and urban planning (Grant Nwaogbe et al., 2025). Underground structures such as tunnels, subways, basements, and underground parking systems play a crucial role in addressing land scarcity by utilizing sub-surface space. These structures help reduce surface-level congestion and preserve valuable land resources for other essential functions. Conversely, above-ground structures, including residential buildings, commercial complexes, bridges, and towers, are easier to construct and maintain but face challenges related to space constraints, environmental exposure, and urban aesthetics (Von Der Tann et al., 2020). The comparative cost–benefit evaluation of these two types of structures is essential to determine their economic viability, sustainability, and long-term performance. Given the rising costs of construction materials and the emphasis on sustainable urban growth, this study seeks to explore which structural system offers the most balanced combination of cost efficiency, functionality, and environmental compatibility. Cost–Benefit Analysis (CBA) provides an analytical framework for evaluating the total costs and benefits over a project's lifespan, enabling engineers and decision-makers to select the most feasible option for modern infrastructure development (Lin et al., 2022).

Structural systems form the core of any civil engineering project, providing the framework that

ensures safety, stability, and functionality (Von Der Tann et al., 2020). Broadly, these systems can be categorized as underground or above-ground, each serving specific purposes depending on project requirements, environmental conditions, and cost considerations. Underground structures are designed to operate beneath the earth's surface and must withstand significant environmental pressures such as soil weight, hydrostatic forces, and seismic loads. Examples include tunnels, subways, underground water tanks, and storage facilities. These systems offer distinct advantages, including space optimization, reduced surface congestion, and environmental integration. However, they also require specialized design, waterproofing, ventilation, and safety mechanisms, all of which contribute to higher initial construction costs. In contrast, above-ground structures such as buildings, bridges, and towers are more visible and accessible. They are relatively simpler to design and construct, with lower excavation and ground stabilization requirements. These structures, however, are more exposed to environmental factors like temperature changes, wind, and seismic vibrations. Understanding the structural, functional, and economic differences between these two systems is vital for determining the most appropriate construction approach (Meral et al., 2024). A comparative evaluation helps to identify how each system performs under different project conditions and assists in selecting the method that best aligns with technical and financial objectives.

1.1 Purpose of the Study

The purpose of this study is to carry out a comparative cost–benefit analysis of underground and above-ground structures to evaluate their relative efficiency in terms of construction costs, sustainability, maintenance requirements, and operational performance. In the modern construction landscape, where urban space is limited and sustainability goals are increasingly emphasized, understanding the economic trade-offs between these two structural systems is critical. Above-ground structures generally have lower initial construction costs but may experience higher maintenance expenses due to exposure to external environmental factors. In contrast, underground structures demand a larger initial investment for excavation, ground stabilization, and waterproofing, but often provide long-term benefits through durability, protection from climatic effects, and reduced land use. The study aims to bridge the gap in current knowledge by providing a systematic comparison of both approaches, offering valuable insights for engineers, developers, and policymakers. Ultimately, this research seeks to guide decision-makers in identifying the most cost-effective and sustainable construction method suited to the needs of growing urban environments.

1.2 Need for Cost–Benefit Analysis (CBA)

In construction and infrastructure projects, financial investment decisions have long-term implications on project success, sustainability, and economic return (Begić & Krstić, 2024). The need for a Cost–Benefit Analysis (CBA) arises from the requirement to evaluate whether the expected benefits of a project justify its total costs over its operational lifespan (Lovrenčić Butković et al., 2023). CBA provides a systematic framework for quantifying and comparing the monetary and non-monetary impacts of alternative construction methods, ensuring rational decision-making in project planning. In the case of underground and above-ground structures, this analysis becomes crucial due to their differing construction processes, environmental impacts, and operational costs. For instance, underground projects may involve significant costs related to excavation and safety measures, while above-ground projects may incur higher land acquisition and environmental mitigation expenses (Novikova et al., 2023). CBA assists stakeholders including engineers, contractors, and policymakers—in identifying projects that deliver the highest value for investment. It also enables risk identification and management, allowing for adjustments in design or materials to improve cost efficiency. Without a structured cost–benefit framework, construction projects are prone to budget overruns, inefficiencies, and suboptimal use of resources. Therefore, the application of CBA is indispensable in achieving balanced, economically sound, and sustainable infrastructure development.

1.3 Principles of CBA in Construction Projects

The effectiveness of a Cost–Benefit Analysis depends on several key principles that guide its application in construction projects (Lovrenčić Butković et al., 2023). One of the fundamental principles is opportunity cost, which considers the benefits forgone by choosing one alternative over another. In construction, this ensures that resources are allocated to projects offering the highest return or societal benefit. Another critical principle is the long-term perspective, where both the immediate and future costs and benefits of a project are evaluated. This approach ensures that short-term savings do not compromise long-term performance or sustainability. The principle of monetary

valuation requires that all measurable benefits and costs be expressed in financial terms, allowing for direct comparison. Similarly, discounting future values accounts for the time value of money by converting future costs and benefits into present values. Finally, key performance indicators such as Financial Net Present Value (FNPV), Financial Rate of Return (FRR), Economic Net Present Value (ENPV), Economic Rate of Return (ERR), and Benefit–Cost Ratio (B/C) are used to evaluate financial viability and societal impact (A. Sharbaf & Schneider-Marin, 2025). These indicators collectively help determine whether a project is economically justified and whether its long-term benefits outweigh its total costs. Adhering to these principles ensures that the evaluation of underground and above-ground structures is comprehensive, objective, and aligned with the broader goals of sustainable development (Fallah Shayan et al., 2022).

1.4 Factors Affecting Costs in Structural Projects

The total cost of any construction project is influenced by numerous interrelated factors that must be carefully managed to ensure economic efficiency. Leadership and management competence play a pivotal role in cost control, as ineffective coordination or poor decision-making can lead to resource wastage and project delays. Material and labor costs also have a major impact, as fluctuations in material prices and workforce availability can alter project budgets significantly. Site conditions, including soil type, groundwater level, and topography, determine the complexity of excavation and foundation design, particularly in underground projects. Design changes and scope modifications during construction often cause unplanned expenses, making early and precise project planning crucial. Additionally, environmental and climatic conditions such as extreme weather, floods, or earthquakes may disrupt timelines and increase costs. Market volatility, inflation, and currency fluctuations further affect cost predictability. Another key factor is the coordination among stakeholders, since miscommunication between architects, engineers, and contractors can lead to rework, inefficiency, and delays. To ensure successful project completion within budget, these factors must be continuously monitored and managed through strategic planning, accurate estimation, and efficient execution.

1.5 Safety Risks and Hazards (Specific to Underground Projects)

Underground construction poses unique safety challenges due to confined working environments, limited accessibility, and exposure to natural forces such as soil and water pressure. Ground instability, resulting in collapses or subsidence, is one of the most significant risks during excavation. To mitigate such dangers, thorough geotechnical assessments and stabilization techniques, such as soil nailing or shotcrete, are often employed. Poor air quality and inadequate ventilation represent another major hazard, as the accumulation of gases like methane and carbon monoxide can lead to suffocation or explosions. Fire and flooding risks are heightened in underground spaces due to restricted evacuation routes. Therefore, comprehensive safety systems—including proper ventilation, fire suppression mechanisms, and emergency exits—are mandatory in such environments. Equipment such as cranes and hoists must comply with OSHA and BIS standards, with regular inspections and maintenance to ensure safe operation. Continuous monitoring, communication systems, and rescue preparedness are also critical for worker protection. In conclusion, maintaining safety in underground construction requires strict adherence to regulatory standards, effective supervision, and the use of advanced safety technologies to minimize occupational risks and ensure structural integrity.

1.6 Aims and Objectives of the Study

The overarching aim of this research is to conduct a comprehensive cost–benefit analysis of underground and above-ground structures to determine their comparative efficiency in terms of construction cost, maintenance, and sustainability. The study seeks to generate practical insights that can assist engineers, planners, and policymakers in making informed decisions based on financial viability and long-term performance. The objectives of the study are sixfold. First, it aims to compare the initial construction costs of underground and above-ground structures, taking into account labor, materials, and design complexity. Second, it evaluates how excavation and foundation requirements influence total project costs. Third, it analyzes the installation and maintenance costs of utilities and supporting infrastructure in both types of structures. Fourth, it assesses long-term maintenance and lifecycle costs to determine the true economic performance over time. Fifth, it examines the influence of site-specific conditions, such as soil characteristics and groundwater levels, on cost-effectiveness. Finally, the study seeks to provide recommendations for selecting cost-efficient and sustainable construction

solutions based on project type and environmental considerations. Through these objectives, the research aims to contribute to more rational, data-driven decision-making in civil and structural engineering, ensuring that infrastructure development aligns with both economic and environmental goals.

2. Literature Review

The literature on the comparative cost-benefit analysis of underground and above-ground structures presents a comprehensive understanding of how different factors influence overall construction economics. Numerous studies emphasize that underground structures tend to have higher initial costs due to excavation, specialized foundation systems, and the need for waterproofing and ventilation mechanisms. However, above-ground structures, while being less costly in the early stages of construction, often incur higher long-term maintenance expenses because of exposure to environmental degradation and weathering. Researchers agree that the decision between underground and above-ground development is not merely an economic choice but also a spatial, environmental, and functional consideration. For example, urban settings with limited land availability often favor underground construction despite its higher initial cost, as it offers space optimization, reduced noise pollution, and minimal visual disturbance to the environment.

In addition, several studies have explored the influence of site-specific conditions such as soil type, rock strength, and groundwater levels on cost dynamics. Underground structures demand extensive geotechnical analysis and stabilization measures, which can substantially increase costs, particularly in unfavorable soil conditions. Above-ground structures, on the other hand, are more influenced by climatic and environmental conditions that affect their durability and maintenance frequency. The decision-making process, therefore, involves evaluating both immediate and long-term economic implications alongside safety, functionality, and sustainability. Cost-benefit analysis (CBA) serves as a vital tool in this evaluation, allowing engineers and policymakers to quantify both tangible and intangible factors influencing project feasibility.

Overall, the literature suggests that understanding the balance between construction costs, operational efficiency, and lifecycle sustainability is essential for selecting the most economically viable and environmentally responsible construction type. With urbanization accelerating and land availability decreasing, the integration of financial, technical, and environmental analyses in cost-benefit studies has become increasingly relevant. This integrated approach enables a more holistic understanding of the trade-offs involved in underground versus above-ground construction, providing a solid foundation for sustainable infrastructure planning in modern cities.

2.1 Underground Structures Have Higher Excavation and Construction Costs

Underground structures are consistently identified as being more capital-intensive compared to above-ground structures due to the complexity of excavation and the necessity for advanced engineering solutions. Excavation for underground projects often involves tunneling, cut-and-cover methods, or deep open excavations, all of which demand specialized machinery, reinforced support systems, and high safety standards. Studies by Doneva et al. (2015) and Maruvanchery et al. (2020) show that excavation and reinforcement activities alone can constitute up to 60% of total project costs, especially in large-scale projects such as subways, tunnels, and underground caverns. These costs are further compounded by the need for groundwater control, dewatering systems, and robust ventilation networks to ensure structural stability and safety during construction and operation.

Moreover, researchers such as Paraskevopoulou et al. (2013) and Saputra et al. (2025) have emphasized the impact of geotechnical conditions and safety management in determining the financial viability of underground construction. Adverse soil conditions or geological uncertainties often lead to increased material use, prolonged timelines, and higher labor costs. Safety risks, such as excavation collapse, flooding, or exposure to hazardous gases, necessitate advanced monitoring and emergency response systems, further elevating the cost structure. Despite these challenges, underground construction is favored in dense urban areas due to its ability to optimize land use and preserve surface aesthetics. The Decision Aids for Tunneling (DAT) framework developed by Maruvanchery et al. (2020) has proven useful for predicting construction costs and durations, thereby improving feasibility assessments during the early planning stages.

In conclusion, while underground structures demand higher initial investments, they offer long-term benefits such as reduced surface congestion, enhanced security, and better land utilization. However, the literature collectively suggests that the economic feasibility of such projects depends heavily on accurate geotechnical assessment,

technological efficiency, and effective safety management. Without these, underground developments risk cost overruns and reduced long-term profitability. Thus, optimization of design, coupled with predictive cost modeling, is crucial to enhancing economic efficiency and sustainability in underground infrastructure development.

2.2 Research Gap

Despite extensive research on cost comparisons between underground and above-ground structures, significant knowledge gaps remain. One major limitation is the insufficient understanding of how varying geotechnical and hydrological conditions—such as soil type, rock composition, and groundwater fluctuations—affect construction cost estimates and design parameters. While several studies provide cost breakdowns for underground projects, few incorporate dynamic site-specific variables that significantly influence cost and safety. Furthermore, most existing studies focus on initial construction expenses, with limited attention to long-term maintenance and lifecycle costs, which are critical for evaluating overall project feasibility. The lack of standardized methods to incorporate lifecycle costs into economic analyses often results in incomplete or biased cost-benefit assessments.

Another major research gap lies in the limited integration of safety, risk management, and environmental factors into economic evaluations. While some studies have acknowledged safety risks in underground projects, few have proposed real-time data-driven frameworks to predict and mitigate these risks effectively. Similarly, environmental benefits—such as reduced land use, decreased urban noise, and lower visual pollution—are rarely quantified in economic terms, leading to their underrepresentation in decision-making processes. Moreover, traditional cost-benefit models tend to overlook indirect social and environmental advantages, such as enhanced urban aesthetics and improved air quality, which can significantly influence public perception and policy outcomes. Lastly, there is a noticeable gap in the use of emerging technologies like Building Information Modeling (BIM), Artificial Intelligence (AI), and Geographic Information Systems (GIS) in optimizing cost-benefit analyses. These digital tools can enhance accuracy in design, monitoring, and predictive modeling, offering more comprehensive and sustainable infrastructure planning solutions. Future research should thus focus on developing integrated, technology-enabled CBA frameworks that encompass economic, technical, environmental, and social dimensions, ensuring more data-driven and sustainable decision-making for both underground and above-ground construction projects.

3. Research Methodology

Data Collection

In this study, the Cost-Benefit Analysis (CBA) of the quality management method was carried out by introducing Scan-vs-BIM, a system that utilizes 3D scanning technology (TLS) in comparison to traditional visual inspection methods. The data collection for this analysis was conducted at Dongyang Structural Engineers Group, where the employees involved had no prior knowledge of Terrestrial Laser Scanning (TLS). To ensure fair assessment, the workers did not undergo specialized training on TLS. Instead, they continued with their standard measurement processes until the performance of TLS-based measurement methods matched or surpassed that of traditional visual inspection techniques.

The main objective of the CBA conducted was to evaluate whether the costs involved in generating and analyzing data through TLS scanning technology were justified by the benefits it offered compared to the traditional visual-inspection-based measurement approach. This evaluation was based on comparing the costs and benefits of each approach, with an emphasis on ensuring that the level of data generated and analyzed by TLS was at least as accurate as that produced by the visual inspection method.

To define the cost and benefit factors, expert interviews were conducted to gather insights on the monetary implications of using TLS. The experts provided detailed information about various factors influencing costs and benefits, such as the initial investment in scanning equipment, the time required for data acquisition, the need for software to process and analyze data, and the potential labor savings due to increased measurement efficiency. Benefits, on the other hand, were related to improved accuracy, reduced errors, and faster project turnaround times.

Table 3, referenced in the study, presents a detailed breakdown of these cost and benefit factors, which were derived from the expert interviews. The monetary value of each factor was carefully considered in the analysis, allowing for a comprehensive financial evaluation. This detailed data collection process ensured that the CBA was grounded in practical, real-world considerations, providing a solid foundation for determining whether the adoption of TLS technology in the measurement process provided a net positive financial return compared to traditional methods.

The primary work topic, the organization's size, and its role may all affect cost variables. By using expert interviews to create a model of fundamental cost elements, we set a general norm in this

research. A model of fundamental cost components should be presented by a CBA in order to provide a broad foundation. The initial and ongoing expenses of gear, software, and human resources are typical cost issues for Scan-vsBIM-based quality management. But thanks to ongoing digital transformation, Dongyang Structural Engineers Group's skills have progressed from the visual inspection approach to the Scan-vs-BIM method. As a result, CBA was limited to cost parameters (such as insurance costs and software and hardware investment costs) that were also used for Scan-vs. BIM-based quality management in this research. The benefit elements were divided into two categories: qualitative aspects that were unable to be quantified in monetary units and quantitative ones that could. The CBA need to be conducted in monetary units. Thus, the decrease in labour input and the reduction in work time, which could be translated into monetary units, were examined as benefit factors in this research. Only onsite data measurement and processing activities completed throughout each case's work were extracted to create the data utilised in this research. The TLS technique and the visual inspection approach were used to measure the amount of data collected. The reverse-engineering case project was given to the TLS team and the traditional visual inspection team by the Dongyang Structural Engineers Group. The following was the onsite investigation procedure used by the visual inspection team. Prior to measuring the structure, a preliminary inquiry was carried out by reviewing design documents and associated data as the first stage of reverse engineering for structural displacement analysis, field analysis, and conversion design. When the structure was in use, measurements taken on-site were used to augment any information that was lacking, such as the lack of plans, their inconsistency, or degradation. At least two on-site inspections are necessary for the visual inspection approach.

Additionally, since the examination is done with the naked eye, more time, money, and staff are needed than in the case with TLS equipment.

Furthermore, because the complete result is inferred by sampling from a highly damaged region, precise data cannot be generated in the event of current status analysis by reverse engineering, and economic loss may ensue. The following was the onsite investigative procedure used by the Scan-vs-BIM team. An initial study of the site was carried out to ascertain the goal, extent, and technique of scanning as well as to effectively measure point-cloud data. Following the establishment of the scanning equipment use plan, scanning interval, and arrangement plan in accordance with the site requirements, three-dimensional scanning data were obtained. In this instance, scanning at several areas might provide more precise information. The issue of obtaining the whole result from partial measurements in the visual inspection approach is lessened by this procedure. A comparison between the traditional approach and the TLS method is shown in Figure 3.

The gear and software used by the Scan-vs-BIM-based quality control system were identical to those used by the current approach. Therefore, only the recently acquired gear and software were taken into account for the CBA factor of the Scan-vs-BIM-based quality management in this research. For digital transformation, Dongyang Structural Engineers Group acquired Trimble's TX8, SX10, R10, S5, and Drone hardware as well as its RealWorks software. In addition, there were administration expenses (such insurance) for the gear and software that were acquired. For seamless usage, there were no extra expenses throughout the digital transition process from the current visual inspection approach to TLS and BIM, such as training fees. We examined seven instances in this research where the same hardware and software were used.

As a result, RealWorks and TX8's acquisition and administration costs were chosen as the cost variables. The dependability of Scan-vs-BIM was improved after the digital transition since the manpower-oriented approach was used concurrently to provide results comparable to the amount of effort required by the previous technique. Dongyang Structural Engineers Group was able to decrease both the input time and the personnel input by using both approaches simultaneously. Additionally, there were benefits like the ability to measure locations that were unsafe for humans to measure directly using the current manpower-centered survey approach or that were inaccessible to people (such the plant's pipes) across vast distances. In the CBA, these qualitative advantages could not be quantified in terms of monetary worth. Consequently, time and manpower savings were chosen as the study's benefit variables.

4. Research Method

The Web of Science database will be chosen for the research methodology to demonstrate the broad application of Cost-Benefit Analysis (CBA) techniques for evaluating and assessing the profitability of projects across various sectors. A variety of keywords will be used in the literature search, including: “CBA, construction projects + transport; CBA, construction projects + water

management; CBA, construction projects + waste management; CBA, construction projects + health and safety; CBA, construction projects + BIM," among others. In total, 308 scholarly papers from 2008 to 2022 will be discovered using this search strategy. Any duplicated papers or those with redundant information will be checked in the following step, and 246 papers will remain for further review. Subsequently, publications will be evaluated based on their titles and abstracts, and irrelevant papers will be removed, leaving only 156 potentially relevant papers. Table 1 will show that the majority of the analyzed papers will focus on transportation projects, with 54 research items out of 156 in total (around 41%), likely due to the long-standing priority of investments in this area of infrastructure. Furthermore, in the context of all sustainability initiatives, transportation projects will play a crucial role in supporting the fight against climate change, whether through mitigation or adaptation strategies, while considering the needs of the most vulnerable users.

5. Cost benefit analysis

Bosché et al. analyzed the Scan-to-BIM and Scan-vs-BIM methods to highlight the robustness of the Scan-vs-BIM approach. However, this approach was not previously evaluated in terms of monetary value. Cost-Benefit Analysis (CBA) serves as a fundamental methodology for selecting effective projects. Economic feasibility is assessed using the benefit and the benefit–cost ratio (BCR), where a BCR greater than 1 indicates that the project holds economic value. In this study, the costs and benefits of the project were estimated in monetary terms, converted to present value, and analyzed using either the project's Net Present Value (NPV) or BCR. These metrics provide realistic evaluations as they account for the time value of money through a discount rate. NPV is calculated as the difference between the present value of benefits and the present value of costs over the project's duration. A positive NPV signifies economic feasibility. A social discount rate of 4.5% (r = 0.045) was applied, as per national feasibility study guidelines. The Present Value of Benefit (PVB) and Present Value of Cost (PVC) represent the total present benefits and costs, respectively.

$$NPV = PVB - PVC = \sum_{i=0}^{n} \frac{B_i}{(1+r)^i} - \sum_{i=0}^{n} \frac{C_i}{(1+r)^i} \quad (1)$$

$$Discount\ rate = \frac{1}{(1+r)^i},\ i = 0, 1, 2, \cdots \quad (2)$$

where *i* stands for the year, n for the analysis period, B for the benefit, C for the cost, and r for the discount rate. The BCR may be defined as the ratio of all benefits converted to present value to all expenditures converted to present value. It shows if a project is feasible; a higher BCR means that the project is more economically feasible. A discount rate is used to determine the BCR, and a project is considered economically viable if its BCR is greater than 1. This is how the BCR is computed:

$$BCR\ (B/C) = \frac{PVB}{PVC} = \sum_{i=0}^{n} \frac{B_i}{(1+r)^i} / \sum_{i=0}^{n} \frac{C_i}{(1+r)^i} \quad (3)$$

1. CBA & Transport Projects

In the future, the transportation sector will continue to be recognized as a key driver of economic growth and social inclusion, representing a major investment opportunity for countries worldwide. The most significant infrastructure projects, including railways, highways, and high-speed rails, will be completed in this sector. These transportation projects will enhance people's lives globally, contributing to a clean, green, inclusive, resilient, and safe environment, which will be increasingly important. Although these investments require substantial financial resources, the benefits derived from them will far outweigh the financial expenses. The task of Cost-Benefit Analysis (CBA) will be to demonstrate this positive financial dynamic.

Large transportation projects, when combined with appropriate policies, will generate additional benefits beyond the user benefits calculated using traditional CBA methods. CBA will be the most commonly used assessment technique in transportation projects, as it will assess the expected social and economic impacts of these projects. The focus of transport projects will be to improve the quality of transportation infrastructure by investing in new systems and utilizing existing infrastructure more effectively. This will aim to enhance accessibility, mobility, and safety while meeting transportation demand.

The figure illustrates the capital expenditure (CAPEX) distribution across various categories for an underground infrastructure project. The categories include "Other," "Running," "Stations," "Systems," and "Systems-VentFire." CAPEX is measured in crores (Cr), indicating large-scale investment in the project. From the graph, it is evident that the "Running" category incurs the highest CAPEX, reaching approximately 2500 Cr. This suggests that major expenditures are related to civil works such as tunneling, track laying, and associated running infrastructure, which are critical for the underground system's functionality. The second-highest CAPEX is allocated to "Stations," with an investment close to 2000 Cr. This highlights significant funding directed towards station construction, including architectural design, structural stability, and passenger amenities, which

are crucial for operation and user experience. "Other" and "Systems-VentFire" categories exhibit moderate CAPEX allocations of around 600 Cr and 400 Cr respectively, indicating investment in miscellaneous elements and specialized systems like ventilation and fire safety. The "Systems" category has the lowest CAPEX, near 200 Cr, showing relatively limited investment in operational systems such as signaling, communication, and power supply compared to civil components. Overall, the figure emphasizes that civil construction (Running and Stations) dominates the expenditure profile, while system-specific investments constitute a smaller fraction of the overall budget.

This bar chart highlights the top 10 cost drivers for underground metro construction projects. The most significant cost contributor is TBM Tunneling (Twin Bores including segments), which far exceeds all other components, crossing approximately 2000 crore INR. This indicates that tunnel boring is the most resource-intensive and expensive activity in underground metro projects. The Raft/Base Slab & Internal RCC is the second-largest cost component, followed by Architectural Finishes & MEP and Station Box Excavation & Temporary Struts, all of which contribute moderately. Other components such as diaphragm walls, utility diversions, ventilation systems, and signalling/telecom have comparatively lower costs but still play a crucial role in overall expenditure. Grouting, waterproofing, and ballastless track construction have the smallest cost share. The graph underlines that effective cost management should focus on optimizing tunneling operations, as it represents the majority share of total project cost, influencing budget control and project feasibility.

This Graph illustrates the Life Cycle Cost Analysis (LCCA) components for underground metro projects. The data clearly shows that CAPEX (Capital Expenditure) is the largest cost driver, exceeding 5500 crore INR and forming the majority of the life cycle cost. This highlights the significant upfront investment required for infrastructure development, including tunneling, station construction, and systems installation. The Present Value of Operations and Maintenance (PV O&M) is the second-largest component, around 1500 crore INR, indicating that operational costs, although substantial, are much lower than the initial capital investment. PV Replacement (PV Repl) costs are minimal in comparison, reflecting relatively low replacement requirements during the project's lifecycle. PV Salvage (-) is nearly negligible, suggesting limited residual value recovery at the end of the project life. Overall, the chart emphasizes that managing CAPEX efficiently is crucial, as it overwhelmingly impacts the total life cycle cost of underground metro systems.This stacked bar chart represents the Annual Operations & Maintenance (O&M) costs by category for underground metro projects over a 30-year period. The total annual O&M cost is around 135 crore INR, remaining relatively constant throughout the years. The largest contributor is the Running category, which accounts for roughly 50 crore INR annually, emphasizing the significant recurring costs involved in running the metro services. Stations form the second-largest cost component, followed by Systems and Systems-VentFire, which together add to maintenance and safety expenditures. The Other category has a minimal share, indicating that miscellaneous costs are relatively small compared to primary O&M activities. This chart highlights that annual O&M expenses are dominated by operational and station-related activities, requiring consistent funding over the system's lifecycle. Efficient management of these recurring costs is essential to ensure long-term financial sustainability and reliable metro service operations.

The figure illustrates the top ten cost drivers influencing total project expenditure, measured in crores (Cr). The highest cost contributor is Station Superstructure & Architecture, followed by Segment Casting and Segment Erection & Post-Tensioning. These components involve complex construction and material requirements, significantly impacting overall costs. Land Acquisition and Ballastless Track (BLT) & Track Slab also account for considerable expenses due to urban space limitations and material use. Meanwhile, Pier Shafts & Caps, Station Foundations, and Signalling (CBTC & Telecom) contribute moderately to total costs. The least cost drivers include Piling (Piers) and Overhead Catenary Equipment (OHE), which are essential but less capital-intensive elements of infrastructure development.

The figure illustrates the annual undiscounted cash flows of an elevated infrastructure project over a 30-year operational period. Each bar represents the combination of operation and maintenance (O&M) expenses, replacement costs, and the final salvage value. During the initial years, cash flows remain relatively steady, reflecting consistent O&M expenditures. Around years 10, 15, 20, and 25, noticeable spikes occur due to major replacement or rehabilitation activities, indicating periodic capital reinvestments. The positive peaks between years 20–25 suggest increased expenditure or upgrades, while the final negative cash flow at year 30 represents the deduction of salvage value or decommissioning costs. This analysis highlights

lifecycle cost variability and the importance of maintenance planning for financial sustainability.

The figure compares the Capital Expenditure (CAPEX) distribution between elevated and underground transit systems across various project components. It clearly shows that underground construction demands substantially higher investment, particularly in *TBM & Tunnels*, *Civil–Running*, and *Ground/Waterproof* works due to extensive excavation, tunneling, and waterproofing requirements. Elevated systems, in contrast, incur higher costs in *Stations–Civil/MEP* and *Traffic/Utilities* segments but remain significantly lower overall. Land logistics, environmental provisions, and system installations contribute moderately to both types. This comparative analysis highlights that while elevated systems are more cost-effective and faster to construct, underground systems, though costlier, are preferred in dense urban areas for minimal surface disruption and better spatial utilization.

The figure presents a comparative cost analysis of key system components for elevated and underground metro corridors. It reveals that underground systems incur significantly higher costs across all major categories due to complex safety, ventilation, and signalling requirements. *Ventilation & Smoke Extraction (SACC)* and *Fire Detection/Suppression & SCADA* dominate underground system costs, reflecting the need for robust environmental and safety systems in confined spaces. *CBTC Signalling & Telecom* and *Platform Screen Doors (PSD)* also contribute notably to the cost. Conversely, elevated systems show relatively lower costs, with major expenditure observed in *OHE* and *Signalling* components. Overall, underground systems demand greater investment in safety and automation, while elevated systems focus on structural and operational efficiency.The figure compares the total annual operation and maintenance (O&M) costs for elevated and underground transit systems over a 30-year period. It shows that the O&M cost for underground systems remains significantly higher, approximately around ₹140 crore annually, whereas the elevated system maintains a much lower and steady cost near ₹25 crore. This trend indicates that underground systems require more resources for ventilation, lighting, and maintenance of complex infrastructure, leading to greater recurring expenses. In contrast, elevated systems are more economical due to easier accessibility and lower maintenance requirements. Over time, this cost difference highlights the long-term financial advantage of elevated systems for sustainable urban transport planning and budget optimization.

This table compares the life-cycle financials of constructing a 5 km metro line using Elevated versus Underground alignments. The Elevated option requires a capital expenditure (CAPEX) of ₹1,587 crore, with present value (PV) of operations and maintenance at ₹308 crore and replacement costs of ₹55 crore, partly offset by a ₹8 crore salvage value. The resulting Total Net Present Value (NPV) is ₹1,942 crore, translating to ₹388 crore per km. In contrast, the Underground option demands far higher investments: CAPEX of ₹5,683 crore, PV of O&M at ₹1,549 crore, and replacement costs of ₹164 crore, with only ₹10 crore salvage. Its Total NPV rises to ₹7,386 crore, or ₹1,472 crore per km. These figures clearly show that while underground construction may offer urban or environmental advantages, its life-cycle cost is almost four times that of the elevated alignment, making the elevated route substantially more economical for equivalent length and service.

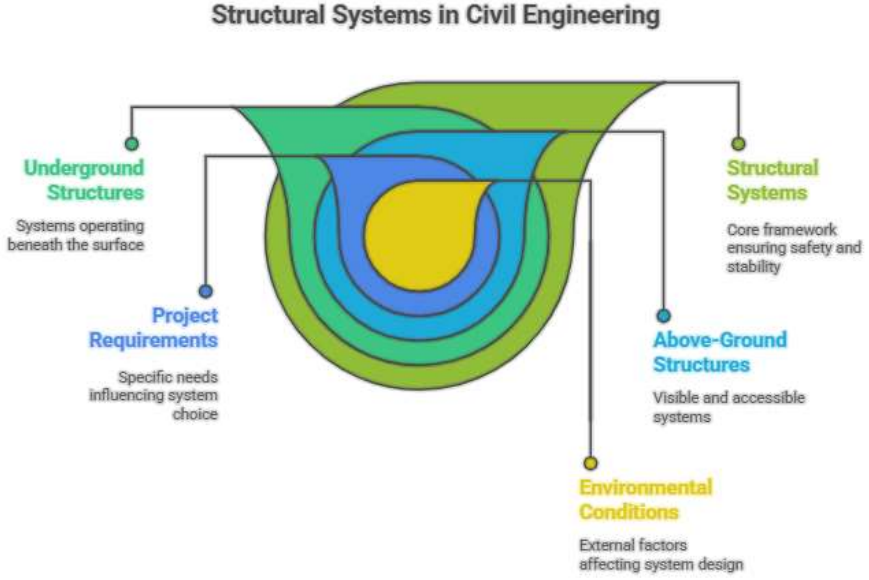


Figure 1: *Structural System in Civil Engineering*



Figure 2: *Underground Construction Safety challenges*

Table 1. *Cost and benefits factors of Scan-vs-BIM.*

Classification	Factor	Detail Factor	Calculate in Monetary Value
Cost	Investment cost	Hardware	Able
		Software	Able
	Insurance cost	Hardware	Able
		Software	Able
	Education cost	Hardware	Able
		Software	Able
Benefit	Manpower input	Measurement time	Able
		Data processing time	Able
	Accuracy	Error of measurement	Unable
		Error of data processing	Unable
	Corporation value	Reliability	Unable
		Customer service satisfaction	Unable

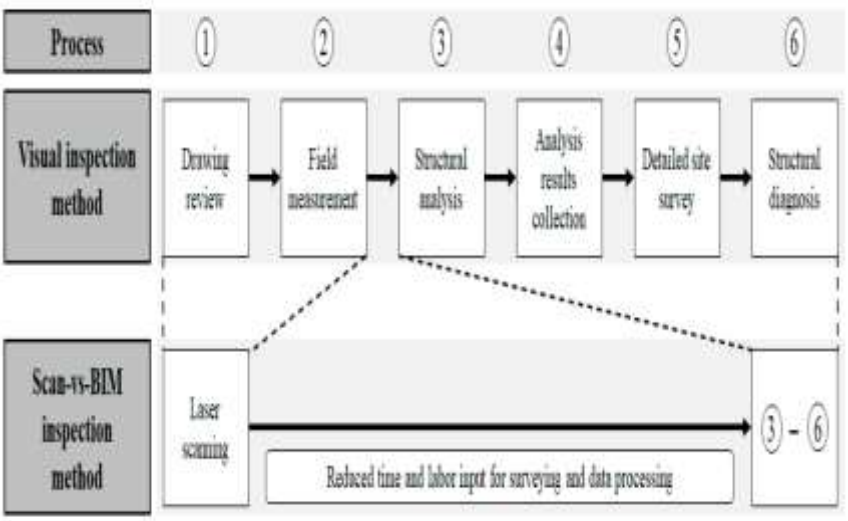


Figure 3. *Comparison of traditional and Scan-vs-BIM processes.*

Table 2. *Distribution papers according to application sectors*

Application sectors	Number of papers	Percentage (%)
Transport	64	41,02

Water management	26	16,67
Waste management	18	11,54
Health & Safety	6	3,85
Building Information Modeling	42	26,92
Total	**156**	**100,00**

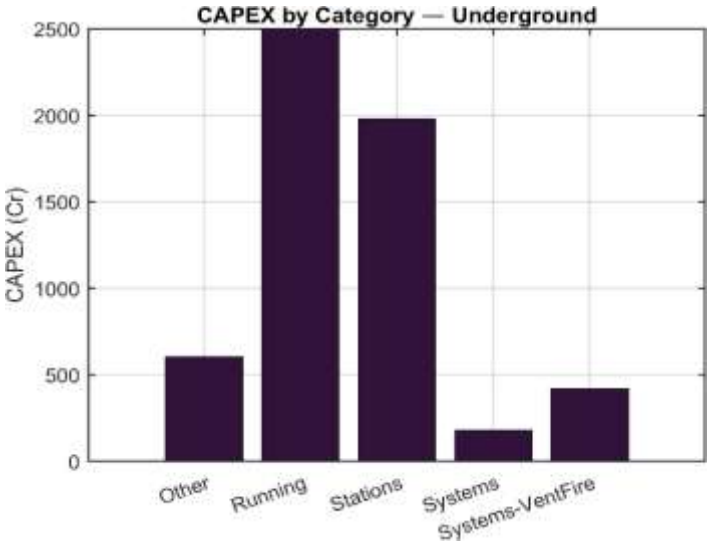


Figure 4: *CAPEX by Category — Underground*

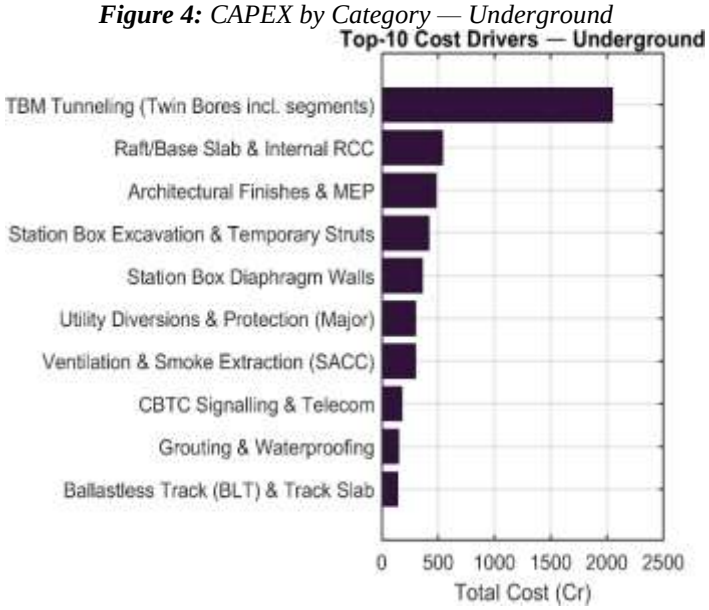


Figure 5: *Top 10 cost drivers for underground metro construction*

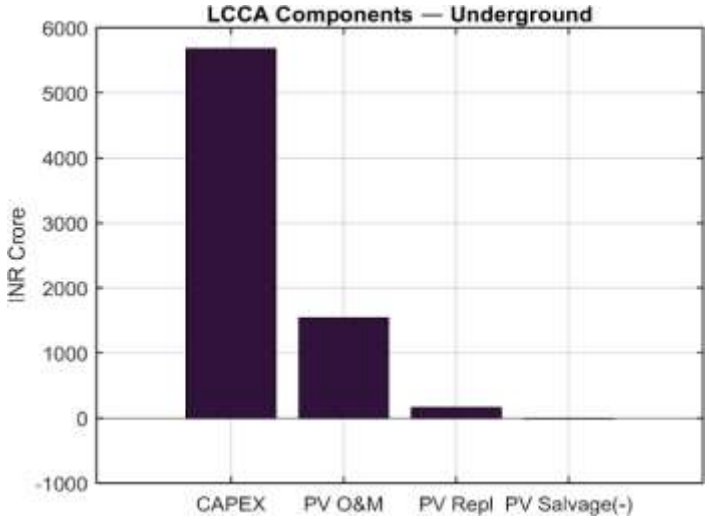


Figure 6: *Life Cycle Cost Analysis (LCCA) components*

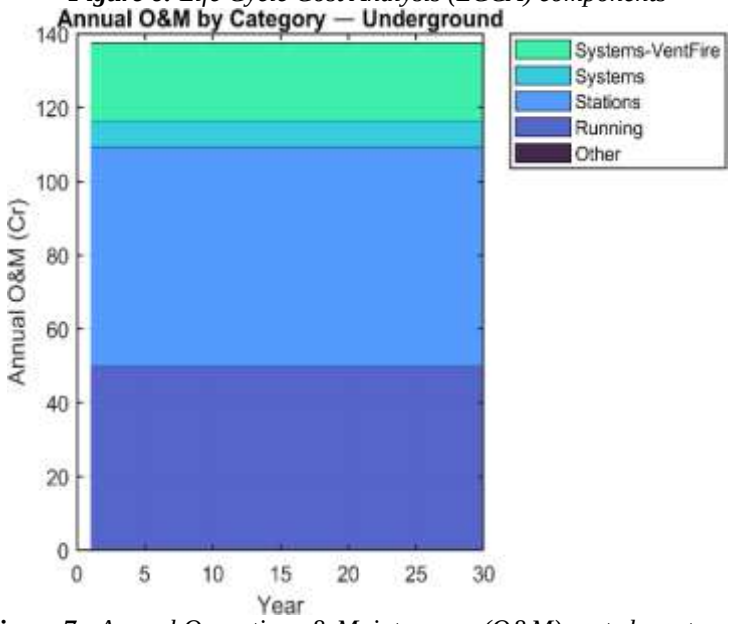


Figure 7: *Annual Operations & Maintenance (O&M) costs by category*

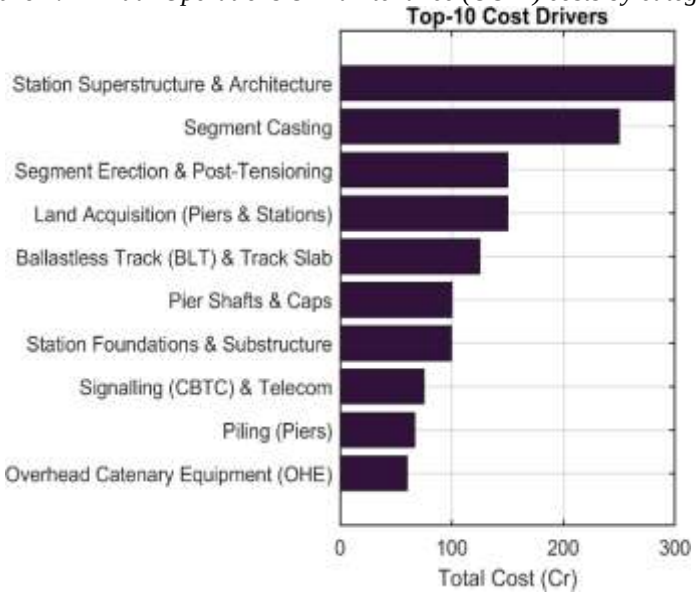


Figure 8: *Top-10 Cost Drivers in Infrastructure Development Projects*

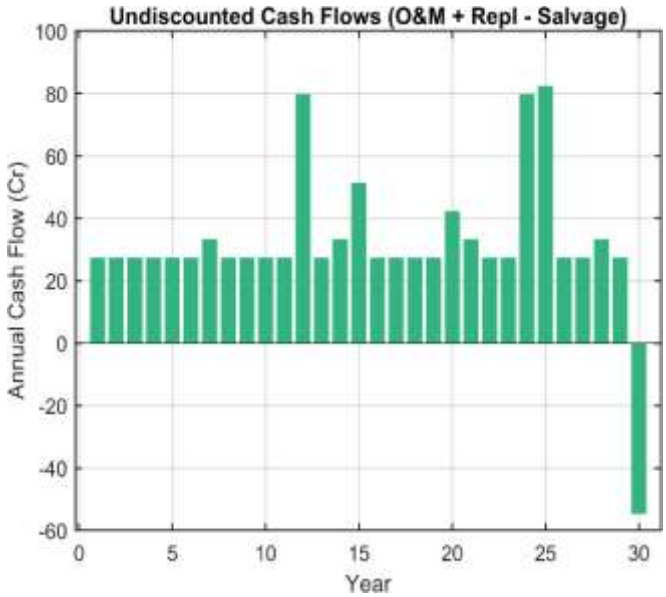


Figure 9*: Undiscounted Cash Flows (O&M + Replacement – Salvage) Over 30 Years*

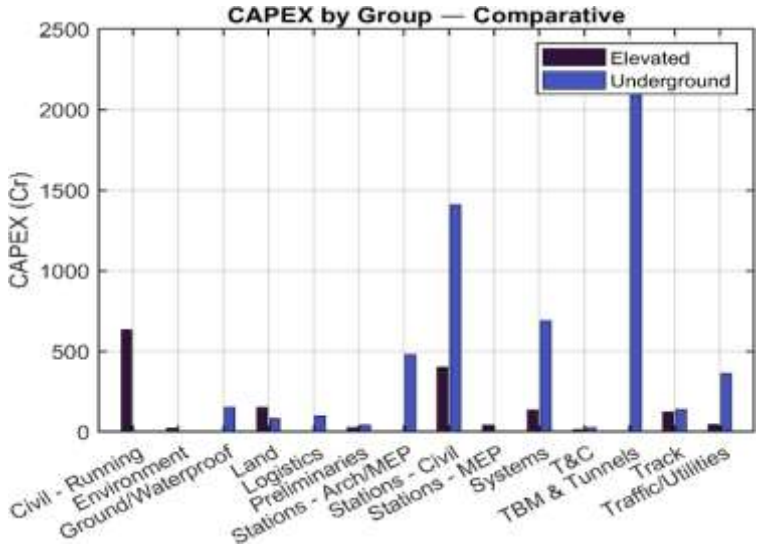


Figure 10: *Comparative CAPEX by Group for Elevated and Underground Systems*

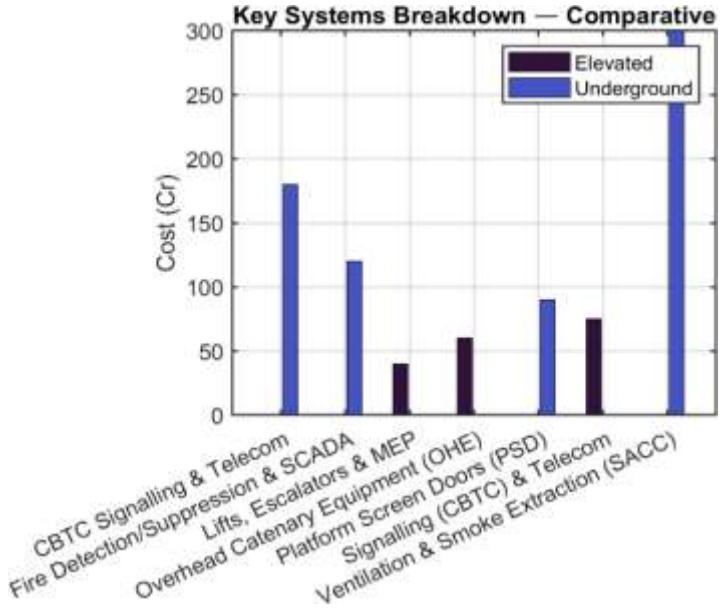


Figure 11: *Key Systems Breakdown — Comparative Analysis of Elevated and Underground Corridors*

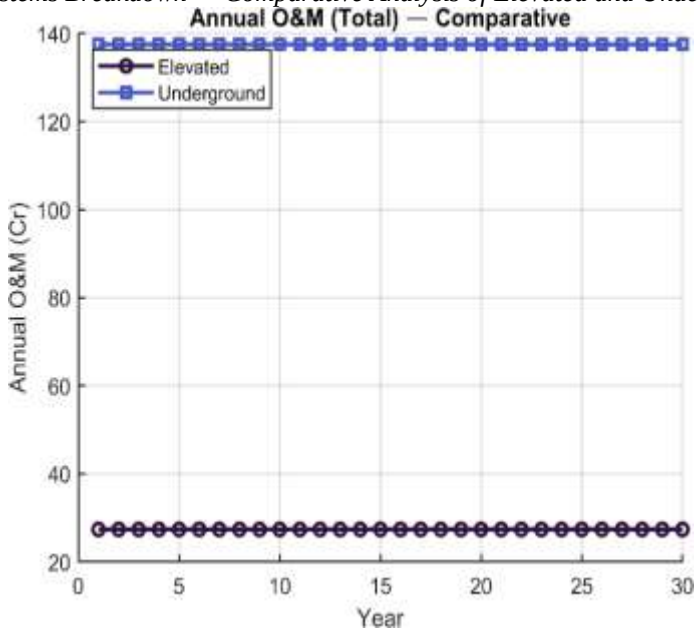


Figure 12: *Comparative Analysis of Annual Operation and Maintenance (O&M) Costs for Elevated and Underground Systems*

Table 3: *Comparative Financial Summary of Elevated and Underground Metro Scenarios*

Scenario	Route_km	CAPEX_Cr	PV_OM_Cr	PV_Repl_Cr	PV_Salvage_Cr	Total_NPV_Cr	NPV_per_km_Cr
Elevated	5	1,587.00	308.24	55.37	8.15	1,942.46	**388.49**
Underground	5.019	5,683.28	1,548.68	164.02	10.22	7,385.76	**1,471.56**

6. Discussion

The results align with previous studies by Doneva et al. (2015) and Maruvanchery et al. (2020), which emphasize the high-cost intensity of underground construction due to complex excavation and tunneling processes. Similarly, Saputra et al. (2025) observed that geotechnical conditions and ventilation needs significantly increase operational expenditures in underground networks. In contrast, Paraskevopoulou et al. (2013) highlighted those elevated structures, while exposed to environmental degradation, are easier and cheaper to maintain. The current study reinforces these findings by quantifying the cost difference, demonstrating that underground systems exhibit an annual O&M cost nearly six times higher than elevated systems. Moreover, the present value (PV) analysis indicates that underground projects are almost four times costlier over a 30-year life cycle. Compared to the findings of Bosché et al., this research extends the discussion by incorporating economic performance indicators like NPV and BCR, validating elevated systems as the more cost-efficient choice for most urban contexts. However, the underground option remains justified in megacities where land availability and noise reduction take priority. Thus, integrating financial and spatial criteria provides a more holistic basis for metro system selection and long-term infrastructure sustainability.

7. Conclusion

The comparative analysis of elevated and underground metro systems demonstrates significant differences in cost distribution, lifecycle expenditure, and operational sustainability. The study concludes that underground systems, though technologically sophisticated and space-efficient, impose much higher capital and operational costs. The major cost drivers include TBM tunneling, ventilation, and waterproofing, which collectively dominate the financial outlay. In contrast, elevated systems exhibit substantially lower CAPEX and O&M costs, making them more financially viable for expanding urban networks. The NPV analysis shows that the total lifecycle cost of underground construction is nearly four times higher, emphasizing the long-term economic advantage of elevated alignments. However, underground systems may still be justified in densely built environments where land scarcity, noise reduction, and aesthetics are critical. The research underscores the necessity of employing advanced cost management strategies and life cycle assessment models during planning stages to enhance financial performance and sustainability. Ultimately, the study recommends prioritizing elevated systems for cost-efficient expansion and adopting underground alternatives only where spatial or environmental constraints demand. Integrating CBA into early decision-making will enable urban planners and policymakers to allocate resources efficiently and achieve a balanced approach to sustainable metro infrastructure development.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The

data are not publicly available due to privacy or ethical restrictions.

- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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