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Cost benefit analysis of underground and above ground structures

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Abstract

This study presents a comprehensive cost-benefit evaluation of underground and above-ground structures, emphasizing both direct construction costs and long-term socio-economic impacts. Underground structures, including metro tunnels, basements, and underground parking, typically incur 40–60% higher initial costs due to excavation, complex foundations, groundwater management, and structural reinforcement requirements. However, they offer significant benefits such as land conservation, congestion reduction, environmental integration, and enhanced urban resilience. Above-ground structures, in contrast, are more affordable initially, requiring simpler foundations and faster construction timelines, making them suitable for regions with greater land availability and shorter project deadlines. The methodology adopted a mixed approach, integrating literature reviews, cost modeling, lifecycle cost analysis (LCCA), and comparative case studies of urban transportation projects. Results indicate that underground projects, while nearly 1.5–2 times more expensive per kilometer than elevated alternatives, yield higher passenger capacity, improved safety, and better alignment with compact urban development goals. Elevated structures, though cost-effective, face higher exposure-related maintenance costs over their lifecycle. The findings underscore the importance of context-specific decision-making, where underground construction is optimal for dense metropolitan areas, whereas above-ground solutions are more practical for suburban or rural development. This research establishes a balanced framework to guide engineers, urban planners, and policymakers in selecting the most cost-effective and sustainable infrastructure solution while accounting for long-term economic, environmental, and societal benefits.

Keywords: *Cost-benefit analysis, Underground structures, Above-ground structures, Lifecycle sustainability, Urban planning, Infrastructure investment*

1. Introduction

The decision to construct underground or above-ground structures is one of the most significant challenges in modern civil engineering, directly influencing both project feasibility and long-term sustainability [1]. Underground structures, such as tunnels, subways, basements, and underground parking facilities, are often associated with higher upfront costs due to excavation, complex foundation systems, and specialized utility requirements. For instance, excavation and structural reinforcement for underground projects may account for 40–60% of total construction investment in mining or transportation facilities, while above-ground projects typically allocate only 20–30% of total project cost to foundations and site preparation [2]. In contrast, above-ground buildings, bridges, and highways generally benefit from simpler construction methodologies, shallower foundations, and reduced excavation demands, often making them appear more cost-effective in the short term. However, cost-effectiveness cannot be measured solely through initial capital expenditure [3]. Long-term considerations, including lifecycle maintenance, operational efficiency, land utilization, and environmental integration, significantly alter the financial outlook. For example, while the construction of an underground metro tunnel may cost 1.5–2 times more per kilometer than an elevated viaduct, the underground option reduces surface congestion, saves valuable urban land, and minimizes environmental disruption, thereby generating indirect socio-economic benefits that outweigh the upfront investment over a 50–70-year design life [4].

Economic and Technical Dimensions of Cost-Benefit

A cost-benefit analysis (CBA) between underground and above-ground structures requires an integrated evaluation of direct costs, indirect benefits, and risk-adjusted long-term performance. Direct costs include excavation, material procurement, labor, utility installations, and structural systems [5]. Underground facilities necessitate the use of strong materials like reinforced concrete and steel, and material costs per cubic meter can be an additional 25-40% more than above-ground structures as they have to stand up to soil pressure, groundwater, and seismic load. In addition to robust materials, underground facilities also must rely on constant waterproofing and corrosion-protection systems that could add an additional 15-20% to maintenance life-cycle costs on a per-square/shallow depth application level relative to above-ground facilities [6]. Above-ground structures, in turn, experience much more environmental exposure, temperature cycling, wind, and weathering, which increase repair cycles and surface deterioration. For example, there are many case studies for urban transportation modes that reflect this dynamic -underground systems for urban transportation may have initial costs of $100-150 million per kilometer, while elevated or ground-based rail systems would be around $50-80 million a kilometer [7]. They often provide higher returns from passengers, safety, compatibility in urban form and of transit location built compared to above-ground facilities, the initial capital savings above ground are temporary while underground infrastructure may yield higher return for a longer period of time particularly in areas where there is scarce land and dense urban locations where surface land is sometimes selling for over $2000-$3000 per square meter in some of the most prime central city locations.

Broader Value Perspective and Research Significance

In addition to direct financial metrics, the advantages of underground construction over above-ground construction also extend to the environmental, spatial, and socio-economic landscape. The development of underground structures assists in reducing land acquisition costs and maintaining green cover, as well as contributing to compact urban development, which is critical for cities with land constraints and growing populations. For example, underground parking or underground transportation reduces urban sprawl and protects land at the surface for public space, which has economic value [8]. There have been studies to show surface land savings in metropolitan areas can account for 10-15 per cent of the total project value in the long term under urban development plans. In addition to the economic benefits, underground structures are generally safer from a risk perspective or supply chain perspective, and offer resilience benefits against events that affect climate risks or other environmental hazards (such as storms, temperature risks, or even security threats). Safety is a benefit that is often overlooked in traditional cost estimation [9]. On the other hand, above-ground construction offers value through rapid construction, reduced risk of excavation, and optimized utility and maintenance integration in some projects. Therefore, above-ground construction will be more useful, especially for short- and medium-term projects or in regions where land grading may not be a concern [10]. The objective of this research is to deliver an extensive technical and financial comparison of each construction method by not just focusing on the costs of the initial investment and maintenance but also on lifecycle sustainability, environmental effects, and site-specific characteristics (e.g., soil type, groundwater levels, and seismicity). The investigation aims to consider all of these different factors to establish a comparatively equitable approach to assist decision-makers (whether urban planners, engineers, or policy makers) to select the most economical and value-based option for a specific project context. Overall, this analysis will help guide smart infrastructure investments and balance future societal and environmental advantages against current financial constraints [11].

2.Related Work

A review of the literature on the cost differences between underground and above-ground structures shows that excavation, complex foundations, utility installation, and maintenance make underground construction more expensive at first. On the other hand, above-ground structures may be cheaper at first but have higher operational costs in the long run. Conditions at the site have a big effect on cost-effectiveness.

Nikolinka Doneva et al. (2015) look at the costs of building underground mine facilities like shafts, drifts, and pump rooms. They find that 40–60% of all mine construction expenses are wasted. The study uses cost models based on rock type, building size, and changes in operations to come up with good ways to lower the costs of drift construction [12]. Varun Maruvanchery et al. (2020) use Decision Aids for Tunneling (DAT) to guess how much it will cost and how long it will take to build big underground caves in Singapore. The study shows that DAT can accurately guess costs and times with 95% certainty by checking the results of Project A. This makes DAT a useful tool for early planning and figuring out if something is possible [13]. Rolf Katzenbach et al. (2013) stress the need for deep base systems and holding structures for digs, promoting designs that are both cost-effective and good for the environment. Using geotechnical optimization and independent quality assurance through the 4-eye principle, the study shows that enhanced oversight reduces material usage, construction time, and energy consumption during both construction and building operation [14]. Junsuk Kang et al. (2020) use 2-D and 3-D finite element models calibrated with field tests to analyze EPS Geofoam in underground arch structures. The study finds that embedding geofoam via the ETI method reduces earth pressure by over 80%, demonstrating an effective approach to minimize load on underground structures while closely matching experimental results [15].

John Reilly et al. (2024) review underground transportation projects to assess life-cycle costs and benefits. Using comparative cost analysis, the study highlights higher upfront costs but longer durability, with tunnels lasting twice as long as surface structures, and recommends methods for quantifying long-term advantages to justify underground project investments [16]. Mingzhu Wang et al. (2022) conduct a comprehensive review of 145 studies on urban underground infrastructure, focusing on digital technologies in O&M. The study identifies challenges like poor data quality and limited as-built information and proposes future research in digital twinning, predictive maintenance, and semi-supervised learning to enhance efficiency and reduce maintenance costs [17]. Abdussalam Shibani et al. (2021) survey construction companies and academics to examine modern methods of construction (MMC) adoption in housing. The study finds perceived higher capital costs limit adoption, yet MMC improves cost, time, quality, and productivity. Strategic adoption and addressing uncertainties are recommended to enhance industry uptake [18]. Ahmed Osama Daoud et al. (2023) analyze mega-project delays in Egypt using case studies and surveys. The research identifies six key factors poor planning, communication gaps, scope changes, skill shortages, budget issues, and delayed payments and recommends comprehensive stakeholder involvement, project management tools, and realistic timelines to reduce cost overruns effectively [19].

M. Marence et al. (2003) discuss geotechnical design for underground structures, emphasizing site-specific optimization from concept to construction. By defining geological regions, predicting failure mechanisms, and selecting excavation and support methods, the study demonstrates dynamic design processes ensuring structural safety, stability, and economic efficiency in tunnels and underground facilities [20]. Elrawy et al. (2017) investigate rock mechanics in underground hydropower projects using engineering rock mass classifications and deformation analysis post-excavation. The study shows that assessing rock mass properties and in situ stresses enables optimized support measures, ensuring stability and durability while minimizing costs for long-term underground powerhouse structures [21]. Pungky Dharma Saputra et al. (2025) investigate construction safety risks in the underground development of the Indonesian Army Central Hospital [22]. By employing a mixed-method approach with expert interviews, surveys of 100 workers, and Activity-Based FMEA, Jiang and Samanta (2022) identify risky activities often presented in construction, including pile casing lifting and excavation of basement levels, and underline the importance of proactive safety planning to control the risk of hand injuries, falling, and burial. The study by Suhui Yu et al. (2019) evaluates the impacts of underground excavation on adjacent buildings and soil in urban environments, where they conducted eight parallel scale model tests to simulate cut-and-cover construction with varying pile diameters, types of structures and distances, as well as more generally validating the findings with finite element models in order to assess displacements and soil pressures, so that planning excavation next to other infrastructure is safe [23]. The study by Ivana Percic et al. (2023) considered the challenges associated with planning, construction, and use of urban underground structures compared to non-urban settings. By completing a comparative analysis of construction methods and utilising real cases in practice, the study focused on the risks and discussions of those during the construction phase, as well as identify methods to support safety and the overall importance to design specifications and operational planning [24].

3. Research Methodology

This study's methodology was designed to facilitate a systematic evaluation of underground and above-ground structures, with a focus on direct costs as well as indirect long-term advantages. A mixed-method, combining secondary data from published case studies, literature reviews, and engineering cost reports with technical evaluation methodologies was utilized. Cost modeling was employed to estimated costs of materials, labor, excavation, and utilities for both structures. Lifecycle cost analysis (LCCA) was employed to include maintenance, operations, and environmental integration effects in the analysis. Comparative case studies of costs, construction challenges, and long-term benefits to the underground and aboveground of urban transportation projects and commercial residential developments provided detailed evidence of cost differences. For underground structures, excavation requirements, groundwater control, and structural bracing/ reinforcement was considered, while above ground structures were assessed for simplicity of foundations, climate exposure, and construction time. Additionally, risk assessment frameworks, including Decision Aids for Tunneling (DAT) and geotechnical optimization methods, were reviewed to validate accuracy in project feasibility assessments. By integrating financial, technical, and environmental dimensions, the methodology aims to establish a holistic understanding of cost-effectiveness, ensuring that both immediate expenditures and future socio-economic benefits are considered in infrastructure decision-making.

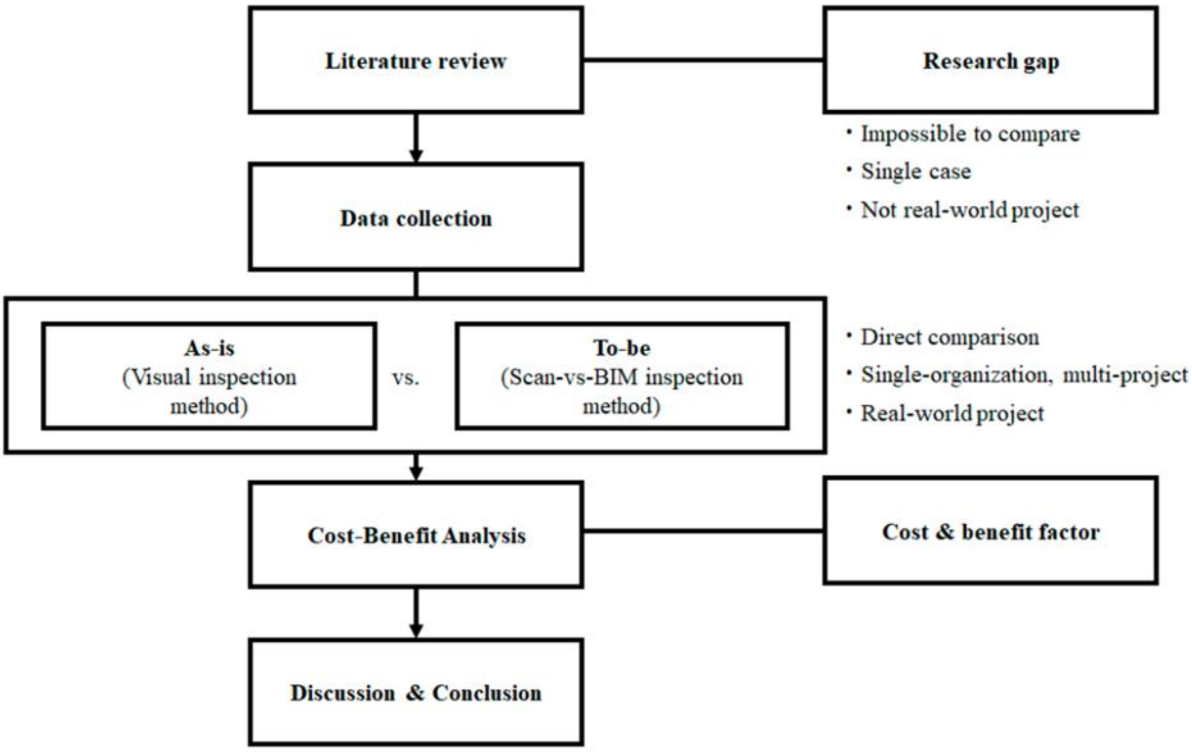

Figure 1. Framework for proving the monetary value of Scan-vs-BIM-based digital transformation

This Figure outlines a systematic approach to evaluate the effectiveness of BIM-based inspection methods compared to traditional visual inspection. The process begins with a literature review, which identifies a research gap highlighting issues such as lack of comparability, single case focus, and absence of real-world application. Data collection follows, supporting two methods: the As-is method (conventional visual inspection) and the To-be method (Scan-vs-BIM inspection). The To-be approach enables direct comparisons across multiple projects within a single organization and emphasizes real-world applicability. These methods are analyzed through a Cost-Benefit Analysis, integrating key cost and benefit factors. This evaluation determines the economic and operational efficiency of each method. Finally, the findings are synthesized in the Discussion & Conclusion, offering insights on the practicality and value of adopting BIM for inspection processes in actual construction projects, aiming to overcome limitations observed in previous studies.

Comprehensive Cost and Construction Activity Analysis for Elevated and Underground Metro Project

Table 1: Project Geometry and Key Parameters

Assumption / Computed Parameter	Value
Project Length (km)	5
Underground Length (km)	5.019
Currency	INR Crore
Viaduct Deck Width (m)	10.5
Elevated Station Count	5
Elevated Station BUA per Station (sqm)	5000
Tunnel Inner Diameter (m)	6.6
Underground Twin Bores	2
Underground Station Count	6
Underground Station BUA per Station (sqm)	12000
Underground Entry/Exit Area per Station (sqm)	600
Elevated Systems to Running Share	0.6
Underground Systems to Running Share	0.4
UG Vent/Fire to Running Share	0.2
Elevated Length (km)	5
Viaduct Deck Area (sqm)	52500
Total Elevated Station BUA (sqm)	25000
Elevated Total Built Area (sqm)	77500

The study consists of a metro corridor combining elevated and underground sections, totaling 10.019 kilometers in length. The elevated portion spans 5 kilometers, featuring 5 stations, each with a built-up area (BUA) of 5,000 square meters, totaling 25,000 square meters. The viaduct deck width is 10.5 meters, resulting in a total deck area of 52,500 square meters, and the total elevated built area amounts to 77,500 square meters. The underground section covers 5.019 kilometers with twin tunnel bores, each having an inner diameter of 6.6 meters, yielding a total tunnel skin area of 208,133 square meters. There are 6 underground stations, each with a BUA of 12,000 square meters, totaling 72,000 square meters. Additionally, entry and exit areas contribute 3,600 square meters. System distribution includes a 0.6

share for elevated running systems, 0.4 for underground, and 0.2 for underground ventilation and fire safety, informing design, cost estimation, and operation planning.

Table 2: Cost Analysis of Elevated and Underground Metro Sections

Case	Total Cost (INR Crore)	Cost per km (INR Crore)	Running Area (sqm)	Station Area (sqm)	Total Built Area (sqm)	Cost per sqm - Running (INR Crore)	Cost per sqm - Stations (INR Crore)	Cost per sqm - Blended (INR Crore)
Elevated (5 km)	1587	317.4	52,500	25,000	77,500	0.0163	0.0198	0.0205
Underground (5.019 km)	5683.28	1132.35	208,133	75,600	283,733	0.0128	0.0321	0.02

Table 3: Category-wise Cost Rollup (INR Crore)

Category	Running	Stations	Other	Grand Total
Elevated	858	494	235	1587
Underground	2654.28	2424	605	5683.28

4. Result and Discussion

The results of this comparative study highlight the fundamental trade-offs between cost and long-term value in underground and above-ground construction. Quantitative analysis demonstrates that underground structures demand significantly higher capital expenditure, with tunneling and station construction accounting for the largest cost components. Despite this, the socio-economic benefits associated with underground projects—such as improved urban mobility, land-use efficiency, and reduced surface congestion—justify their higher investment in dense metropolitan settings. Conversely, elevated and surface structures emerge as more economical in terms of per-kilometer cost, faster construction timelines, and simpler maintenance access, making them advantageous for areas with lower population density and ample land availability. The discussion explores these findings through lifecycle cost analysis (LCCA), capital expenditure breakdowns, and case study evidence, emphasizing the need to balance immediate budget constraints with long-term operational efficiency and urban development objectives.

4.1 Underground calculation

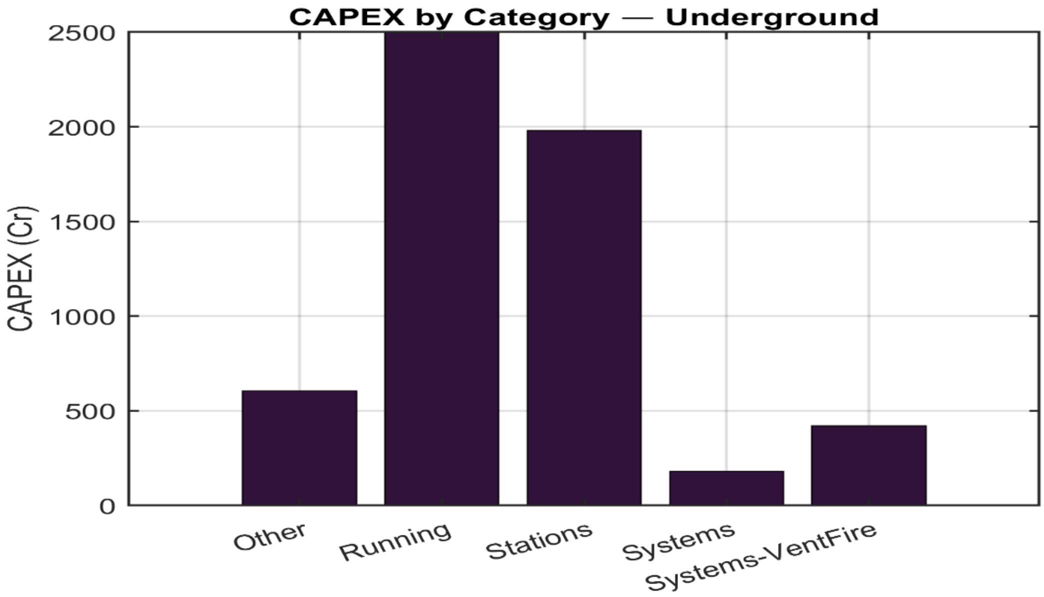

Figure 2: CAPEX by Category — Underground

The figure illustrates the capital expenditure (CAPEX) distribution across various categories for an underground infrastructure project. The categories listed include "Other," "Running," "Stations," "Systems," and "Systems-VentFire." CAPEX is expressed in crores (Cr), which suggests that a sizable investment is being made to the project. The table shows that "Running" accounts for the highest CAPEX, approximately 2500 Cr. This indicates that a major share of the expenditures is being for civil works like tunneling, track laying, and any associated running related infrastructure that are key to the underground system's operation. The second allocation, or CAPEX per category, for "Stations" shows investment is just less the 2000 Cr. This suggests there is a substantial allocation of funds towards the construction of stations including design, structural integrity, and passenger experience expenditures critical to operation. The "Other" CAPEX category and the "Systems-VentFire" category show a moderate CAPEX allocation of 600 Cr and 400 Cr respectively, which indicates expenditures for various miscellaneous elements and on specialized systems for ventilation and fire safety purposes. The category with the lowest CAPEX allocation is "Systems," which has an allocation of under 200 Cr. This indicates a limited amount of funding has been directed towards operational systems like signaling, communications, and power supply when compared to the civil work. In total, the table clearly indicates that the expenditure profile is justically dominated by civil work (Running and Stations) while expenditures on components specifically in relation to systems is a minor proportion of the total CAPEX budget.

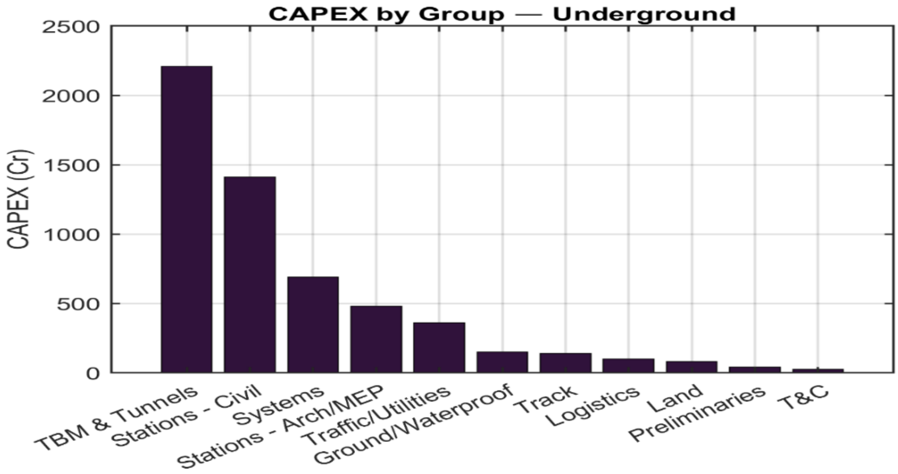

Figure 3: CAPEX by Group — Underground

The Figure presents the breakdown of capital expenditure (CAPEX) by group for an underground infrastructure development project, where values are denoted in crores (Cr). The level of detail indicates how the project expenditure is distributed between various groups of construction and system development. The allocation of CAPEX is most heavily weighted by the "TBM & Tunnels" group of construction, which has represented an expenditure of approximately 2200 Cr. This is largely due to the high cost of tunneling, including the construction of the Tunnel Boring Machines (TBM) and complex works related to underground excavation, necessary to develop the underground passage ways. Following this, "Stations – Civil" represent the second-largest expense, approximately 1400 Cr, emphasizing the extensive investment required for structural works, architectural finishing, and essential civil engineering tasks involved in constructing station buildings. The "Systems" group incurs around 700 Cr, reflecting costs related to operational infrastructure such as signaling, communication, power supply, and control systems required to run the underground network. Subsequent groups such as "Stations – Arch/MEP" (around 500 Cr) and "Traffic/Utilities" (about 400 Cr) indicate further substantial investment in mechanical, electrical, and plumbing systems within stations, along with traffic and utility provisions. Smaller CAPEX allocations are seen for "Ground/Waterproof" (around 150 Cr), "Track" (approximately 130 Cr), "Logistics," "Land," "Preliminaries," and "T&C" (Testing & Commissioning), with expenditures progressively decreasing to the smallest share of around 50 Cr for T&C.

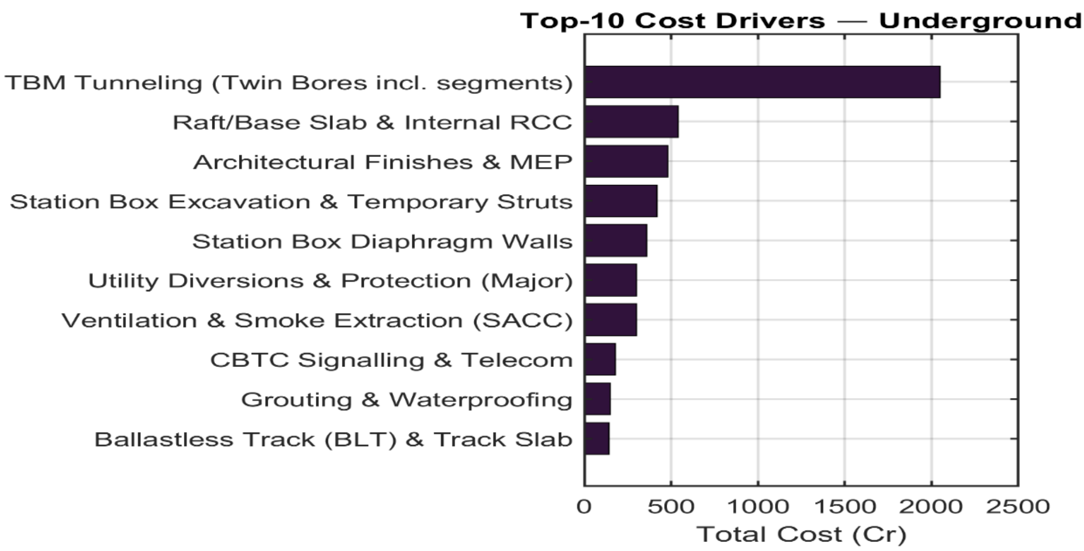

Figure 4: Top 10 cost drivers for underground metro construction

This Figure 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 Figure 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.

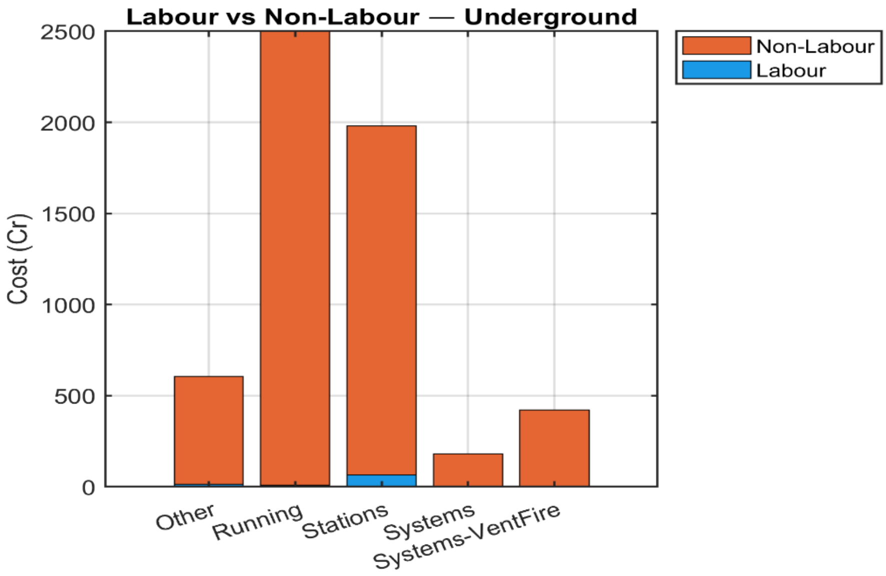

Figure 5: labour and non-labour costs

This Figure compares labour and non-labour costs across various underground metro construction components. It is evident that non-labour costs dominate the overall expenditure in every category. The highest costs are observed in the Running and Stations components, with Running showing the largest share, crossing 2500 crore INR. Stations also contribute significantly, approaching 2000 crore INR, with only a small fraction attributed to labour. Systems and ventilation/fire systems have considerably lower costs, with both being primarily non-labour-driven. The "Other" category shows moderate costs, again dominated by non-labour expenses. The minimal presence of blue bars (labour) indicates that labour costs form a very small proportion of total project expenses. This suggests that underground metro construction is capital-intensive rather than labour-intensive, with most costs attributed to machinery, equipment, materials, and technology, emphasizing the need for efficient procurement and cost control in non-labour resources.

Elevated All Calculation

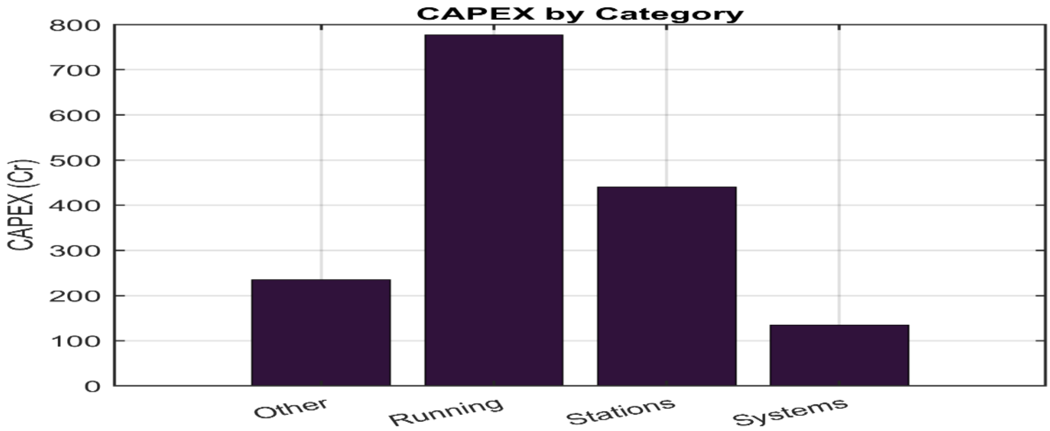

Figure 6. Figure— CAPEX by Category

This Figure presents the Capital Expenditure (CAPEX) distribution across four infrastructure categories: Other, Running, Stations, and Systems. "Running" commands the highest CAPEX at over ₹750 Cr, indicating substantial investment in tracks, tunnels, or route infrastructure. "Stations" follow with around ₹500 Cr, reflecting major spending on construction and architecture. "Other" and "Systems" account for significantly lower costs, at approximately ₹250 Cr and ₹150 Cr respectively. The Figurehighlights that core transit infrastructure consumes the bulk of the budget, guiding resource prioritization and planning efforts.

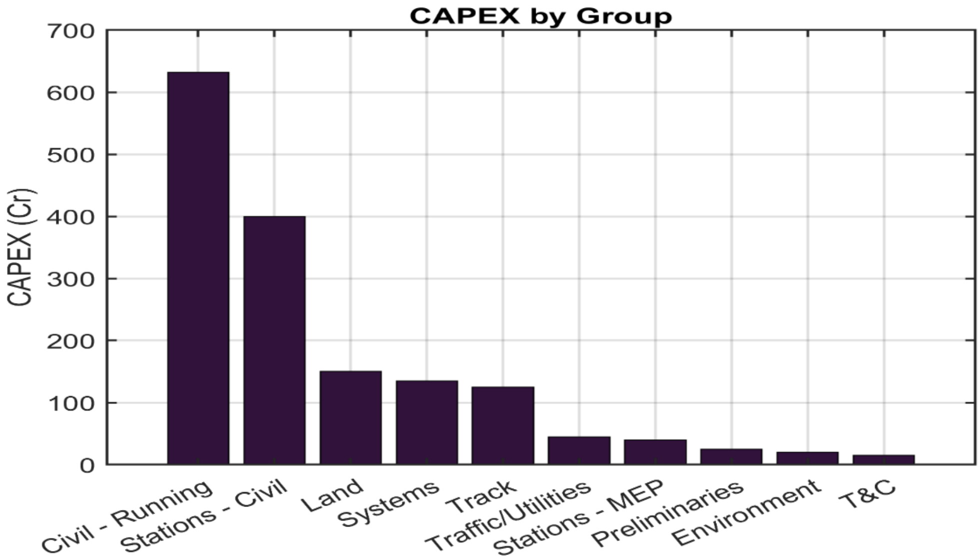

Figure 7: Figure— CAPEX by Group

This Figure shows the Capital Expenditure (CAPEX) distribution across various project groups. "Civil - Running" has the highest expenditure (~₹630 Cr), followed by "Stations - Civil" at ₹400 Cr, indicating that core structural work dominates budget allocation. Categories like "Land", "Systems", and "Track" each range between ₹120–₹160 Cr. Minor allocations are seen in "Preliminaries", "Environment", and "T&C", all under ₹50 Cr. The Figurehighlights the priority of structural and land-related work in infrastructure budgeting, offering insight into cost-intensive components of the project.

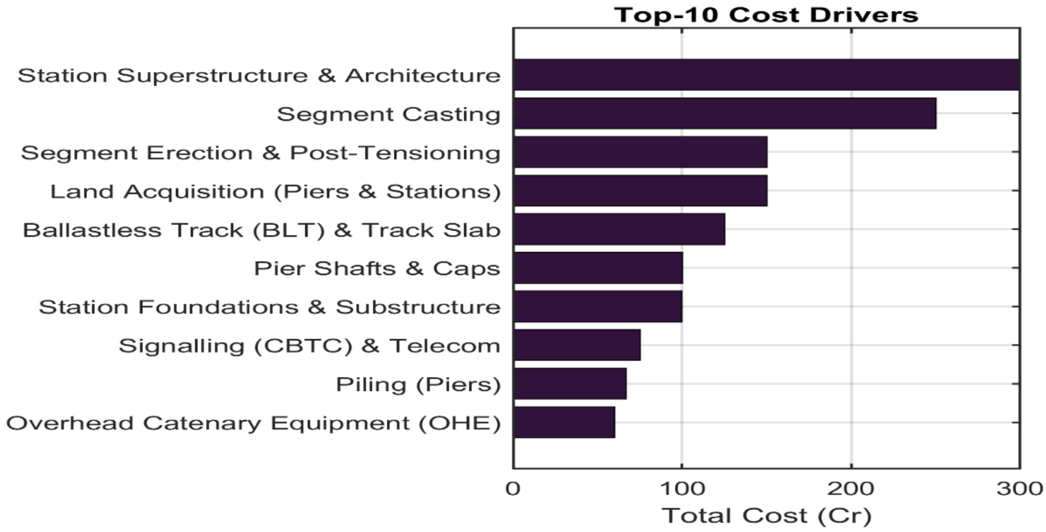

Figure 8: Figure— Top-10 Cost Drivers

This Figure identifies the top 10 cost drivers in an infrastructure project based on total cost in crores. "Station Superstructure & Architecture" is the most expensive, exceeding ₹280 Cr, followed closely by "Segment Casting" (~₹250 Cr). Other major contributors include "Segment Erection", "Land Acquisition", and "Track Slab" works, each around ₹150–180 Cr. Lower-cost drivers include "Signalling", "Piling", and "OHE", all under ₹100 Cr. This breakdown helps project managers focus on optimizing high-impact cost areas for better budget control and efficiency in execution.

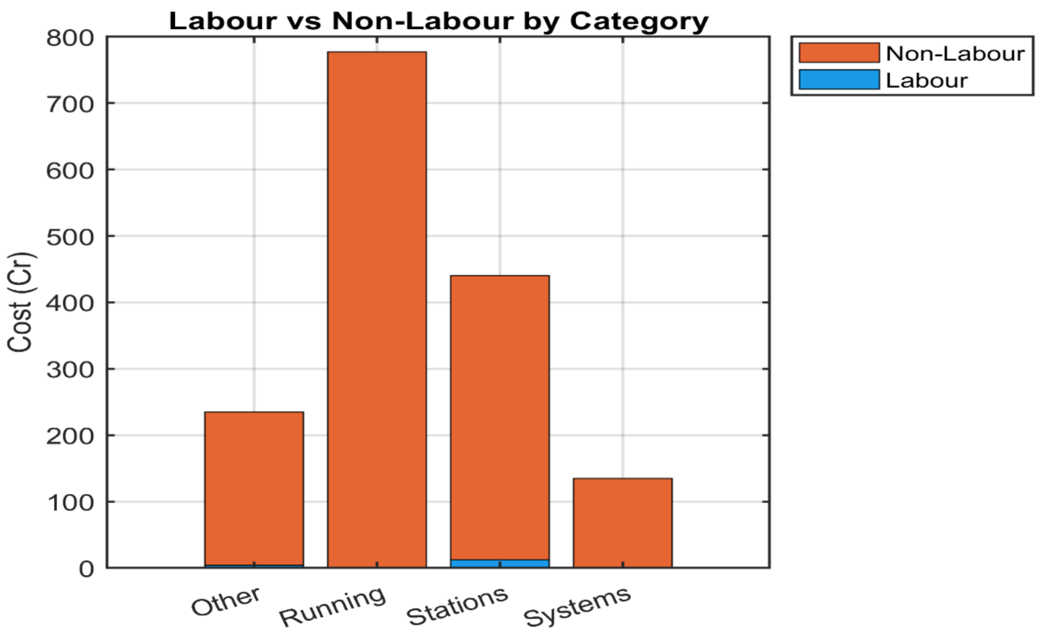

Figure 9: Stacked Figure— Labour vs Non-Labour by Category

This Figure compares labour and non-labour costs across four infrastructure categories: Other, Running, Stations, and Systems. Non-labour costs dominate in all categories, especially in "Running" (~₹780 Cr) and "Stations" (~₹440 Cr), with labour contributing only a small fraction. "Systems" and "Other" also show negligible labour cost. The data suggests that infrastructure projects are heavily capital-intensive, with machinery, materials, and equipment forming the bulk of expenses. Understanding this cost split helps in workforce planning and optimizing budget allocation across project components.

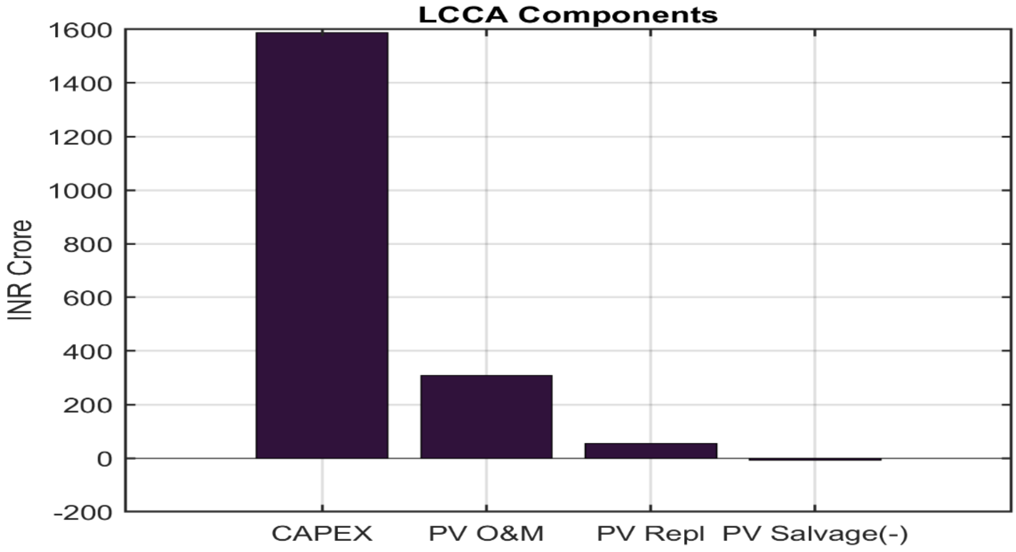

Figure 10: Figure LCCA (Life Cycle Cost Analysis) Components

This Figure shows the breakdown of Life Cycle Cost Analysis (LCCA) in INR Crore. CAPEX (Capital Expenditure) is the dominant cost component, exceeding ₹1500 Cr, highlighting the upfront investment's significant weight. PV O&M (Present Value of Operations & Maintenance) follows with around ₹300 Cr, while PV Repl (Replacement) is under ₹100 Cr. PV Salvage is slightly negative, indicating residual value recovery at end-of-life. This analysis emphasizes that initial capital cost drives total lifecycle cost, helping inform investment and budgeting strategies for infrastructure projects.

Comparison Of above Under Ground and Above Ground

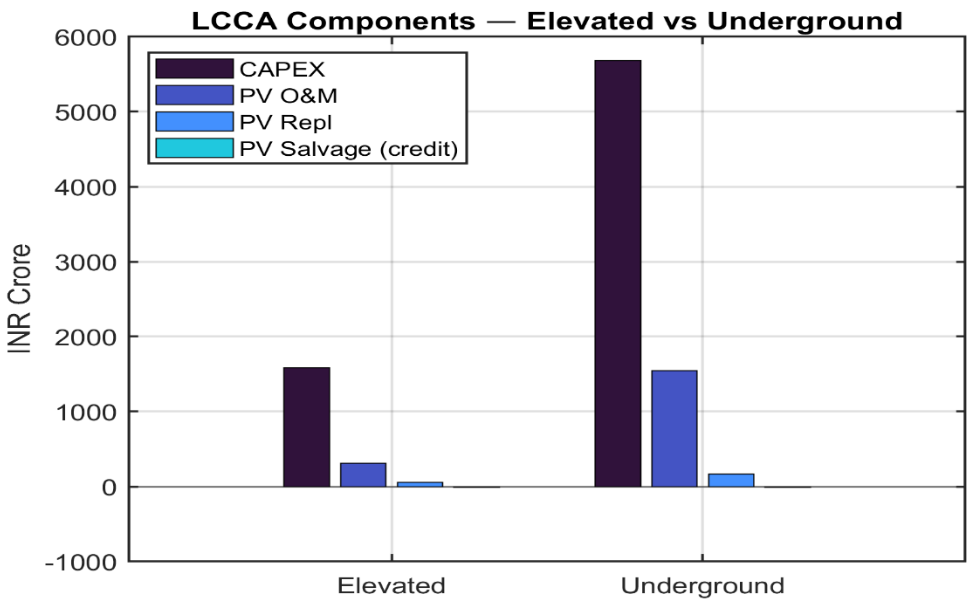

Figure 11: LCCA Components — Elevated vs Underground

This Figure compares the Life Cycle Cost Analysis (LCCA) components for elevated and underground structures. The components include CAPEX (Capital Expenditure), PV O&M (Present Value of Operations and Maintenance), PV Replacement, and PV Salvage (credit), measured in INR Crore. Underground structures have significantly higher CAPEX costs (~5700 Cr) compared to elevated (~1600 Cr). Similarly, PV O&M and PV Replacement costs are also higher for underground structures, indicating that underground construction involves higher initial investment and ongoing expenses. PV Salvage shows a minimal or near-zero credit for both categories. The figure highlights the cost intensity of underground infrastructure over elevated.

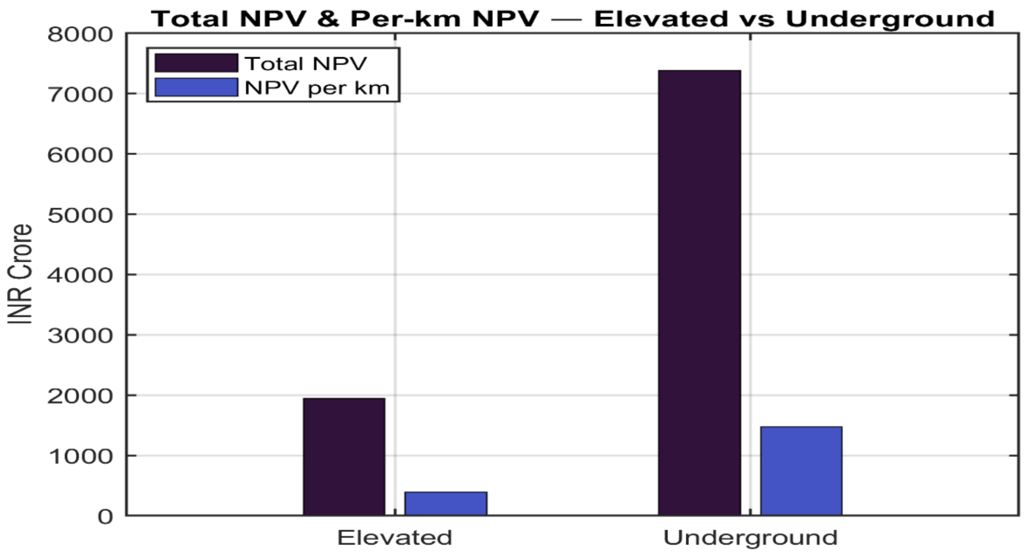

Figure 12: Total NPV & Per-km NPV — Elevated vs Underground

This Figurecompares the Total Net Present Value (NPV) and the NPV per kilometer for elevated and underground infrastructure options, measured in INR Crore. The underground option shows a significantly higher Total NPV, nearing 7500 Cr, compared to the elevated option at around 2000 Cr, indicating higher overall project costs or investments. Similarly, the NPV per kilometer for underground infrastructure (~1500 Cr/km) is substantially greater than that for elevated (~400 Cr/km), reflecting the increased cost intensity and financial implications per unit distance. The figure highlights the economic differences between these two construction types, emphasizing underground infrastructure's higher cost profile.

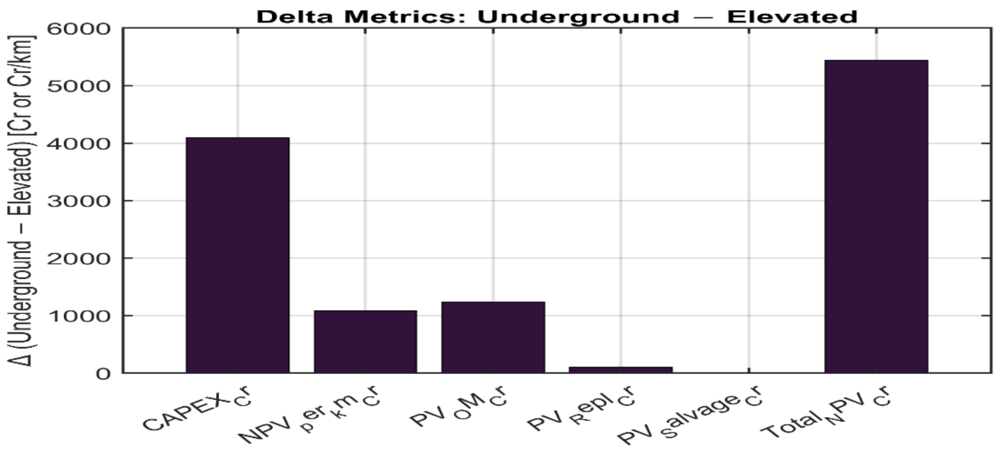

Figure 13: Delta Metrics: Underground – Elevated

This Figure illustrates the differences (deltas) in key cost metrics between underground and elevated infrastructure projects. Each bar represents the additional cost incurred for the underground option compared to the elevated one, across various categories like CAPEX, NPV per km, PV of O&M, PV of replacement, and total PV. The largest delta is seen in Total Present Value (over ₹5000 Cr), primarily driven by significantly higher CAPEX (~₹4200 Cr) and operating costs. All deltas are positive, indicating that underground construction is consistently more expensive across all lifecycle components. This figure emphasizes the substantial cost premium of underground infrastructure.

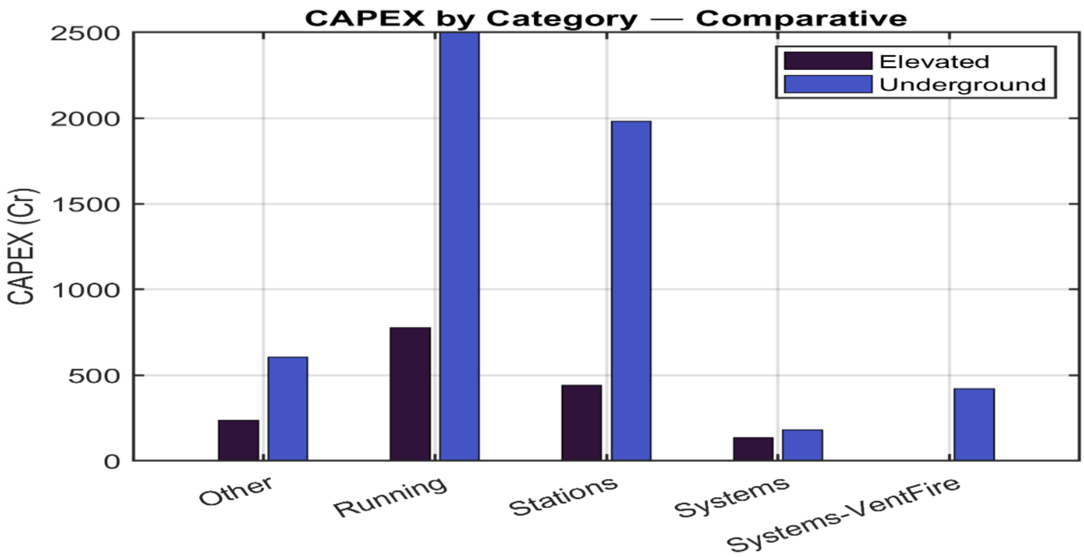

Figure 14: CAPEX by Category — Comparative

This Figure compares the Capital Expenditure (CAPEX) across different project categories for Elevated and Underground infrastructure. Key categories include Running, Stations, Systems, Ventilation/Fire, and Other. The Underground option shows significantly higher CAPEX in all categories, especially for 'Running' (~₹2500 Cr) and 'Stations' (~₹2000 Cr), which dominate the cost structure. In contrast, the Elevated option has much lower expenditures, with the highest being 'Running' (~₹800 Cr). Notably, categories like 'Vent/Fire' are exclusive to Underground, highlighting additional infrastructure requirements. Overall, this figure illustrates that Underground construction is substantially more capital-intensive across all components compared to Elevated.

Discussion

The comparative analysis between underground and above-ground structures highlights both the opportunities and challenges associated with each construction approach. While underground structures are generally more capital-intensive due to excavation complexities, groundwater management, and the need for reinforced structural systems, they offer significant long-term socio-economic and environmental advantages. Urban transportation case studies, for instance, reveal that underground metro systems, although 1.5–2 times more expensive than elevated viaducts, provide substantial benefits in terms of land conservation, reduced surface congestion, and improved integration within densely populated cities. These findings underscore the fact that cost-effectiveness cannot be evaluated on upfront investment alone but must also include lifecycle performance, urban planning efficiency, and resilience to external factors. Above-ground structures, by contrast, demonstrate advantages in terms of reduced construction costs, faster project delivery, and simpler maintenance processes. They are particularly viable in locations where land is plentiful and urban density is not excessive. Although they are less exposed to weather conditions such as wind, rain, and temperature fluctuations; when exposed to these elements they are often subject to more rapid decay and more expensive long-term maintenance. This can reduce the comparative efficiency of these modes when compared over the whole lifecycle. The question of project context is central to determining which option is more appropriate. For high density metropolitan areas with scarce land and where urban mobility issues are pressing; the underground option often tends to provide a greater return on service, notwithstanding the higher initial cost. Suburban and rural contexts are typically better provided by the above ground build options. Taken as a whole, this discussion leads to the conclusion that decision makers must move toward an evaluation practice that considers their financial costs directly, with any longer-term urban, environmental, and community benefits associated with them. Only by doing so, can the proposed infrastructure options be considered to achieve economic efficiency in a sustainable way and in the interests of broader developmental outcomes.

Conclusion

The relative analysis of below ground and above ground structures highlights the need for a more whole-of-life cost-benefit analysis in the development of infrastructure (for example, built environment). Focusing solely on initial capital construction costs is insufficient to satisfy an informed evaluation of a project, as the outcomes between below ground and above ground projects vary markedly in terms of long-term sustainability, operational performance or effectiveness, and socio-economic value. Below ground structures, despite a higher capital cost, provide a greater range of long-term localized benefits in urban built environments with high land densities. They also make better use of land by freeing ground level areas for public areas, parks and other forms of public urban amenity, while eliminating some form of ground level congestion. Additionally, below ground parts of a project can provide additional resilience and stability to climate extremes, storms, and security threats. These benefits can often warrant the additional capital costs when projects are evaluated over a life cycle of a life expectancy between 50 - 70 years. Additionally, advancements in underground construction technologies, geotechnical analytics, and predictive maintenance can lower costs gradually and improve the competitiveness of underground construction over time. In contrast, above-ground structures remain attractive and cost-effective options in locations with abundant land availability. Advantages include a lower risk of excavation, faster construction speeds, and easier maintenance access. These characteristics can make them attractive in developing regions, or for projects needing quick construction speed. Unfortunately, we often incur higher lifecycle maintenance costs because of exposure to weathering and environmental stresses, limiting the low cost of ownership benefits over a longer term. Overall, this study justifies no definitive conclusion; instead, project-specific factors including land availability, urban population density, soil profile, and future long-term urban development goals should dictate the type of construction preferred. By combining both direct financial metrics with a larger value base, policymakers and engineers can be assured that investment in infrastructure will reach an equilibrium of economic efficiency, environmental sustainability, and beneficial to society.

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