Public–Private Partnerships in Indian Metro Rail: Catalysts for Low-Carbon and Smart Mobility in Urban Settings

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Abstract. Transport is at the heart of India's development, but it also lies among the biggest causes of congestion, air pollution, and climate-altering emissions. Road transport alone emits close to 13% of India's CO_2 emissions, with private two-wheelers and cars dominating the sector, states the International Energy Agency (2021). Metro rail modes, as electrified, high-capacity public transport modes, represent a strategic low-carbon option. They offer safety, efficiency, and accessibility while allowing significant reductions in per passenger-kilometre emissions. This paper discusses the contribution of PPP-driven metro projects towards realizing sustainable and driverless transport in India. Based on findings in Delhi, Hyderabad, Kochi, Kanpur, Mumbai, Nagpur, Kolkata, and the Delhi–Meerut Regional Rapid Transit System, the research aggregates six thematic dimensions: carbon emission reductions, smart mobility integration, ridership and modal shift, economic sustainability, autonomous and digital innovation, and rural–urban connectivity. Evidence shows that PPP-equipped metros have registered significant carbon reduction, hastened smart mobility uptake and registered major modal switch from private cars. PPP models have also proved to be essential in revenue diversification via non-fare sources, pushing forward automation like driverless operations, and pushing accessibility into rural areas. The study emphasizes that PPP-led metros are not just funding instruments but drivers of climate action, digital transformation and inclusive growth. Policy recommendations involve incorporating carbon targets, renewable sourcing requirements and smart mobility standards into PPP contracts.

Keywords: PPP, metro rail, Smart Mobility

1 Introduction

Transportation is at the centre of India's development narrative, yet it's also one of its biggest pitfalls. The transport sector, in the [1] estimate, accounts for approximately 13% of the nation's overall CO_2 emissions, where the majority of it comes from private cars. The effects are evident: deteriorating air quality within urban areas, clogged roads, increased oil imports, and unequal mobility opportunities, especially for the poor.

Metro rail networks are a game-changing intervention in this context. As [2] illustrate through their lifecycle analysis, metros produce 60–80% less CO_2 per passenger-

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kilometre than private cars. For India, they not only ensure environmental sustainability but also increase safety, save time, and spur urban renewal through transit-oriented development (TOD).

India is unique in the world in its adoption of Public–Private Partnerships (PPPs) in metro development. The Hyderabad Metro is the world's largest metro project operated under a PPP model, and other cities like Delhi, Kochi, Nagpur, Mumbai, and Kanpur have accepted hybrid models of financing and operating their metro systems. PPPs have introduced private capital, operational competitiveness, and technological advancements that complement public sector funds.

The rationale behind this study stems from the necessity to examine metros not only as transport infrastructure, but as drivers of low-carbon, smart, and inclusive mobility. PPPs are generally characterized in narrow terms as financial or contractual devices, yet this paper contends that they are much more powerful — facilitating climate action, smart mobility integration, modal shift, revenue diversification, automation, and regional connectivity. Additionally, a lot of the international literature on lifecycle emissions, automation, and smart mobility is from European or East Asian backgrounds. There is a relatively limited number of studies that are India-centric and cover environmental, technological, and economic aspects of several metro systems.

This paper fills that gap by examining case evidence from Indian metro PPPs, integrating six dimensions of sustainability, and distilling lessons for national policy and global practice. It seeks to guide how PPP contracts can make carbon reduction targets a part of them, incentivize digital uptake, enhance non-fare revenue innovation, and expand mobility outside cities into regional corridors. In this process, the study helps advance India's net-zero 2070 goals as well as global conversation on sustainable urbanisation.

2 Literature Review

[3] discusses the growth and planning of Indian metro rail networks, emphasizing institutional coordination and leadership for project success. [4] evaluate metro project Environmental Impact Assessments (EIA), weighing short-term environmental costs against long-term advantages like lower emissions. Ramakrishnan discusses infrastructure PPPs, emphasizing their efficiency and financial viability but warning against regulatory and contractual issues. [5] examine Beijing Metro funding innovations, recommending land value capture and PPPs for Indian metros. [6] provide land-based metro finance techniques that promote transit-oriented development and real estate leveraging. A cost-benefit analysis by the [7] validates Chennai Metro's socio-economic benefits. [8] say policy clarity, risk allocation, and stakeholder cooperation are key PPP success factors. [9] advise integration and planning to boost Jaipur Metro ridership. [10] examine Mumbai Metro's shop leasing and advertising non-fare revenue techniques. [11] analyze Delhi Metro (DMRC) station co-branding for revenue and brand visibility. [12] describe Pune Metro's station name and leasing revenue diversification. [13] compare London and Beijing Metro PPP models, emphasizing

governance and stakeholder alignment. [14] recommend smart city infrastructure PPPs be flexible. Finally, [15] construct a data-driven approach to understand retail ecosystem changes from new urban developments for city planning.

[16] suggest that in terms of the URT sector in China, value creation goes beyond conventional performance indicators to partnerships originating from value co-created through cooperation and synergy between public and private actors. [17] study the pioneer train project in South Sumatera, Indonesia, which is a compelling example because it is an exploration of the feasibility of PPP in a developing context. [5] proposed a case-based decision-making model using empirical data, which builds stakeholder expectations, service quality, and asset performance into the value-for-money (VfM) framework.

The literature indicates that PPPs, mostly, speed the delivery of commercial and technological outcomes owing to private commercial incentives and procurement laxities - e.g. Hyderabad for TOD commercialization, Mumbai/Nagpur digital ticketing; but they may not perform if procurement relies on unrealistic revenue assumptions, and public land-use policies are not conducive to TOD e.g. (World Bank & PPP investigations, Hyderabad case studies).

3 Methodology

This study adopts a multi-method approach based on a literature review from secondary research, consulting case studies, and comparative benchmarking.

- Secondary Literature Review: The review of peer-reviewed secondary literature supplied baseline evidence and witness statements concerning carbon emissions and lifecycle analysis with regard to the impacts of automation, including [18], [2], and [19].

- Case Study Analysis: The research involved case study analysis of metro systems in Indian cities, including Delhi, Hyderabad, Kochi, Kanpur, Mumbai, Nagpur, and Kolkata, among others, and the Delhi-Meerut RRTS. The research adopted a case study approach by analyzing and consulting case studies from annual reports, mainly DMRC 2021 and KMRL 2022, and related supplementary information sources from available government paper and news articles.

- Comparative Benchmarking: The study contextualized the evidence base from Indian cities through benchmarking the evidence against globally recognized good practice from other contexts, notably in the cases of East Asian metros, for example, lifecycle carbon evidence produced in the case of Shenzhen, [20].

The sources of evidence included both quantitative sources, such as CO_2 avoided, digital tickets adoption, and farebox recovery ratio, and qualitative sources, including but not limited to PPP governance arrangements, commuter insights/preference studies, policy

and governance frameworks, etc. The objective was to use a mixed-methods methodology approach in developing metro PPPs as an enabler toward low-carbon and smart mobility.

4 Conceptual framework

The present research is derived from a theoretical model, which posits that the design of Public-Private Partnership (PPP) contracts is the key to translating private sector capacity into measurable sustainability impacts. Evidence from metropolitan cities in India and world-wide benchmarks i.e. Hong Kong, Singapore, Shenzhen and from the model's six sustainability factors are:

1. Carbon reduction and renewable integration;
2. Smart mobility and digital interoperability;
3. Ridership growth and modal shift;
4. Economic sustainability through non-fare revenues and Transit Oriented Development (TOD);
5. Modernization and Predictive Maintenance (Automated Train Control-ATC/Automated Train Operation- ATO);
6. Regional Connectivity and Inclusion.

PPP Contracts drive these outcomes through the following three mechanisms:

(a) Contractual Incentives

Private sector concessionaires typically respond most effectively to Contractual Incentives by committing to using the following elements in their PPP contracts:

- Investment in Digital Systems and Advanced Fare Collection (AFC) /National Common Mobility Card (NCMC) Systems and Automating Train Control/Automated Train Operation Systems (CBTC/ATO)
- Renewable Energy Procurement
- Commercial Real Estate Development.

Examples of notable incentives provided by specific contractors are:

- Hyderabad – Via the rapid rollout of automated systems and the monetization of retail spaces.
- Kochi Metro – Integration of 51% of the solar energy purchased, due to the explicit sustainability requirements of the contract.

(b) Risk Allocation

Balanced allocation of revenue, demand, land-value, and technology risk supports innovation. Studies show PPP failures occur when demand risk is unrealistic (World Bank & PPP investigations) while successful cases, like MTR-Hong Kong, show that well-distributed risk leads to stable innovation and investment.

(c) Performance KPIs

Operators respond to Key Performance Indicators (KPIs) more favourably than to prescriptive rules. Key Performance Indicators that operators typically use include:

- Energy performance, tCO_2 avoided
- Availability /Uptime
- Milestones Digital Adoption
- Revenue - Transit Oriented Development (TOD)
- Quality of Service.

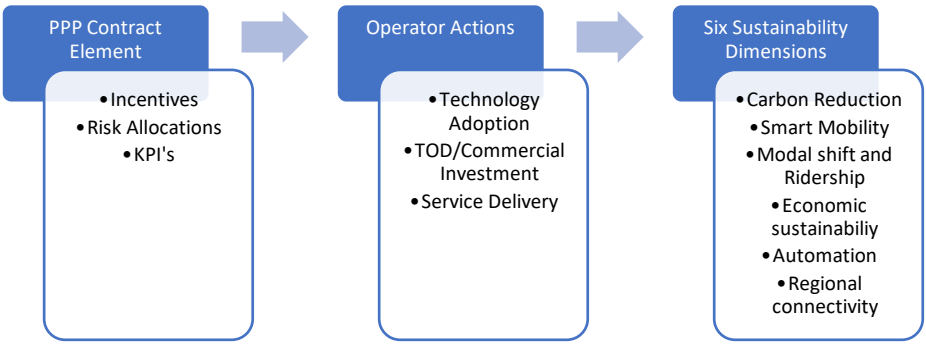

Fig. 1. Conceptual Framework Linking PPP Contract Elements to Sustainability Dimensions
Source: Compiled by Authors

5 Policy Implications & Practical Contract Design Recommendations

For India's metro PPP's to continue long-term sustainability as well as advancement of Digital Transformation, an integrated approach using formally measured and quantified requirements for both sustainability and Digital Transformation, as recommended by systems existing in Delhi, Hyderabad, Kochi, Mumbai, and International systems (see Table 1):

1. Include KPIs for Carbon and Renewable Energy
   All concession agreements should:

- provide a mandate as to the minimum percentage of renewable energy to be procured;
- provide for annual reporting of tCO_2 avoided; and
- provide for operators to raise the necessary financing through the issuance of "green bonds" collateralized by the Energy assets themselves. Kochi Metro has, for example, demonstrated the contractual ability to achieve the 51% renewable shares from Solar.

2. Require Digital Interoperability and Open Infrastructure
   - Require Conforming to AFC/NCMC;
   - Require API sharing; and
   - Require Transparency of Data.
   - To the extent that milestones are linked to digital technology adoptions, consider utilising such benchmarks for establishing payment structures.

3. Structure TOD and Value Capturing Based on "conservative triggers"
   - Stage revenue triggers;
   - Realistic assumptions regarding Land; and
   - Revenue Floors for revenues to be generated in the future.
   - A conservative approach will eliminate the land-market shocks experienced in Hyderabad's case.

4. Use Performance-Linked Payments and Bonuses
   Compensation should be tied to:
   - availability/uptime energy efficiency
   - digital adoption
   - automation milestones

5. Include Social Inclusion Provisions in Contracts
   - Concessional Fares
   - Gender-Inclusive Design of Stations
   - Last-Mile Services (feeder services)
   - Regional accessibility requirements

Table 1. Policy Actions and Expected Outcomes (Source: Compiled by Authors)

Policy Action	Expected Outcome
Renewable/Carbon KPIs in concession contracts	Measurable CO_2 reduction; access to green bonds and concessional climate finance
Mandatory NCMC/AFC interoperability	Faster digital adoption; multimodal integration; improved system efficiency
Conservative TOD/value-capture triggers	Reduced financial distress; predictable revenue; stable PPP performance
Performance-linked payments	Higher service quality; faster automation adoption; better maintenance outcomes
Social inclusion clauses	Equitable access; increased ridership; improved affordability for peri-urban users

For PPPs to deliver sustainable, technologically advanced and resilient metros, contracts must move beyond financial structuring and embed clear, measurable, enforceable sustainability and digital transformation requirements. The evidence indicates that when carbon KPIs, digital standards, and risk-balanced TOD clauses are included, PPPs contribute significantly more towards national climate targets, smart mobility goals, and long-term operational efficiency.

6 Public–Private Partnerships and Public Delivery: Comparative Insights from Indian Metro Projects

The initial observation is that, where the contracts are well designed, PPPs tend to outperform non-PPP arrangements in terms of adoption of innovation, revenue diversification, and integration of renewable energy (See Table 2). For example,

- The Hyderabad Metro, a PPP that allowed for a rapid expansion of the network while utilizing private real-estate expertise to generate revenues from the commercialized assets as quickly as possible such that it speeded monetization of the non-fare revenue potential; its fiscal adaptations have indicated both the risks of power forecasts and the almost 0 mechanisms to hold public officials accountable for the systems with weak oversight.

- Kochi Metro is a public-sector led project with sustainability as a focus, achieving high solar energy share - approximately 51%, showcasing significant project plans demonstrating an explicit renewable energy integration approach that results in carbon considerations which could be measured and were significant. This has come about because of strong sustainability targets present in the original project, and also due to a proactive implementation of the project team.

- Delhi Metro provides one example of a public agency with a well-resourced commercial arm which successfully monetizes property and pursues CDM and other green financing opportunities that generate comparable environmental and revenue generates to PPPs. This proves that the institutional capacity for commercial rigor is as important as the ownership model in project design.

The advantages associated with PPPs are once explained by commercial skills on the part of private partners in undertakings such as Transit Oriented Development and retail leasing. Further alluded to the connection between speedier procurement processes, including digital/automated processes and financing green capital costs that can be sourced from PPPs, which are at least impactful decisions, if not predictable project operational costs.

Social projects are very crucial because public/private entities working for social good can considerably uplift the vulnerable communities from poverty and create long-lasting public projects with significant public objectives. For example, public social projects we often mention are DMRC - Delhi Metro Rail Corporation, who equally may have been established on a PPP model, but in its own history, it is an entity that is similar yet with the benefit of a public entity being a monopoly in a sense that had developed pre-term public sector objectives the development [non-linear design development] yet be equally competitive in accessing commercial KPI's.

Table 2. Comparative Performance of Indian Metro Delivery Models (Source: Compiled by Authors)

Metro System	Delivery Model	Strengths (with Evidence)	Limitations / Risks	Key Quantitative Indicators
Hyderabad Metro	PPP (L&T Metro Rail)	• Fast project delivery due to private procurement efficiency • Strong commercialization of retail + TOD [21] • Early adoption of digital systems & automation [22]	• High exposure to real-estate market cycles • Revenue overestimation created financial stress [23]	TOD-linked commercial revenue projected 15–20% of total income
Kochi Metro	Public (KMRL)	• Strong sustainability-first planning • Solar integration achieved through institutional commitment [24] • Community-focused operations and inclusion	• Slower commercial development • Lower real estate monetization than PPP-led models	Achieved ~51% solar energy sourcing
Delhi Metro	Hybrid Public Model (DMRC)	• High institutional capacity and technical expertise • Strong property development arm [6] • Consistent financial performance and ridership	• Requires sustained public funding support • Not as speed-driven as PPP in procurement cycles	Farebox recovery >70%; strong non-fare revenue diversification

In conclusion, a best policy approach for India is hybrid conditional: using PPPs as necessary from skilled and upfront working capital, yet protecting the public interest through strong contractual KPIs, carbon, technical/ digital/inclusion assumptions, conservative financial assumptions, and transparent profit motives. When public agency has the commercial and technical capacity to do so (DMRC), an effective approach can also be undertaken through hybrid and public delivery.

6.1 Hyderabad Metro – Strengths of PPP Innovation

Hyderabad exemplifies how PPPs can build large-scale urban transport infrastructure efficiently and utilize commercial revenues from TODs, Station Retail, and automation technologies. Studies which support Hyderabad have identified the synergy of commercial incentives and Performance Objectives/KPIs as a catalyst for PPP projects to innovate and adopt new technologies more rapidly than those not aligned with commercial interests.

6.2 Kochi Metro – Strengths of Public Sustainability Governance

Kochi Metro illustrates how a public sector can deliver outstanding sustainability results when climate goals are embedded during the early stages of project development. Kochi Metro has exceed most global systems with their 51% solar energy sourcing and provides the potential for Planning Energy Mandates (PEM) to eliminate the need for

private sector financing, thereby achieving 100% sustainability from an equity perspective.

6.3 Delhi Metro – Strengths of Hybrid Institutional Capacity

Delhi Metro demonstrates how an institution's strength can be a substitute for the private sector incentive. Delhi Metro's strong commercial business model and Life Cycle Carbon Management (LCCM) processes are indicative of internationally recognized best practices (e.g., Hong Kong MTR, Shenzhen Metro). The consistently high levels of farebox recoveries and diversification of non-fare revenue collections have established Delhi Metro as a leader within hybrid governance.

6.4 When PPPs Outperform and When They Do Not

PPPs outperform when:

- Innovative technology (AFC, NCMC, automation) is required quickly
- TOD/non-fare revenues are essential for the financial model
- Performance-linked KPIs are embedded in contracts
- Renewable procurement is mandated (enabling green bonds/RECs)

Public or Hybrid Models outperform when:

- Strong institutional capacity exists (DMRC model)
- Social equity, inclusion, and affordability are priorities
- Sustainability targets are defined during planning (KMRL model)
- Market risk (land value, ridership uncertainty) must remain with the public sector

6.5 Governance Implications for India

Evidence-based research indicates that India's best and most effective governance model will likely be a conditional hybrid governance approach. Specifically:

- Use PPPs when speed, innovation, and the desire for commercial revenue are important; and
- Use public or hybrid models when sustainability and social inclusion and/or the need to mitigate taxpayer risk is the objective.

Embed KPI metrics that track carbon emissions, digital milestones, and renewable energy sourcing requirements into all future metro system concession models and infrastructure project designs and/or PPP contracts; this will allow for measuring and tracking the success of a project delivered under any model.

7 International Metro Sustainability Examples & Implementation in India

International metro systems provide a wealth of techniques and practices that describe how to embed sustainability, carbon reduction, digital technology, and financial resilience into transit governance; four important international examples are identified and described below along with how each example can be effectively adapted to strengthen Indian metro system PPPs and Hybrid Delivery Models.

7.1 Hong Kong MTR: Rail + Property Model for Sustainable Financing

International Insight.

The Hong Kong MTR demonstrates how integrated Rail + Property (R+P) development can provide stable, long-term financing for metro systems while keeping fares affordable. Revenues from commercial development around stations fund operations, system upgrades, and energy-efficient technologies.

Relevance to Sustainability.

Financial stability enables continuous investment in:

- renewable energy procurement,
- energy-efficient rolling stock,
- station retrofits, and
- transit-oriented development (TOD), which reduces urban sprawl and associated emissions.

Implementation in India.

Indian PPPs can adapt the R+P model by:

- Incorporating staged land-value capture clauses within concession agreements to reduce market risk.
- Creating joint public–private SPVs for station-area development, ensuring transparent revenue sharing.
- Using conservative valuation assumptions, reflecting lessons from Hyderabad's TOD revenue volatility.

This approach can provide stable, climate-aligned funding for metro operations.

7.2 Shenzhen Metro: Lifecycle Carbon Management and Renewable Energy Integration

International Insight.

Shenzhen's lifecycle carbon studies show that 70–80% of a metro's total emissions arise from electricity consumption, not construction. Accordingly, Shenzhen has prioritized renewable sourcing, depot electrification, carbon accounting, and energy-efficient operations.

Relevance to Sustainability.

This approach aligns directly with low-carbon mobility objectives and demonstrates that operational decarbonization requires clear, enforceable energy policies.

Implementation in India.

Indian metros can apply these practices by:

- Mandating minimum renewable procurement percentages in PPP contracts (e.g., solar/wind PPAs).
- Requiring annual tCO_2 avoided reporting, similar to international climate-finance guidelines.
- Integrating depot and station rooftop solar, following the successful example of Kochi Metro's ~51% solar share.
- Allowing concessionaires to access green bonds or concessional climate finance for renewable capex.

This ensures that metro operations support India's national net-zero 2070 goals.

7.3 Singapore and European Systems: Digital Interoperability and Predictive Maintenance

International Insight.

Singapore and many European metros have embedded digital technologies—such as open AFC/NCMC systems, predictive analytics, CBTC automation, and API-based integration—into their governance frameworks to improve energy efficiency, reliability, and multimodal connectivity.

Relevance to Sustainability.

Digital systems reduce energy consumption through optimized train control, lower maintenance emissions, and fewer operational disruptions.

Implementation in India.

To replicate these outcomes, Indian metro PPP agreements should:

- Require NCMC-compliant AFC, open APIs, and digital data-sharing to support multimodal journeys.
- Link concession payments to digital adoption milestones, including QR ticketing and integrated fare systems.

- Introduce KPIs for energy use per passenger-km, mean time between failures (MTBF), and automation readiness.
- Include provisions for predictive maintenance, aligning operator incentives with long-term asset health and energy savings.

These measures accelerate India's adoption of smart, low-carbon mobility technologies.

7.4 European Green Procurement: Solar Integration and Energy-Efficient Assets

International Insight.

European metros apply structured green procurement policies, including requirements for rooftop solar, low-carbon construction materials, and energy-efficient rolling stock. Such policies reduce lifecycle carbon emissions and stabilize long-term energy costs.

Relevance to Sustainability.

These practices directly support operational decarbonization and reduce reliance on fossil-fuel-based grids.

Implementation in India.

India can scale these practices nationally by:

- Requiring depot and station solar installations within PPP scopes of work.
- Allowing concessionaires to meet renewable obligations using PPAs or RECs.
- Setting minimum energy-efficiency criteria for rolling stock, signalling, and HVAC systems.
- Integrating green materials and low-carbon construction options into tender conditions.

Kochi Metro already illustrates the feasibility of this approach within an Indian context.

7.5 Synthesis: Integrating Global Sustainability Lessons into Indian PPP Design

Across global cases, a common principle emerges: Low-carbon outcomes occur only when sustainability requirements are explicitly written into metro contracts and institutional frameworks.

Key lessons for India include:

- Embedding carbon KPIs, renewable procurement targets, and energy-efficiency metrics into concession agreements.
- Using risk-balanced TOD/value capture to support long-term sustainable financing.

- Enforcing digital interoperability and predictive maintenance through performance-linked payments.
- Integrating green procurement and solar mandates into all project delivery models.

By adopting these strategies, India can strengthen PPP-led and public metro systems as catalysts for sustainable, low-carbon, and digitally integrated urban mobility.

8 Findings and Discussion

8.1 Carbon Reduction and Renewables

Metro systems can reduce per passenger emissions when compared to private ownership vehicles, but the magnitude of emissions reduction depends on energy sources and previous contractual obligations. For instance, Delhi Metro's documented modal shifts and avoided vehicle-km lend credence to emissions benefits when a metro experiences high ridership and exhibits a greater share of mode substitution from passengers moving from car use. Conversely, where the concession agreements specifically required the acquisition of renewable energy and where the operator invested in generation on site, the operational carbon footprint decreased at a faster rate. For example, Kochi Metro accepted approximately 51% of electricity from solar through rooftop and park installations as a result of explicit sustainability objectives embedded within the planning process and project financing, monetizing equity in green assets. In contrast, while some of the public projects implemented zero renewable key performance indicators the practices lagged on-site renewable generation, as procurement cycles and project negotiations inhibited implementation. Hence, by embedding renewable-procuring KPIs into the PPP concession agreements, operators can unlock green financing and achieve measurable emissions reductions in CO_2.

Key takeaway:
Including renewable energy procurement, accuracy of energy consumption data or reporting mechanisms for energy consumption and for total Carbon Dioxide emissions (tCO_2) into contracts under a Public Private Partnership (PPP) arrangement will greatly accelerate the decarbonization process and provide the PPP partner(s) the ability to take advantage of the green financing options.

8.2 Smart Mobility & Digital Interoperability

Digital ticketing, open AFC/NCMC interoperability, and integration with mobility-as-a-service (MaaS) provide huge operational efficiencies and superior user experiences. WRI India illustrates that digital public infrastructure and open e-platform designs enable 'scalable upgrades to take place across multiple modes'. For instance, Mumbai and Nagpur-these are states/metros where there is a strong private push for system upgrades-were able to realize rapid transitions to QR, contactless cards, and integrated fares only because procuring the AFC systems were flexible under the PPP or hybrid arrangements. In many public projects without any commercial partners, this process of

procurement and integration was slow due mainly to public procurement timelines, was not ideal, and there was little incentive for the developer. Thus, PPP contracts that mandate NCMC/interoperability and link milestones to payments lead to quicker smart mobility adoption.

8.3 Economic Sustainability, TOD Performance, and Modal Shift

The literature indicates that ridership tends to respond most significantly to travel time, reliability, and last-mile connectivity, and therefore the performance of transit-oriented development (TOD) and non-fare revenue mechanisms is closely linked with modal shift outcomes. For example, the Delhi Metro's considerable mode shift and reduction in vehicle-km are fundamentally tied to extensive network reach and high service quality, while a similar experience was observed in the property arm of the Delhi Metro Rail Corporation (DMRC), a publicly led commercialization model, where good outcomes were found when public asset management is proactive. Value capture and TOD are often considered key sources of non-fare revenue that stabilize project funding, as demonstrated through the Hyderabad public–private partnership (PPP), where private partners were allowed to monetize real estate and retail at stations, leading to significant non-fare revenue opportunities. The Hyderabad PPP was also successful in delivering shelf-like network corridors quickly while improving accessibility and attracting riders; however, the concession was sensitive to land-market cycles because projected revenues were dependent on opportunity development (TOD) revenue. In contrast, fully public projects—particularly those without strong commercialization arms for property surrounding transit stations—have the potential to under-utilize station areas, thereby limiting revenue generation and weakening incentives to expand last-mile services that could otherwise support future ridership growth. The most significant distinction lies in execution capability: private concessionaires can deliver a greater degree of commercial service and raise capital in advance for integrated property development, whereas public agencies often do not deliver at the same pace or possess comparable marketing capabilities. At the same time, private-sector commercialization increases exposure to land-market risk, as purposefully optimistic forecasts or downturns in land-market conditions can financially distress concessions, as highlighted in several PPP case studies. Therefore, it is evident that PPPs that combine service-quality KPIs with realistic revenue frameworks, staged income triggers, and clear public controls over affordable access can realize private-sector efficiencies in marketing and leasing, achieve higher non-fare revenues than comparable non-PPP projects, and drive greater and more sustainable modal shift. Conversely, when revenue assumptions are optimistic and land-use policy is unsupportive, PPPs can fail or require bailouts, a conclusion consistent with the World Bank's review of PPP projects and critiques of the Hyderabad project.

Key takeaway:
Economic sustainability is at its strongest when contracts are based on realistic expectations through the development of TODs and supporting last-mile service delivery provisions and supporting the diversification of non-fare revenues for reinvestment into green mobility initiatives.

8.4 Automation, Predictive Maintenance and Digital Innovation

Automation (CBTC/ATO) and predictive maintenance reduce headways, energy use, and life-cycle costs. Studies show energy savings from operations automation and efficient control strategies. PPP concessions, through performance incentives and access to private IT/maintenance vendors, often adopt such technologies faster than purely public bodies: Hyderabad and Mumbai phases implemented digital maintenance and CBTC upgrades under PPP/hybrid arrangements, while some public projects took longer to budget and procure such systems. Linking contractual bonuses to availability and energy-efficiency metrics accelerates adoption of digital innovations.

Key takeaway:
Digital interoperability and automation should be treated as a requirement of performance, not an optional upgrade.

8.5 Rural–urban/ regional connectivity: the RRTS example

Large regional projects-such as the Delhi-Meerut RRTS-already provide measurable travel-time and peri-urban access benefits and are rapidly integrating renewable power at scale through rooftop solar and depot panels, as documented for example in ADB and the project EIA documentation. For regional systems where land and revenue markets are different from those in the inner city, PPP models, which incorporate a joint provision of land by the public and private sector coupled with private operations, can work well. However, such models must explicitly spell out regional affordability obligations (or lack of exclusion) as part of the agreed regional integration obligations if accessibility by all groups in the regional region is to be ensured.

Key takeaway:
India's most resilient governance approach is likely to be the conditional hybrid model, where PPPs are employed for the more innovative, capital-heavy or digital-focused elements, while public agencies take the lead with respect to the equity, affordability and regional access component.

8.6 Cross-cutting synthesis: when PPPs beat non-PPP

Instances where public-private partnerships (PPPs) excel versus non-PPPs: they are typically faster to procure digital/automation systems; they use commercial management for transit-oriented development (TOD) and retail in the system; they more aggressively procure renewable energy if the funding is a secured green finance mechanism; and they deliver contactless ticketing faster if it is specified under the concession agreement. Examples of PPP that demonstrate this position or capability include Hyderabad (quick service delivery under service, but some TOD commercialization forecasts were risky) and Kochi (proportion of strong renewable share due to sustainability planning).

Occurrences where non-PPP can be equally competitive or superior to PPP: established public agencies that integrated property and can credibly prioritize fiscal oversight and

public interest over focused commercial interests (policy framing), ex: DMRC in Delhi; and public agencies gain realizable additional social interest benefits in service delivery, (lower fares, equity agenda), if they retain sufficient capacity, and political will.

PPPs (Project Delivery and Public Procurement) are not always better. PPPs are good in contracts that: (a) involve significant revenue concepts and they are feasible and practical; (b) involve payments for performance based upon measurable KPIs (e.g., carbon, uptime, and digital adoption), (c) provide for procurement to be innovative; and (d) provide various public interest protections with regard to land use and affordability. If any of these features are not present in the contract, a public model that is not a PPP but considers public structures with capacity can be good.

9 Conclusion

In this research, it is evident that PPPs, when implemented correctly in the development of metro rail systems in India, will provide more favourable outcomes than traditional public delivery methods provided that the contract between the two parties aligns the financial incentives of the private sector with the long-term social sustainability goals of the public sector. In fact, properly structured PPPs have a significantly higher potential to reduce carbon emissions, incorporate smart mobility technology, provide for innovative solutions to existing public-sector problems and create opportunities for revenue diversification. The success of Indian metros largely depend on the governance design and institutional capacity rather than ownership.

The success of Hyderabad Metro demonstrates the potential for commercialisation, while Kochi Metro shows that a structured sustainability mandate in the public sector can deliver exceptional results. Delhi Metro demonstrates that the operation and continual development of metro rail systems can achieve equal benefits to those achieved by PPPs through a robustly built and appropriately commercialized public institution.

Findings suggest that PPPs are most effective when there is increased transparency in the sharing of risks, the inclusion of realistic demand assumptions, and clearly defined performance indicators. When poorly structured, PPPs may suffer from revenue stress or social equity challenges, as seen in global and national cases. Thus, the most viable avenue for the future governance of metro rail systems in India would be a hybrid model that combines public-sector accountability, private-sector innovation, financing and digital technologies in equal measure.

Integrating carbon KPIs into concession agreements, along with phased automation targets, digital interoperability requirements and green finance mechanisms is essential to ensure the long-term sustainability of metro projects in India. Drawing upon global best practices for metro PPPs such as Hong Kong's value-capture model, Shenzhen's low-carbon procurement framework and European predictive maintenance systems, India can further enhance the metro PPP frameworks. Ultimately, metro PPPs must not only be treated as financing instruments but also as governance tools that align with

sustainability and inclusion goals, and will enable the transformation of Indian metro systems into an important driver of low-carbon urban development, thereby supporting India's ambition to achieve net-zero emissions by 2070.

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