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Techno-Thermal Analysis and Performance Optimization of Electric Bus Battery Systems under Extreme Ambient Conditions- Key Findings

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Abstract: *Business-as-usual approaches based on proprietary vendor technologies, lock in inefficiencies and make integrating and upgrading systems harder. Traditional bus operations depend on various systems, such as those for Vehicle Location and Tracking (VLT), Automatic Fare Collection (AFC), and fleet management. E-buses require new services for energy management, battery health, charging schedules, and power purchase contracts. If standards for exchanging information are not clear, if each vendor must develop its own proprietary solutions, with no opportunity to share, and integrate these, costs for technology and upgrades will be far higher than necessary. Transformative outcomes seen in India's DPI efforts come from careful planning. In identity, banking, payments, e-commerce, and healthcare, these outcomes were not simply the result of isolated technological solutions but stemmed from a systemic approach that focused on creating foundational digital building blocks that were available to the ecosystem. In this case, ecosystem refers to a complex network of actors and their services that interact with and rely upon others to function effectively. The small interventions that created these building blocks allowed different actors in the ecosystem, both public and private, to innovate and create scalable solutions, proving that doing less can, in fact, achieve more. By rethinking the bus sector through the DPI model, we can envision a core framework that integrates technology architecture, governance, and market driven innovation.*

Keywords: *market driven innovation*

I. INTRODUCTION

Buses play a vital role in India's transportation system, serving millions of passengers daily across urban and rural areas. As part of a broader strategy to reduce emissions and improve passenger services, India plans to electrify up to 800,000 buses over the next seven years, a transition involving public, private and institutional fleet operators. The government is creating policies and partnerships that aim to reimagine contracting and operating models for buses. The transition from internal combustion engines (ICE) to EVs poses both opportunities and challenges in the complex bus transportation system. It will require an approach that can manage the added complexities of batteries replacing ICE, charging stations replacing fuel pumps, and renewable energy replacing conventional fuels. In addition, current bus operations and maintenance systems were designed in isolation from one another. They are not integrated in ways that support communication across stakeholders—passengers, operators, manufacturers, financiers, and regulators. This disjointed setup results in delays and higher operational costs and hinders the cost-effective and sustainable deployment of EV buses at scale. Two key challenges impede progress

Objective

The primary objective of this working paper is to identify key challenges and opportunities in extending DPI principles to e-bus transition and adoption. It proposes a new blueprint for designing e-bus service platforms based on DPI principles and referred to as the open e-bus blueprint (see Digital Public Infrastructure—An Approach to Population-Scale Complex Problems) that addresses major challenges in transit operations and service. We invite stakeholder

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comments and consultations on strategic and functional considerations for designing this technology blueprint. Its implementation roadmap are designed to stimulate discussion rather than present final recommendations. WRI India and the Foundation for Interoperability in Digital Economy (FIDE) understand that there might still be gaps with respect to practical implementation.

Approach for developing this working paper

This working paper employs a qualitative research methodology, combining unstructured interviews with a comprehensive review of secondary literature. A review of the academic literature, government consultation papers, think-tank reports, articles, and blogs were conducted with focus on the following: 1. Technology implementation challenges in public transport and corresponding policy recommendations. 2. Systemic issues with current technology deployments in Indian public transport agencies. 3. DPI implementation experiences in other sectors. 4. DPI principles and architectural considerations derived from diverse sectoral applications. To ensure data reliability and credibility, we focused primarily on English national dailies and reputable think-tank blogs to illustrate real-world examples of challenges and successes

Key findings

Business-as-usual approaches based on proprietary vendor technologies, lock in inefficiencies and make integrating and upgrading systems harder. Traditional bus operations depend on various systems, such as those for Vehicle Location and Tracking (VLT), Automatic Fare Collection (AFC), and fleet management. E-buses require new services for energy management, battery health, charging schedules, and power purchase contracts. If standards for exchanging information are not clear, if each vendor must develop its own proprietary solutions, with no opportunity to share, and integrate these, costs for technology and upgrades will be far higher than necessary. Transformative outcomes seen in India's DPI efforts come from careful planning. In identity, banking, payments, e-commerce, and healthcare, these outcomes were not simply the result of isolated technological solutions but stemmed from a systemic approach that focused on creating foundational digital building blocks that were available to the ecosystem. In this case, ecosystem refers to a complex network of actors and their services that interact with and rely upon others to function effectively. The small interventions that created these building blocks allowed different actors in the ecosystem, both public and private, to innovate and create scalable solutions

Problem of standards

Standardizing information flow for bus operations has not been a priority in India. Traditionally, bus systems have come up with a patchwork of solutions to manage operational data (route network, passenger count, schedules, stops) and passenger information (Real-time data, PIS boards, timetable, etc.) This fragmented landscape creates the following problems: Larger bus agencies or fleet owners: These often rely on proprietary systems tailored to specific needs, where hardware and software are bundled together, allowing vendors to impose proprietary protocols and operations and management contracts. The absence of standards leads to a lack of interoperability within and outside the agency, resulting in vendor lock-in (Bachu, Roy, and Roychowdhury 2024).

Planning inefficiencies: Due to limited observability of bus performance, bus operators cannot estimate charging infrastructure requirements. This constrains service coverage and route planning, leading to inefficient resource allocation and underutilization of e-buses. In Nagpur, for example, 34 percent of the electric bus fleet remained idle due to a lack of charging stations (Chakraborty 2024). ▪ Scheduling inefficiencies: Without consistent information exchange on bus tracking, crew and bus schedules, passenger counts and network information, route planning and scheduling becomes cumbersome and potentially inefficient. ▪ Gaps in passenger information: Inconsistent data formats block a unified view of bus operations, hindering resource allocation and smooth service. Passengers experience this in Delhi, where one of the operators, DIMTS' proprietary application Poocho (offering real-time information for cluster buses) is unable to integrate with another operator, Delhi Transport Corporation's systems, leaving most buses with static route

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and schedule data that may not be up to date (Abisla 2019). ▪ Stifling of innovative models and sustainability: Observability extends beyond data—it's about fostering innovation and sustainability by enabling policy interventions that leverage digital infrastructure within the transportation network. For instance, in Telangana, repurposing school buses for passenger transport faced roadblocks as there was no system in place to assess and adjust risk for such a unique use case, which made it challenging for insurers to justify lower insurance premiums for buses used as passenger vehicles during off-hours (The Times of India 2019). Poor visibility in public-private partnerships in bus operations such as leasing buses on a gross cost contract (GCC)6 or net cost contract (NCC)7 —where agencies partner with private operators to manage and maintain buses—causes friction between public agencies, operators, and other stakeholders in the following (Kharwal and Khandelwal 2021): ▪ Managing contracts and service levels. This requires strong contract management and performance monitoring systems in place to ensure timely payments, service quality, and compliance with contractual obligations. Poor visibility and data validation have led to significant friction between bus operators and agencies, resulting in disputes and service disruptions. ▪ Bankability. Lack of clear, real-time data on bus operations, payment statuses, and contract compliance prevents creditors from accurately assessing performance and risks, which diminishes investor confidence in bus operators, limiting the flow of capital into the bus sector. ▪ Financing challenges in e-buses. Without accurate data, the financial viability of e-bus investments remains uncertain, deterring potential investors and slowing the adoption of e-buses. Investors require reliable data on asset quality, particularly battery performance and degradation, to assess risk and make informed decisions. This data gap hinders understanding of total cost of ownership (TCO), operational efficiency, and repayment ability. For instance, research points out that a 20 percent reduction in battery life can increase TCO by 2.2 percent. This effect is magnified as reduced battery range (10-30 percent decrease) leads to further TCO increases of 13-30 percent. These figures can vary significantly across geographies due to differences in climate, terrain, and usage patterns. However, without realworld data on battery performance, investors can't predict future maintenance costs or battery lifespan. This uncertainty discourages investment, even when it might be financially viable, because the risk of unexpected costs remains too high (Vijaykumar et al. 2020).

II. CONCLUSION

The transition to e-buses presents a pivotal opportunity to transform India's public transportation. As the country targets electrifying 800,000 buses over the next decade, the current fragmented bus ecosystem creates inefficiencies and increases operational costs, limiting the scalability of e-bus deployment and infrastructure. Addressing these challenges will require more than isolated technological fixes. Our proposed alternative is a robust, foundational digital infrastructure. The open e-bus blueprint, rooted in Digital Public Infrastructure (DPI) principles, provides a sustainable approach to technology integration and scalable solutions. Inspired by India's DPI successes, this blueprint emphasizes reusable digital building blocks that reduce core infrastructure investment while enabling significant improvements in efficiency and cost reduction. By "doing less," we can achieve a large-scale impact, driving reach and inclusivity across the bus ecosystem. This approach allows bus operators, OEMs, CPOs, financial institutions, and technology service providers to innovate collaboratively, offering choice and flexibility for future solutions while minimizing the risks tied to proprietary systems.

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