

Designing Digital States through DPI: A Comparative Analysis of India Stack and Estonia's X-Road

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Abstract

Digital Public Infrastructure (DPI) has emerged as a foundational approach to digital state-building by enabling interoperable, secure, and scalable public services. This paper compares two prominent DPI models: India Stack and Estonia's X-Road. Through a comparative analysis of their technical architecture, governance frameworks, functional scope, and developmental outcomes, the study highlights contrasting pathways to digital transformation. India Stack emphasises scale, financial inclusion, and ecosystem innovation through modular digital rails, while Estonia's X-Road prioritises secure interoperability, legal coherence, and citizen trust. The findings demonstrate that effective DPI design is context-dependent, requiring alignment with institutional capacity, demographic scale, governance priorities, and public value objectives.

Introduction

Digital technologies have become ubiquitous in the twenty-first century, fundamentally reshaping how states, markets, and societies operate (Desai & Manoharan, 2024). Governments worldwide are increasingly prioritising the digital transformation of public services to enhance administrative efficiency, increase transparency, and foster inclusive economic growth (Dunleavy et al., 2006; Desai et al., 2023). Digital transformation, understood as a broad socioeconomic change driven by the adoption and use of digital technologies across institutions and ecosystems (Dąbrowska et al., 2022), has progressed beyond the mere digitisation of services to include integrated identity systems, real-time payment platforms, interoperable data exchange frameworks, and consent-based data governance structures.

This shift reflects a transformation in public administration from traditional e-government towards more integrated models, including digital government, mobile government, ubiquitous government, and smart governance (Manoharan & Ingrams, 2018). Digital transformation is not purely technological; it is fundamentally socio-technical, requiring coordination among regulatory institutions, private innovators, and citizens (Van Veldhoven & Vanthienen, 2021). Increasingly, digital solutions are provided either as digital public goods governed by the state or as digital private goods driven by market actors, raising new questions about ownership, accountability, and public value (Eaves et al., 2024; Mazzucato et al., 2024).

Until recently, public and private spheres in digital governance were often conceptualised as largely separate domains. However, emerging models of Digital Public Infrastructure (DPI) challenge this dichotomy by treating digital capabilities such as identity, payments, and data exchange as foundational, society-wide infrastructure. Instead of choosing between state control and market-led innovation, some countries now use hybrid approaches, blending publicly governed digital platforms with private-sector innovation, prompting important questions about scale, governance, inclusion, trust, and economic effects.

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This paper explores two influential approaches to DPI that have attracted global focus: India's India Stack, a modular DPI framework integrating digital identity, payments, and consent-based data sharing; and Estonia's e-government system centred on X-Road, a secure and interoperable data exchange platform. Although both nations are widely recognised for their digital governance, they differ markedly in scale, institutional structure, regulatory consistency, and innovation focus.

Against this backdrop, this paper poses two research questions:

RQ1: *How do India Stack and Estonia's X-Road differ in their architectural design, governance logic, and developmental outcomes?*

RQ2: *Under what institutional, demographic, and economic conditions is each model more suitable?*

By comparing these two models, the study broadens the ongoing debates on digital public infrastructure beyond just the public-private divide. It introduces an analytical framework that examines how factors such as scale, trust, regulatory consistency, and innovation ecosystems influence the results of digital transformation. As a result, the paper offers practical insights for policymakers seeking to design digital systems that balance inclusion, efficiency, security, and democratic legitimacy.

As governments become more interconnected, it is crucial to analyse how various regions adopt and implement digital government, considering both technological and administrative aspects. A global comparison allows scholars and practitioners to assess cross-national patterns and identify best practices across different e-government dimensions. In this regard, India's India Stack and Estonia's X-Road are recognised as effective yet contrasting models of digital public infrastructure, frequently cited as global benchmarks. This paper compares these two models to demonstrate how scale, institutional capacity, and governance influence the design, dissemination, and outcomes of DPI, and to explore the conditions under which different architectural approaches are most suitable for various countries.

India Stack

India Stack represents one of the most comprehensive DPI initiatives globally, designed to address the challenges of scale, heterogeneity, and financial exclusion in a population exceeding 1.4 billion. Rather than building a single monolithic e-government system, India developed a modular and layered architecture that integrates digital identity, paperless verification, interoperable payments, and consent-based data sharing (Carrière-Swallow et al., 2021; D'Silva et al., 2019). The core layers comprise presence-less identity (Aadhaar), paperless verification (e-KYC), cashless payments (Unified Payments Interface – UPI), and consent-based data exchange (Account Aggregator framework).

The Aadhaar identity layer provides a biometrically linked digital identity that enables remote authentication and reduces onboarding costs for financial and welfare services (Desai et al., 2023). Aadhaar-based e-KYC further lowers compliance costs by allowing institutions to verify identity electronically, significantly reducing the time and resources needed to open bank accounts and access formal finance (D'Silva et al., 2019). This foundation underpins the Jan Dhan–Aadhaar–Mobile (JAM) trinity, which has facilitated rapid expansion of financial

inclusion through large-scale account opening and direct benefit transfers. The payments layer, UPI, has transformed India's retail payments ecosystem by enabling real-time, interoperable, low-cost digital transactions across banks and fintech applications. UPI's open architecture allows banks and fintech firms to build user-facing applications while maintaining settlement through regulated banking channels. The resulting surge in digital transactions has expanded the digital footprint of individuals and micro-enterprises, supporting alternative credit scoring and improved access to formal finance (Desai & Manoharan, 2024).

More recently, the Account Aggregator framework introduced consent-based financial data sharing, empowering individuals to control how their financial data is accessed and shared across institutions. By standardising consent, sharing, and portability of financial information, this framework strengthens user agency while catalysing innovation in digital lending, wealth management, and other financial services. (Desai et al., 2023). Empirical evidence suggests that well-designed digital payments and data infrastructure can stimulate credit growth and financial inclusion, contributing to broader economic formalisation and poverty reduction (Chakravarty & Pal, 2013; Jeanneney & Kpodar, 2011).

India Stack thus represents a hybrid governance model where publicly governed digital rails are combined with private-sector innovation. While concerns persist regarding privacy, data protection, regulatory fragmentation, and the persistence of the digital divide, India Stack demonstrates how modular DPI can generate scale, inclusion, and ecosystem dynamism in large and diverse economies.

Estonia's X-Road

Estonia's digital transformation is anchored in X-Road, a secure and decentralised data exchange layer that underpins the country's e-government ecosystem. Following independence in 1991, Estonia prioritised digital governance as a nation-building strategy, embedding technological innovation within a coherent legal and institutional framework that prioritised security, transparency, and citizen trust (World Bank, 2016; Dunleavy et al., 2006). X-Road, launched in the early 2000s, enables secure, encrypted, and authenticated data exchange between distributed public and private databases without centralising data storage (World Bank, 2016).

Instead of large-scale biometric identity systems, Estonia relies on a cryptographic digital identity infrastructure built around secure electronic ID cards and related authentication mechanisms. Citizens verify their identities and sign legally binding documents using secure electronic ID cards. This feature has been enabled by robust legislation, such as the Digital Signatures Act (2000) and the Public Information Act (2001), which established clear legal frameworks for electronic authentication and data access, thereby enhancing institutional trust and accountability (World Bank, 2016). This legal foundation reflects key principles of digital-era governance, emphasising integration, transparency, and accountability (Dunleavy et al., 2006).

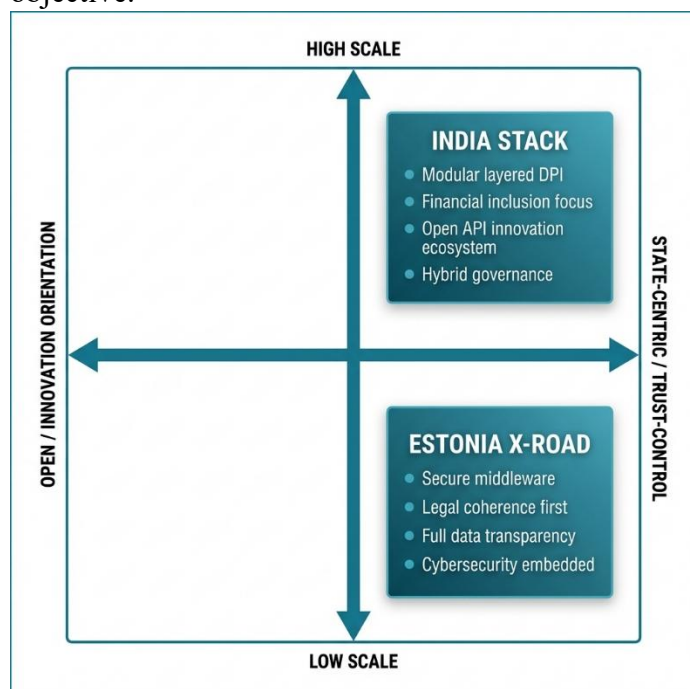
X-Road serves as middleware that enables seamless data exchange among ministries, agencies, and private-sector entities. Data remains stored at the original institutions, but each transaction is digitally signed, encrypted, and logged. Citizens can track who accessed their data, increasing transparency and trust (World Bank, 2016). Security and cyber resilience are fundamental to Estonia's system, aligning with broader frameworks that emphasise the socio-technical dimensions of digital transformation (Van Veldhoven & Vanthienen, 2021).

Nearly all public services in Estonia – around 99 percent - are accessible online, with only a few services requiring in-person interaction. This high degree of digitalisation generates substantial administrative efficiency, with estimated annual savings of about 2 per cent of GDP (World Bank, 2016). Estonia’s experience shows how a small, digitally literate country can achieve near-total digitalisation by focusing on interoperability, legal consistency, and citizen trust. Although this approach might be challenging for larger, more diverse societies to replicate, it sets a standard for secure, deeply embedded digital governance.

Comparing India Stack with X-Road

The comparative analysis of India Stack and Estonia’s X-Road reveals two distinct models of DPI shaped by differences in scale, institutional capacity, and governance philosophy (see Table 1). Technically, India Stack employs a modular, layered architecture designed for extreme scalability. It integrates identity, payments, and consent-based data sharing as interoperable “digital rails” for innovation by public and private actors. Its design emphasises high transaction volumes and ecosystem expansion. In contrast, Estonia’s X-Road prioritises secure interoperability rather than layered service expansion. It operates as decentralised middleware that connects distributed databases, embedding encryption, digital signatures, and transaction logging at its core. The Estonian model optimises reliability, integrity, and cybersecurity at scale.

Functionally, India Stack extends beyond administrative efficiency to support market enablement and financial inclusion. It has catalysed digital payments, fintech growth, and the development of alternative credit-scoring mechanisms. Estonia’s system, while highly advanced, is primarily oriented toward seamless public service delivery, administrative integration, and citizen-centric access to information. Financial innovation is not its central objective.



From a regulatory and governance perspective, India represents a hybrid model combining public digital infrastructure with private-layer innovation. However, its legal

environment is distributed across multiple regulators and evolving privacy frameworks. Estonia, by contrast, embedded digital governance within a cohesive legal architecture early in its transformation process. Trust in Estonia is institutionally reinforced through legal clarity, citizen data visibility, and cybersecurity integration. In terms of impact, India demonstrates large absolute economic effects by expanding financial access and reducing transaction costs, and formalising previously informal economic activity, although challenges related to inequality and rights protections remain. Estonia demonstrates high proportional gains in administrative efficiency and public trust. The two systems, therefore, create public value through different pathways: India through inclusion and market dynamism; Estonia through institutional coherence and transparency.

Table 1: India Stack and Estonia – X-Road

Main Dimension	Sub-Dimension	India Stack	Estonia – X-Road
Technical Architecture	System Design	Modular, layered Digital Public Infrastructure (Identity, e-KYC, Payments, Consent)	Decentralised middleware connecting distributed databases
	Data Storage Model	Federated but functionally layered; some centralised elements (e.g., Aadhaar database)	Fully decentralised data ownership; no central data repository
	Interoperability Mechanism	API-driven interoperability across sectors	Protocol-based secure data exchange via X-Road
	Authentication Method	Biometric + OTP-based authentication	Cryptographic digital certificates (e-ID)
	Cybersecurity Model	Regulator-driven, evolving sectoral safeguards	Embedded encryption, digital signatures and full transaction logging
	Core Services	Identity, payments, KYC, consent-based financial data sharing	Secure data exchange across all government services
	Financial Inclusion Role	Strong focus on banking, payments and credit expansion	Limited direct financial inclusion function
Functional Scope	Citizen Interface	Multiple private apps built on public rails	Unified e-government services via secure login
	Legal Framework	Fragmented across the IT Act, DPDP Act and RBI regulations	Early integrated digital legislation (Digital Signatures Act, Public Information Act)
	Data Governance Philosophy	Consent-based model evolving (Account Aggregator framework)	Built-in transparency; citizens can track data access

Main Dimension	Sub-Dimension	India Stack	Estonia – X-Road
	Institutional Coordination	Multi-regulator ecosystem (UIDAI, NPCI, RBI, MeitY)	Centralised coordination with strong state oversight
	Trust Model	Built through scale and usability, privacy debates are ongoing	Built through legal clarity, transparency, and cybersecurity
	Market Development	Strong fintech ecosystem growth	Administrative optimisation; limited market-layer expansion
	Social Inclusion	Focus on unbanked, MSMEs, and low-income groups	Universal service access in digitally literate society
Replicability & Transferability	Suitability by Country Size	Highly suited to large, diverse, developing economies	Best suited to small, high-capacity states

With respect to replicability, India’s modular DPI is better suited to large, developing, and heterogeneous economies seeking rapid inclusion and ecosystem growth. Estonia’s model is most effective in smaller, high-capacity states where institutional trust and legal coherence are already strong. Neither model is universally applicable; each reflects contextual trade-offs between scale and control, innovation and trust(Refer to Figure 1)

Conclusion and Policy Implications

The comparison between India Stack and Estonia’s X-Road demonstrates that digital transformation is not governed by a single universal blueprint but is shaped by national objectives, institutional capacity, and socio-economic context (Dąbrowska et al., 2022; Desai et al., 2023). Both systems represent effective models of DPI, yet they generate public value through different pathways. India Stack emerged from the developmental imperative of financial inclusion and economic formalisation at a very large scale (Carrière-Swallow et al., 2021; D’Silva et al., 2019). Its modular architecture—integrating digital identity, interoperable payments, and consent-based data sharing—prioritises scalability, openness, and ecosystem innovation. Public digital rails such as Aadhaar and UPI reduce transaction costs and enable extensive private participation, expanding credit access and market dynamism (Desai & Manoharan, 2024). This hybrid governance approach links inclusion with innovation, demonstrating how state-built infrastructure can catalyse competitive private ecosystems (Desai et al., 2023).

Estonia’s X-Road, in contrast, was conceived as a state-building instrument anchored in legal coherence and cybersecurity (World Bank, 2016). Its decentralised interoperability framework emphasises secure data exchange, transparency, and institutional trust. Early legislative embedding and digital signatures formalised accountability and enhanced administrative efficiency (Dunleavy et al., 2006). The Estonian model illustrates how tightly

integrated legal and technical design can sustain high levels of citizen trust and deep penetration of digital services. The divergence between the two systems underscores a central policy lesson: architecture must follow an objective. Large, diverse economies may benefit from modular, innovation-driven DPI that enables rapid scale and ecosystem participation. Smaller, high-capacity states may instead prioritize legally embedded interoperability and cybersecurity to reinforce trust and administrative coherence. Policymakers should therefore align DPI design choices with demographic scale, institutional maturity, and governance priorities.

Future digital governance strategies are likely to combine elements of both approaches—integrating India’s focus on scalability and ecosystem innovation with Estonia’s emphasis on legal coherence, transparency, and security. Ultimately, successful digital transformation depends less on replicating specific technologies but more on institutional alignment, regulatory foresight, and sustained public legitimacy.

References

- Carriere-Swallow, Mr Yan, Mr Vikram Haksar, and Manasa Patnam. (2021). *India’s approach to open banking: some implications for financial inclusion*. International Monetary Fund, 2021.
- Chakravarty, S. R., & Pal, R. (2013). Financial inclusion in India: An axiomatic approach. *Journal of Policy Modeling*, 35(5), 813-837. <https://doi.org/10.1016/j.jpolmod.2012.12.007>
- Dąbrowska, J., Almpantopoulou, A., Brem, A., Chesbrough, H., Cucino, V., DiMinin, A., Giones, F., Hakala, H., Marullo, C., Mention, A.-L., Mortara, L., Nørskov, S., Nylund, P. A., Oddo, C. M., Radziwon, A., & Ritala, P. (2022). Digital transformation, for better or worse: A critical multi-level research agenda. *R&D Management*, 52(5), 930–954. <https://doi.org/10.1111/radm.12531>
- Desai, A., Manoharan, A. P., Jayanth, S. S., & Zack, S. (2024). Public Value Creation Through Combined Consumption of Multiple Public Services – Case of India Stack. *International Journal of Public Administration*, 47(9), 600–611. <https://doi.org/10.1080/01900692.2023.2243401>
- D’Silva, D., Filková, Z., Packer, F., & Tiwari, S. (2019). The design of digital financial infrastructure: lessons from India. *BIS paper*, (106).
- Dunleavy, P., Margetts, H., Bastow, S., & Tinkler, J. (2006). New public management is dead— long live digital-era governance. *Journal of public administration research and theory*, 16(3), 467-494.
- Jeanneney, S. G., & Kpodar, K. (2011). Financial development and poverty reduction: Can there be a benefit without a cost? *Journal of Development Studies*, 47(1), 143–163. <https://doi.org/10.1080/00220388.2010.506918>
- Manoharan, A. P., & Ingrams, A. (2018). Conceptualizing E-Government from Local Government Perspectives. *State and Local Government Review*, 50(1), 56-66. <https://doi.org/10.1177/0160323X18763964>
- Mazzucato, M., Eaves, D., & Vasconcellos, B. (2024). Digital public infrastructure and public value: What is ‘public’ about DPI?.(Working Paper Series (IIPP WP) 2024-05). UCL Institute for Innovation and Public Purpose: London, UK.
- Van Veldhoven, Z., Vanthienen, J. Digital transformation as an interaction-driven perspective between business, society, and technology. *Electron Markets* 32, 629–644 (2022). <https://doi.org/10.1007/s12525-021-00464-5>



World Bank Group. (2016). *World Development Report 2016: Digital Dividends*. World Bank Publications.