IPIC 2026 12th International Physical Internet Conference June 8-10, 2026 | Bordeaux, FRANCE
alice Alliance for Logistics Innovation through Collaboration in Europe

From Fragmented Digitalization to Physical Internet Coordination: Achieving Concrete Data Interoperability

Liz Araceli Cristaldo[1] and Marion Cottet [1]

1. Alliance for Logistics Innovation through Collaboration in Europe (ALICE), Bruxelles, Belgium

Corresponding author: marion.cottet@etp-alice.eu

Abstract: *Data interoperability is essential for coordination in urban mobility and logistics systems in Europe, yet in practice, data remains difficult to share and reuse across actors, systems and platforms. Despite extensive policy efforts and numerous initiatives, data interoperability remains fragmented, limiting effective coordination between transport systems. This paper explores this challenge through the lens of the Physical Internet, which emphasizes standardized and interconnected systems to enable coordinated logistics networks. Based on a combined review of European policies, standards, and data space initiatives, complemented by an exploratory survey of practitioners, the paper identifies persistent gaps across technical, semantic, governance, and operational dimensions. The results show that interoperability challenges are not primarily due to a lack of solutions, but to misalignment across these dimensions, reflected in inconsistent data definitions, unclear governance rules, and limited reuse of data models and APIs. Based on these findings, the paper highlights priority areas for action to better align data interoperability efforts with Physical Internet principles and support more coordinated and scalable urban mobility and logistics systems.*

Keywords: *Data interoperability, European Data Spaces, Urban, Logistics, Mobility, Standardization, Physical Internet.*

1 Introduction

Mobility and logistics systems involve numerous organizations and stakeholders whose operations increasingly rely on digital information exchange and data-driven processes (Pan et al., 2021). In this context, the ability to generate, exchange, interpret, and reuse data across organizational and territorial boundaries, referred to here as *data interoperability*, becomes essential for coordinating urban mobility and logistics systems.

At the same time, European urban mobility and logistics systems face growing pressure to become more sustainable, efficient and resilient. Policy frameworks emphasize the role of data in supporting decision-making, improving performance monitoring, and addressing the diverse and often conflicting needs of stakeholders, while simultaneously supporting the achievement of multiple local policy goals. However, despite these ambitions, effective data sharing between public and private actors remains difficult to implement, limiting the use and reuse of available data (Expert Group for Urban Mobility, 2024). Existing data ecosystems remain fragmented, with heterogeneous data models, and developed through systems that do not communicate effectively with each other (Delaplace, 2024).

In parallel, the Physical Internet (PI) has emerged as a paradigm for coordinating mobility and logistics through standardized units, shared interfaces, and open protocols, enabling seamless interaction between actors and systems (Montreuil, 2011; Wu et al., 2025). More recent research highlights that PI evolves as a cyber-physical paradigm, requiring close integration between physical flows and digital information layers (Crainic and Montreuil, 2016; Wu et al., 2025).

From this perspective, without the ability to consistently share and reuse data across actors and systems, coordination in European urban mobility and logistics remains limited and cannot scale.

Against this background, this paper addresses the following research question: *how are data interoperability frameworks experienced in practice by European mobility and logistics stakeholders, and how do these challenges affect the realization of Physical Internet?*

To answer this question, an analysis incorporating practitioner perspectives is conducted to identify which interoperability barriers are perceived in practice as most critical for enabling coordination across actors, transport modes, and territories. The results provide a basis for prioritizing actions toward more operational and scalable data interoperability frameworks in the European context.

The remainder of this paper is structured as follows. Section 2 introduces the PI perspective on data and standardization. Section 3 reviews European policy, standardization, and data space landscape. Section 4 presents practitioner perspectives to assess and prioritize the main data interoperability gaps. Finally, Section 5 discusses these findings' implications, concludes this paper, and outlines directions for future research.

2 The Physical Internet Perspective on Data Interoperability

The PI provides a conceptual framework for coordinating logistics and mobility systems by drawing inspiration from the architecture of the Digital Internet (Montreuil, 2011; Wu et al., 2025). It proposes a shift from fragmented and vertically integrated transport systems toward an open, distributed, and interconnected network, where flows can move seamlessly across infrastructures and service providers. The objective is to improve efficiency, sustainability, and resilience by enabling greater consolidation, sharing of resources, and coordination across actors (Montreuil, 2011).

A central principle of PI is modularity. Goods are encapsulated into standardized, modular units that can be handled and routed across different networks and operators (Crainic and Montreuil, 2016; Montreuil, 2011). This modular structure allows physical flows to become independent from specific carriers or infrastructures, enabling flexible and dynamic routing across a network of interconnected services. However, achieving such flexibility requires more than physical standardization.

PI also relies on standardized interfaces and protocols, like those of the Digital Internet, enabling independent actors to interact within a common system without requiring centralized control. In this context, coordination emerges from the ability of these actors to exchange information and align their operations based on common rules and communication mechanisms. As a result, PI is increasingly understood as a cyber-physical paradigm, where digital information flows synchronize physical operations across actors, locations, and time scales (Wu et al., 2025).

Within this paradigm, digital systems support routing decisions, coordinate operations, and enable collaboration across actors. These functions depend on the ability of information systems to exchange, interpret, and reuse data across organizational and technical boundaries (Crainic and Montreuil, 2016; Wu et al., 2025). As a result, data interoperability becomes a core coordination layer of PI-enabled systems, particularly in urban mobility and logistics systems, where multiple transport modes, operators, and services coexist and interact within the same physical space.

In such environments, effective coordination relies on the ability of independent systems to exchange data through standardized formats, interfaces, and communication protocols, while remaining operationally autonomous (Pan et al., 2021). However, current data environments remain fragmented, with differences in data models, standards, and governance frameworks limiting data sharing and reuse, constraining coordination, and reducing system efficiency (Bakri et al., 2023; Laborda et al., 2023).

From a PI perspective, these limitations highlight that data interoperability is not only a technical issue, but a structural condition for urban mobility and logistics coordination. Without interoperable data infrastructures, PI remains confined to isolated project pilots or local applications and cannot scale across networks and territories (Delaplace, 2024; Wu et al., 2025).

3 European Context: Policies, Standards, and Data Spaces

Over the last decade, Europe has developed a wide range of policies, regulatory instruments, and technical initiatives aimed at improving data availability, effective data sharing, and interoperability. This section reviews the main components of this landscape, including emerging data space initiatives, standardization efforts, and policy frameworks.

3.1 Data Spaces initiatives

At the technical level, initiatives such as GAIA-X and the International Data Spaces Association (IDSA) provide key building blocks for federated data sharing, including identity management, access control, usage control, and trust mechanisms. IDSA proposes a reference architecture and interoperability protocols, while GAIA-X focuses on a federated trust framework and governance rules. Together, these initiatives support interoperability across technical and organizational layers.

However, important limitations remain. While IDSA explicitly addresses semantic interoperability through shared vocabularies and models, and GAIA-X enables domain-specific extensions, neither provides fully specified data models tailored to specific sectors. As a result, domain-level semantics must often be developed within individual data spaces, which limits consistent data interpretation across systems (Bakri et al., 2023; Delaplace, 2024).

In addition, challenges persist regarding liability and accountability. While these initiatives define frameworks for access control, identity, and usage policies, they do not fully resolve how responsibility should be allocated when shared data is reused, combined, or used for decision-making (Picht, 2020; Vellinga and Hailevich, 2024).

3.2 Standardization frameworks

Standardization efforts at European and international levels, led by organizations such as European Committee for Standardization (CEN) and International Organization for Standardization (ISO), provide essential building blocks for interoperability by defining data models, exchange specifications, and, in some cases, process frameworks across transport and logistics domains (Bakri et al., 2023). These standards contribute to a shared technical foundation and can facilitate data exchange within specific domains, particularly when consistently implemented. For instance, standards such as DATEX II for traffic and road exchange or NeTEx for public transport provide structured data models that support interoperability among stakeholders.

However, in practice, their effectiveness is often limited by heterogeneous implementation across actors (Gharehgozli et al., 2019). Standards may leave room for interpretation, meaning the same concept may be understood differently depending on context. For example, what constitutes a “delivery event” (e.g., vehicle arrival at a distribution center or proof of delivery). Sometimes, cities and operators include fields to adapt the standard to their own operational needs, however these custom additions are not always documented or shared, which limits reuse by other stakeholders.

These differences mean that even when common standards are adopted, variations in interpretation, context, and usage may lead to inconsistencies in how data is produced and consumed.

As a result, while standardization is a necessary condition for interoperability, it is not sufficient on its own to ensure seamless data exchange across the full urban mobility and logistics ecosystem. Achieving effective interoperability requires additional alignment at the semantic, organizational, and operational levels.

3.3 European policies, initiatives and funded projects

At a broader level, the European Interoperability Framework (EIF) provides a common reference for interoperability across public administrations in Europe. It defines interoperability as the ability of organizations to exchange and use information to achieve shared objectives, and highlights that it requires alignment across multiple layers, including legal, organizational, semantic, and technical dimensions (European Commission. Directorate General for Informatics., 2017). While the EIF is not specific to urban mobility and logistics, it establishes a general structure that supports many European digital initiatives and helps frame interoperability as a systemic, multi-layer challenge rather than a purely technical issue.

One key regulatory instrument in the transport domain is the electronic Freight Transport Information (eFTI[1]) Regulation, which focuses on the digitalization of freight transport information exchanges between economic operators and public authorities. Its primary objective is to replace paper-based documents with electronic data, harmonize reporting obligations across Member states, and reduce administrative burdens while ensuring regulatory compliance (Delaplace, 2024). However, its scope remains limited to regulatory reporting (business-to-administration) and does not yet address operational coordination between logistics actors.

In parallel, the European Commission has launched the European Mobility Data Space (EMDS[2]) as part of the broader European Data Strategy. EMDS aims to provide a federated and trusted environment for sharing mobility and logistics data across public and private stakeholders. Its objectives include improving data accessibility, supporting innovation, and enabling new services across passenger and freight transport (Bakri et al., 2023; Laborda et al., 2023). While EMDS explicitly addresses challenges related to interoperability, data sovereignty, and governance, its operational implementation and integration with existing initiatives are still ongoing. The project is expected to run until October 2026.

Numerous European R&I projects (e.g. DELPHI[3], DISCO[4], DECARBOMILE[5], GREEN-LOG[6], UNCHAIN[7], URBANE[8]) are exploring data sharing and interoperability in urban logistics through data spaces, either by building their own infrastructure or aligning with data space principles and architectures. Although developed in specific local contexts, some also explore opportunities for scalability and integration. For instance, URBANE solutions have been integrated into DISCO's Urban Freight Data Space, pointing to a possible pathway towards cross-project interoperability. Yet such approaches remain an exception rather than the norm. Furthermore, the long-term sustainability of these solutions beyond project funding remains a significant challenge.

3.4 Identified Challenges and Gaps

The literature and policy landscape highlight several persistent gaps that continue to limit data interoperability in urban mobility and logistics, despite significant efforts through data space frameworks, standardization initiatives, and European projects. This subsection synthesizes these barriers and analyzes how they translate into operational challenges.

First, technical interoperability remains constrained by semantic heterogeneity. Data models, vocabulary, and metadata structures vary across platforms and initiatives, even when addressing

[1] https://transport.ec.europa.eu/transport-themes/logistics-and-multimodal-transport/efti-regulation_en
[2] https://transport.ec.europa.eu/transport-themes/smart-mobility/creating-common-european-mobility-data-space_en
[3] https://cordis.europa.eu/project/id/101104263
[4] https://cordis.europa.eu/project/id/101103954
[5] https://cordis.europa.eu/project/id/101069806
[6] https://cordis.europa.eu/project/id/101069892
[7] https://cordis.europa.eu/project/id/101103812
[8] https://cordis.europa.eu/project/id/101069782

similar use cases such as shipment tracking, transport planning, or multimodal coordination. This limits the reuse of technical components such as APIs and data models beyond their original context. While such approaches often accelerate experimentation within individual projects, they also result in solutions that are tailored to specific pilots, or local contexts, thereby limiting data interoperability and reuse across initiatives.

Second, significant challenges relate to governance and trust. Data access conditions, usage rights, and reuse mechanisms remain fragmented and inconsistently defined, creating uncertainty for stakeholders and discouraging data sharing. In practice, it is often unclear under what conditions data can be reused, by whom, and for which purposes, particularly in multi-actor and cross-border environments, where it is often unclear which actor is accountable in case of errors or misuse. In addition, the lack of clearly defined and widely adopted trusted intermediaries or third-party governance mechanisms further complicates data sharing, as no neutral entity consistently ensures compliance, trust, and coordination across stakeholders.

Third, policy and standardization efforts, while supporting digitalization and data sharing, do not fully ensure data interoperability in practice. Instruments such as eFTI focus on specific regulatory use cases, particularly business-to-administration data exchange. At the same time, broader European frameworks and standardization initiatives provide general principles and guidelines without defining how data interoperability should be put into practice across the different systems and actors.

Finally, implementation and scalability remain major barriers. Solutions developed in pilot projects are often tailored to specific local contexts and face difficulties in scaling across cities, regions, or countries due to differences in governance structures, digital maturity, procurement practices, and legacy systems. As a result, data-sharing initiatives remain largely project-specific.

Despite the growing body of work on data spaces and interoperability frameworks, limited attention has been paid to how these challenges are experienced and addressed in practice. In particular, empirical evidence on the operational barriers, trade-offs, and strategies adopted by urban mobility and logistics operators, when engaging in data sharing initiatives, remains limited.

To address this gap, the next section presents practitioner perspectives based on an exploratory survey conducted among stakeholders involved in data-sharing initiatives. This empirical approach provides insights into how interoperability challenges are perceived and managed in operational contexts.

4 Practitioner Perspectives: Survey Insights on Data Interoperability

4.1 Methodology

To complement the conceptual and policy analysis, an exploratory survey was conducted among practitioners involved in the design, deployment, or operation of data-sharing solutions in European urban mobility and logistics. The survey was open for 6 weeks (from the beginning of February to mid-March 2026) and gathered 55 responses from a diverse set of stakeholders, including public authorities, R&I projects, transport and logistics operators, and digital solution providers.

Respondents cover a balanced representation of operational, technical, and governance roles in data-sharing ecosystems, including data users (29.6%), policy or coordination roles (25.9%), platform or infrastructure providers (18.5%), and data providers (9.3%). An additional 16.7% selected ‘Other’, reflecting roles such as data space operators, research and innovation managers, or data processing and coordination functions.

The survey combined multiple-choice questions, Likert-scale assessments, and open-ended questions, structured around key dimensions of data interoperability, including semantic alignment, technical reuse, governance and trust, and policy and standardization.

The objective of the survey was to validate the gaps identified in the previous section, understand how they are experienced in practice, identify which limitations are perceived as most critical for enabling data interoperability, and highlight points of convergence and divergence between policy ambitions, standardization efforts, and operational realities.

4.2 Main Results

Survey results are structured around key dimensions of data interoperability, including technical interoperability, governance and trust, policy and standardization, implementation and scalability. They are as follows:

Technical Interoperability

Technical interoperability emerges as a major bottleneck in practice. 64.8% of respondents agree or strongly agree that differences in data meaning and terminology hinder interoperability. Notably, 25.9% of respondents report insufficient experience to assess this issue.

Qualitative responses further explain how these challenges manifest in practice. Respondents highlight that semantic differences lead to additional data transformation, manual alignment, and interpretation efforts, increasing costs and slowing down integration.

Beyond purely technical aspects, respondents also point to broader organizational and contextual barriers, including differences in business practices, legacy systems, and varying levels of data maturity. Some responses highlight the need for common vocabularies and standardized data models, while others stress the importance of coordination mechanisms and clear use case definition.

A minority of respondents (9.3%) disagree or strongly disagree that semantic differences significantly hinder interoperability, suggesting that in some contexts other factors, such as data availability, communication issues, or the lack of standardized protocols and governance frameworks, may be more critical.

Additional challenges encountered relate to data quality and system constraints, including missing, incomplete, or inconsistent data across sources, as well as differences in spatial and temporal resolution. In addition, legacy systems, versioning constraints, and cybersecurity considerations further increase the complexity of reusing data across systems. Limited training and support for end users, as well as highly customized and insufficiently maintained solutions, also slow adoption and reinforce fragmentation.

Semantic heterogeneity limits integration across systems, particularly in multi-actor environments. These challenges arise from differences in terminology, data structures, and definitions across stakeholders, requiring significant preprocessing. As a result, the impact of semantic interoperability varies depending on system maturity, data availability, and existing levels of standardization.

Governance and Trust

Fragmentation is also evident in how data-sharing mechanisms are implemented. When asked whether mechanisms to control data access, reuse, and governance (e.g., consent, usage rules, sovereignty) are implemented in fragmented or project-specific ways, 94.4% of respondents agree or strongly agree, while only 5.6% report insufficient experience to assess the issue.

Beyond technical issues, governance and trust-related challenges are identified as major barriers to data sharing. When asked whether a lack of clarity on data governance rules and usage rights limits trust in data sharing, 88.9% of respondents agree or strongly agree, while 11.1% remain neutral.

When analyzing operational practices, only 11.1% of respondents consider the conditions for data access, usage, and reuse to be clear and well defined. A majority (59.3%) report that they are only partially clear, while 14.8% consider them unclear or poorly defined, and another 14.8% indicate that the question is not applicable to their context.

When asked which aspects are mainly unclear, respondents identify usage rights and restrictions (30%) as the primary source of uncertainty, followed by reuse and redistribution conditions (22.5%), data ownership (20%), and liability and responsibilities (17.5%). Issues related to duration of access (5%) and other context-specific concerns are mentioned less frequently.

Responsibility allocation further illustrates this lack of structure. When asked who should bear operational responsibility for decisions made based on shared data no clear consensus emerges. Responses are distributed across multiple actors: 12% assign responsibility to data providers, 16% to data users, 24% support shared responsibility between these two, 12% to public authorities, and 6% to platforms or intermediaries. In addition, 16% of respondents indicate that responsibility should be defined case by case through contracts, while 14% consider it depends on the specific use case.

Some respondents further underline that barriers often perceived as technical barriers are closely linked to governance and organizational factors, such as unclear data access conditions, or reluctance to share commercially sensitive data.

Governance and trust remain major barriers to data interoperability, as data-sharing mechanisms are fragmented, responsibilities are unclear, and conditions for data access and reuse are insufficiently defined. This lack of clarity and alignment undermines trust and limits stakeholders' willingness to share data, highlighting that data interoperability challenges emerge not only from technical issues, but from the interaction between governance, organizational, and economic factors.

Policy and Standardization

When asked whether existing European policies effectively support data interoperability, qualitative responses (approximately 50% of the sample) highlight several recurring gaps.

Respondents first point to the lack of clear and operational implementation guidelines. While policies such as the Data Governance Act, Data Act, or EMDS define high-level principles, they often do not provide concrete guidance, tools or support for implementation in real operational contexts.

Fragmentation across governance levels also emerges as a major issue. Respondents report inconsistencies between European, national, and local regulations, as well as differences in interpretation (e.g., GDPR), leading to heterogeneous implementations across cities and countries.

In addition, uncertainty related to GDPR and data sensitivity is another recurrent concern, particularly in distinguishing between personal and operational data. While GDPR is recognized as essential, it is often perceived as restrictive or difficult to interpret in logistics contexts.

Finally, respondents highlight a lack of alignment between policies, standards, and operational practices. Existing frameworks are not sufficiently connected to technical standards, business needs, or real-world use cases.

While policy and standardization frameworks provide strategic direction, they remain insufficiently operational, fragmented across governance levels, and poorly aligned with implementation needs, which limits their effective adoption and constrains data interoperability in practice.

Implementation and Scalability

Qualitative responses highlight the importance of business incentives and value creation in making data interoperability a reality. Technical solutions alone are insufficient if data providers and users

do not perceive clear operational or economic benefits from data exchange. Without appropriate business models or incentives, stakeholders have limited interest in making their data available. Some responses further suggest that challenges often attributed to technical issues are, in fact, rooted in misaligned business interests. When incentives are aligned and value is clearly demonstrated, stakeholders are more willing to address semantic differences and related issues.

Data reuse rates further highlight these limitations. When asked how often data models or APIs are reused beyond their original purpose or context, most respondents report limited reuse: 66.7% indicate that reuse occurs only occasionally, rarely, or never, while only 3.7% report systematic reuse. In addition, 29.6% of respondents indicate that this question is not relevant in their context.

This limited reuse is reflected in the weak connection between pilot projects and standardization processes. When asked whether results from pilots or projects contributed to formal standards or specifications, only 24.1% of respondents reported such contributions, while 50% indicated that the question was not applicable to their context.

Qualitative responses provide further insight into how such contributions occur in practice. Reported contributions are predominantly indirect, taking place through participation in European research and innovation projects, pilot implementations, or ecosystem initiatives such as iSHARE, IDSA, or GAIA-X-related developments. Only a limited number of responses refer to direct contributions to formal standards (e.g., ISO or DATEX II).

While projects play an important role in developing interoperability solutions, their solutions are rarely consolidated, formalized, or translated into widely adopted standards. This reflects both a weak connection to standardization pathways and a lack of viable business models and incentives to support sustained participation.

5 Results Discussion, Conclusions and Research Avenues

This paper examines data interoperability as a key condition for coordination in European urban mobility and logistics systems. In this context, it addresses the following question: *how are data interoperability frameworks experienced in practice by European mobility and logistics stakeholders, and how do these challenges affect the realization of Physical Internet?*

To answer this question, the paper conceptualizes data interoperability as the alignment of five interdependent layers: (1) policy frameworks defining the conditions for data sharing, (2) governance mechanisms defining access, responsibilities, and incentive structures, (3) semantic standards ensuring consistent data interpretation, (4) technical interfaces enabling data exchange, and (5) operational practices enabling data reuse across services and territories, including stakeholder capabilities and incentives.

By combining European policies analysis, standardization and data spaces initiatives review, along with practitioner perspectives, it shows that data interoperability remains limited not due to a lack of solutions, but due to misalignment across these dimensions. While many European initiatives actively address these layers individually, they remain insufficiently connected to enable scalability across systems.

Survey results confirm that these challenges are experienced in practice. Semantic heterogeneity continues to limit data integration across systems, while governance and trust issues significantly affect stakeholders' willingness to share data. In parallel, policy and standardization frameworks remain insufficiently operational and not enough aligned with implementation needs, and project-based approaches struggle to scale due to weak links with standardization processes and a lack of sustainable business models.

These findings indicate that data interoperability cannot be treated as a purely technical or policy objective, but as a systemic coordination and integration matter involving technical, governance, and economic dimensions. In this sense, data interoperability is not simply an enabler, but a prerequisite for scalable and efficient decentralized coordination.

From a PI perspective, this misalignment is particularly significant, as coordination across actors, systems, and territories relies on the ability to exchange, interpret and reuse data consistently. When this is not ensured, physical operations remain fragmented and cannot scale, limiting the implementation of PI in practice.

Addressing this gap therefore requires moving from fragmented data interoperability efforts to a more systemic, PI-aligned, coordination of data practices, governance structures, and operational processes (Figure 1). In practice, achieving concrete data interoperability means enabling (1) shared semantic models that support consistent interpretation of transport and logistics data, (2) clear governance frameworks defining data access, usage rights, and responsibilities, (3) interoperable interfaces that allow data exchange and reuse beyond individual use cases, and (4) viable business models that create value and incentivize stakeholders to share and reuse data.

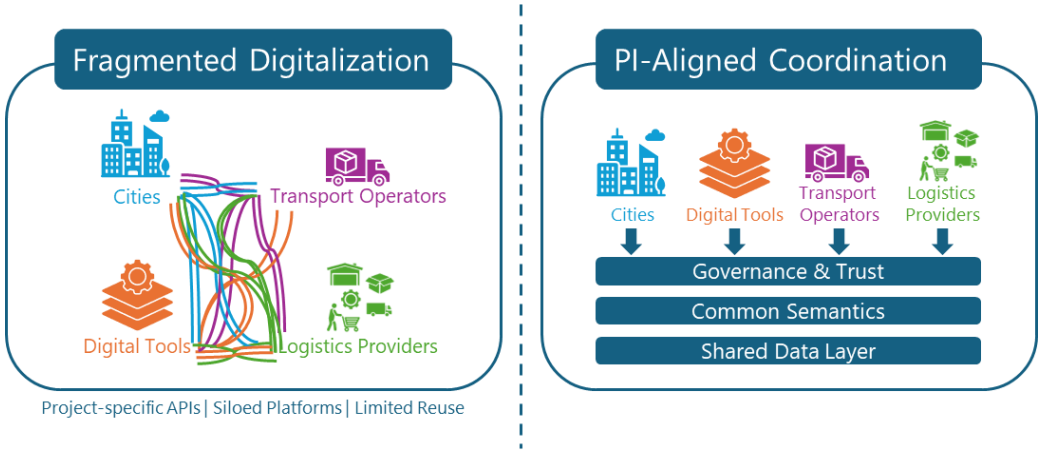

Figure 1. From fragmented digitalization to a PI-aligned coordination

As an exploratory study, this analysis presents some limitations. The survey sample size (55 respondents) remains relatively limited, although it was specifically targeted at stakeholders actively involved in urban mobility and logistics R&I or data-sharing initiatives. In addition, respondents exhibit varying levels of experience and familiarity with data interoperability, as reflected in the share of answers indicating insufficient experience to assess certain issues. This heterogeneity highlights that data interoperability challenges also relate to differences in knowledge and understanding across stakeholders.

This suggests that the current ecosystem remains in a transitional phase, characterized by uneven levels of maturity across stakeholders and limited integration between projects, standards, and policy frameworks.

Building on these findings, several priority directions emerge to achieve. First, greater efforts are needed to support semantic alignment across stakeholders, not only through standardization but also through shared interpretation frameworks and practical guidance. Second, governance mechanisms must be clarified and strengthened, including clearer definitions of roles, responsibilities, and data usage conditions, as well as the development of trusted coordination structures. In this regard, initiatives focused on stakeholder alignment and capacity building, such as the Digital Urban Freight (DUF) Community[9], can contribute to aligning practices and improving the collective understanding

[9] https://www.etp-logistics.eu/alice-urban-freight-community/

of data interoperability in operational contexts, by reducing knowledge gaps, fostering collaborative environments, and supporting the convergence of practices. Third, stronger links should be established between pilot projects, standardization bodies, and policy frameworks to ensure that operational insights are effectively consolidated and translated into widely adopted standards. Finally, the development of viable business models and incentive structures is essential to support long-term engagement in data sharing and interoperability initiatives.

Overall, this paper contributes to bridging the gap between existing interoperability approaches and the realities experienced by stakeholders. Future research could further explore mechanisms to support cross-domain data interoperability and assess how emerging governance and coordination models can be scaled across different contexts.

References

Bakri, T., Bastiaansen, H., Benmayor, A., Blaya, M., Böge, G., Cases, J.-F., Eisenrauch, A., Engh, E., Epardeau, D., Federl, S., Fernandes, E., van der Hoeven, G., King, L., Kirstein, L., Kraft, V., Lenz, G., Lilja, J., Morgan, J., Nagel, I., Öörni, R., Pretzsch, S., Scholliers, J., Schulz, H., Spijkers, N., 2023. Towards a common European mobility data space: Perspectives, recommendations and building blocks (Deliverable). PrepDSpace4Mobility.

Crainic, T.G., Montreuil, B., 2016. Physical Internet Enabled Hyperconnected City Logistics. Transp. Res. Procedia 12, 383–398.

Delaplace, J., 2024. Digitalization of the logistics - Cartography of the data sharing and exchange initiatives in Europe and recommendations for the introduction of the "Shared Data Language" developed by Geodis into this landscape. Paris, France.

European Commission. Directorate General for Informatics., 2017. New European interoperability framework: promoting seamless services and data flows for European public administrations. Publications Office, LU.

European University Institute, 2023. Creating a common European mobility data space. Publications Office, LU.

Expert Group for Urban Mobility, 2024. Data Sharing for Zero Emission Urban Logistics.

Gharehgozli, A., De Vries, H., Decrauw, S., 2019. The role of standardisation in European intermodal transportation. Marit. Bus. Rev. 4, 151–168.

Laborda, J., Dani, E., Bates, L., Ahtes, J., Touma, R., 2023. Unlocking the Future of Mobility with European Data Spaces. EIT KIC Urban Mobility S.L.

Montreuil, B., 2011. Toward a Physical Internet: meeting the global logistics sustainability grand challenge. Logist. Res. 3, 71–87.

Pan, S., Trentesaux, D., McFarlane, D., Montreuil, B., Ballot, E., Huang, G.Q., 2021. Digital interoperability in logistics and supply chain management: state-of-the-art and research avenues towards Physical Internet. Comput. Ind. 128, 103435.

Picht, P.G., 2020. Towards an Access Regime for Mobility Data. IIC - Int. Rev. Intellect. Prop. Compet. Law 51, 940–976.

Vellinga, N., Hailevich, E., 2024. The Legal Framework for Sharing Mobility Data: On the Road to an EU Mobility Data Space.

Wu, H., Li, M., Yu, C., Ouyang, Z., Lai, K., Zhao, Z., Pan, S., Wang, S., Zhong, R.Y., Kuo, Y.-H., Zhang, F., Huang, W., Shen, Z.-J.M., Ballot, E., Huang, G.Q., 2025. Towards cyber-physical internet: A systematic review, fundamental model and future perspectives. Transp. Res. Part E Logist. Transp. Rev. 197, 104051.