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Market Readiness Analysis for City Digital Twins:

A Strategic Marketing Approach

Exploring market acceptance and commercialization dynamics in Smart Cities with a focus on Cooperative, Connected and Automated Mobility (CCAM) applications.

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Patras, Greece, September 2026

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Abstract

This dissertation examines the market readiness of City Digital Twins (CDTs) in smart-city environments, with a focus on Cooperative, Connected and Automated Mobility (CCAM) applications. The technical promise of these systems is not really in question; the harder problem is whether they can become accepted, trusted and commercially sustainable offerings rather than perpetual demonstrators. We use the Horizon Europe FRODDO project as the main case context because it brings the relevant pieces together in one place (Digital Twin architecture, CCAM safety, Operational Design Domain continuity, physical and digital infrastructure, predictive analytics, data governance, pilots and exploitation planning) which makes it well suited to studying the distance between a working demonstrator and a market-ready solution.

The analysis takes a strategic marketing perspective, drawing on technology readiness, innovation diffusion, technology acceptance, value co-creation and Business-to-Government innovation, and it weighs adoption drivers and barriers ranging from usefulness and trust to interoperability, data security, legal compliance, procurement logic, organisational capacity and clarity of the value proposition. Methodologically it follows a qualitative, literature-based case synthesis drawing on academic literature, policy sources and FRODDO project material. The central argument is that technical validation, while necessary, is not sufficient: a City Digital Twin becomes market-ready only once it is useful, trusted, legally safe, institutionally compatible and clearly positioned for the actors expected to adopt it.

Keywords

City Digital Twins, Cooperative, Connected and Automated Mobility, Market Readiness Analysis

Περίληψη

Η παρούσα διπλωματική εργασία εξετάζει την ετοιμότητα αγοράς των Ψηφιακών Διδύμων Πόλης σε περιβάλλοντα έξυπνων πόλεων, με έμφαση στις εφαρμογές Συνεργατικής, Συνδεδεμένης και Αυτοματοποιημένης Κινητικότητας. Το ερώτημα δεν είναι αν τα συστήματα αυτά είναι τεχνικά υποσχόμενα. Το πιο δύσκολο ζήτημα είναι αν μπορούν να εξελιχθούν σε αποδεκτές, αξιόπιστες και βιώσιμες λύσεις αγοράς.

Το έργο Horizon Europe FRODDO χρησιμοποιείται ως βασικό πλαίσιο μελέτης περίπτωσης. Συνδυάζει αρχιτεκτονική Ψηφιακού Διδύμου, ασφάλεια CCAM, συνέχεια του Επιχειρησιακού Πεδίου Σχεδιασμού, φυσικές και ψηφιακές υποδομές, προγνωστική ανάλυση, διακυβέρνηση δεδομένων, πιλοτικές εφαρμογές και σχεδιασμό αξιοποίησης. Έτσι, προσφέρει ένα χρήσιμο πεδίο για τη μελέτη του κενού ανάμεσα σε έναν λειτουργικό επιδεικτικό μηχανισμό και σε μια λύση έτοιμη για την αγορά.

Η εργασία υιοθετεί μια στρατηγική προσέγγιση μάρκετινγκ, αντλώντας από την τεχνολογική ετοιμότητα, τη διάχυση της καινοτομίας, την αποδοχή της τεχνολογίας, τη συν-δημιουργία αξίας και την καινοτομία Business-to-Government. Εξετάζει παράγοντες και εμπόδια υιοθέτησης, όπως η χρησιμότητα, η εμπιστοσύνη, η διαλειτουργικότητα, η ασφάλεια δεδομένων, η νομική συμμόρφωση, η λογική των δημόσιων προμηθειών, η οργανωσιακή ικανότητα και η σαφήνεια της πρότασης αξίας.

Η έρευνα ακολουθεί μια ποιοτική σύνθεση βιβλιογραφίας και μελέτης περίπτωσης, αξιοποιώντας ακαδημαϊκή βιβλιογραφία, πηγές πολιτικής και υλικό του έργου FRODDO. Υποστηρίζει ότι η τεχνική επικύρωση είναι αναγκαία, αλλά δεν αρκεί. Ένα Ψηφιακό Δίδυμο Πόλης γίνεται έτοιμο για την αγορά μόνο όταν είναι χρήσιμο, αξιόπιστο, νομικά ασφαλές, θεσμικά συμβατό και καθαρά τοποθετημένο για τους φορείς που αναμένεται να το υιοθετήσουν.

Λέξεις – Κλειδιά

Ψηφιακά Δίδυμα Πόλεων, Συνεργατική, Διασυνδεδεμένη και Αυτοματοποιημένη Κινητικότητα, Ανάλυση Ετοιμότητας για την Αγορά

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List of Abbreviations & Acronyms

AI : Artificial Intelligence
ALLEA : All European Academies
API : Application Programming Interface
AV : Automated Vehicle
CAGR : Compound Annual Growth Rate
CAV : Connected and Automated Vehicle
CCAM : Cooperative, Connected and Automated Mobility
CDT : City Digital Twin
CEF : Connecting Europe Facility
CIM : City Information Model
C-ITS : Cooperative Intelligent Transport Systems
CORDIS PORTAL : Community Research and Development Information Service
DATEX II : European standard for traffic data exchange
DFB : Data Fusion Bus
DMP : Data Management Plan
DPIA : Data Protection Impact Assessment
DPO : Data Protection Officer
DSS : Decision Support System
DT : Digital Twin
DTC : Digital Twin Consortium
EMDS : European Mobility Data Space
ENISA : European Union Agency for Cybersecurity
ERTRAC : European Road Transport Research Advisory Council
EU : European Union
EWS : Early Warning System
FAIR : Findable, Accessible, Interoperable, Reusable
GA : Grant Agreement
GDPR : General Data Protection Regulation
GeoJSON : Geographic JavaScript Object Notation
GIS : Geographic Information System
glTF : GL Transmission Format
GNSS : Global Navigation Satellite System
GovTech : Government Technology
GUI : Graphical User Interface
HMI : Human-Machine Interface
CL5 : Horizon Europe, Cluster 5 (Climate, Energy and Mobility)
IAM : Identity and Access Management
ICT : Information and Communication Technology
IoT : Internet of Things
IPR : Intellectual Property Rights
ISO : International Organization for Standardization
IT/OT : Information Technology / Operational Technology
KPI : Key Performance Indicator
LDT : Local Digital Twin
LiDAR : Light Detection and Ranging

NIS2 :	Network and Information Security Directive 2
NTUA :	National Technical University of Athens
ODD :	Operational Design Domain
OECD :	Organisation for Economic Co-operation and Development
OEM :	Original Equipment Manufacturer
PEST :	Political, Economic, Social, Technological (analysis)
PNT :	Positioning, Navigation and Timing
PRISMA :	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PVT :	Position, Velocity, Time
SAE :	SAE International (automated-driving levels)
SLR :	Systematic Literature Review
SPAR-4-SLR :	Scientific Procedures and Rationales for Systematic Literature Reviews
TAM :	Technology Acceptance Model
TEN-T :	Trans-European Transport Network
TRI :	Technology Readiness Index
TRL :	Technology Readiness Level
UDT :	Urban Digital Twin
UTAUT :	Unified Theory of Acceptance and Use of Technology
WP :	Work Package

1 Introduction

City Digital Twins (CDTs) are moving from smart-city applications into a more operational role. They are no longer only digital replicas used for visualisation or urban planning. In advanced mobility contexts they begin to support prediction, simulation, data exchange and decision-making. This dissertation examines that shift through the lens of market readiness, with a specific focus on Cooperative, Connected and Automated Mobility (CCAM). The Horizon Europe funded FRODDO research project is used as the embedded research context, since the project develops a federated cyber-physical infrastructure for Operational Design Domain (ODD) continuity in CCAM environments [European Commission, CORDIS PORTAL, 2026]. The dissertation asks a broad question: when does a CDT become not only technically promising, but adoptable, procurable and scalable?

1.1 Background and Rationale

Smart cities have spent years accumulating data through sensors, traffic platforms, Geographic Information Systems (GIS) layers, dashboards, mobility apps and environmental monitoring systems, to the point where availability is no longer the binding constraint. The real question is whether that data can be connected, interpreted and turned into decisions that matter. CDTs answer this only partly by linking urban representations with data streams, models, analytics and simulation. The recent literature describes CDTs as genuine tools for smart-city development while still identifying persistent barriers around data integration, governance, interoperability, privacy, validation and scalability [Mazzetto, 2024]. In that sense, the promise has outrun the implementation.

CCAM raises the stakes further due to the fact that automated mobility cannot rely on the vehicle alone, it depends on road context, connectivity, infrastructure, weather, hazards, traffic behaviour and human interaction. The European CCAM Partnership describes this as a coordinated agenda for safe and sustainable automated road transport, binding together a complex value chain of public and private actors [CCAM Association, 2023]. This means the problem is less about building better cars than about building a better operational understanding of the environment those cars move through and that is precisely where a CDT shifts from a planning aid into something closer to infrastructure intelligence: in ordinary smart-city use, it might help a planning department test scenarios, but in a CCAM setting it helps road operators and public authorities judge whether automated mobility can operate safely under specific conditions.

1.2 Research Problem and Objectives

The research problem is the gap between technological promise and market readiness. CDTs are becoming more advanced, especially through AI, simulations, data spaces, geospatial modelling and dashboards. But market adoption is slower. Procurement is unclear. Value propositions are often too broad. Public-sector buyers may not know whether they are buying software, infrastructure, decision support, simulation, data governance, or all of these at once.

This is a problem for CCAM because the market cannot wait for perfect maturity. Automated mobility pilots, connected infrastructure and traffic-management innovation are already moving. Yet a CDT solution that is technically validated may still fail commercially if it lacks buyer clarity, trust, governance, interoperability or evidence. OECD work on GovTech stresses that public-sector digital innovation depends on enabling conditions such as procurement mechanisms, data governance, funding, skills and implementation capacity [OECD, 2024]. This applies strongly to CDT deployment since it is evident that technology alone does not create adoption.

The aim of this dissertation is to analyse the market readiness of CDTs for smart cities, with a focus on CCAM applications implemented within the FRODDO project context. It does not try to forecast market size in a narrow financial sense. The aim is more diagnostic: to identify what makes a CDT ready, or not ready, for market entry and scaling.

The first objective is to clarify how CDTs and CCAM interact as a market domain. The second is to develop a framework linking technology maturity, market readiness and value proposition. The third is to apply this framework to FRODDO evidence: project objectives, Digital Twin (DT) architecture, pilot logic, stakeholder requirements, data governance and exploitation planning. The fourth is to draw strategic implications for market entry, public-sector adoption and scaling.

This is why the dissertation uses strategic marketing theory next to innovation diffusion and stakeholder ecosystem thinking. It is not enough to ask whether the system works. The better question is: who sees value, who buys, who operates, who trusts, who carries risk?

1.3 Scope and Focus on CCAM and CDTs

The scope of this dissertation is deliberately narrow. We do not examine all smart-city platforms, all DTs markets or all automated mobility technologies. We focus on CDTs for CCAM, where urban digital infrastructure, mobility data, automated-vehicle operations and public decision-making overlap.

The FRODDO project is the main research context. The project is not treated as a distant external case. It is the Horizon Europe setting through which the study examines how CDT-related results move from technical development toward market readiness. Within the project the author holds several roles that bear on this analysis. He serves as the project's Quality Manager, leading the quality and risk-management task, he leads the task developing the Decision Support Dashboards and the associated deliverable D4.6, he has led the task developing the FRODDO Pilot Framework and the associated deliverable D5.1 during the first one and half year of the project and he also leads the task coordinating clustering activities with other EU-funded CCAM projects. This involvement is the source of the study's depth, giving direct access to project logic, design decisions, deliverable content and pilot structure that an external observer could not readily obtain. It also introduces a clear risk of bias, since several of the documents analysed here are deliverables developed with the author’s contribution and certainly neutrality is not claimed over them. The principal safeguard applied here is triangulation: FRODDO material is read against independent academic and policy sources rather than treated as self-validating, so that the project's own claims are tested against an external evidence base rather than accepted on their own terms. The findings should nonetheless be read as those of an embedded participant, with the analytical advantages and the limits that this position implies. FRODDO consortium defines the project around federated cyber-physical infrastructure for ODD continuity, next to advanced sensing, machine learning, hybrid AI and simulation, and the FRODDO DT as dynamic, federated and AI-assisted, integrating real-time data, predictive analytics and simulation for automated-vehicle operations [European Commission, CORDIS Portal, 2026], making the project directly relevant.

The CCAM focus also changes the meaning of market readiness. A CDT for cultural heritage or urban planning may be adopted through planning departments. A CDT for CCAM enters a more demanding space. It touches traffic operations, safety, infrastructure management, AI-supported prediction, data sharing and public trust. Mistakes are not just modelling errors. They may affect mobility decisions.

The dissertation therefore focuses on three market-readiness dimensions. Technology maturity covers the architecture, data flows, AI functions, interoperability and pilot validation. Market readiness covers procurement, governance, buyer clarity, stakeholder cooperation and scalability. Value proposition covers how different actors understand the system's practical benefit.

This scope excludes detailed technical validation of algorithms, full financial modelling, and legal interpretation of every regulatory obligation. Those are important, but outside the dissertation's size and purpose. The focus stays on strategic market readiness.

1.4 Research Questions and Hypotheses

The dissertation is focused in three research questions.

- RQ1: What technological, organisational and market conditions shape the readiness of CDTs for CCAM deployment?
- RQ2: How does FRODDO, as an embedded Horizon Europe CCAM project context, illustrate the movement from technical maturity toward market readiness?
- RQ3: What strategic marketing actions can support CDT market entry and scaling in smart city and CCAM ecosystems?

Because the study is qualitative and exploratory, the dissertation uses research propositions rather than statistical hypotheses. P1 states that technical maturity alone is insufficient for CDT market readiness unless it is supported by governance, procurement pathways and stakeholder trust. P2 states that CCAM increases the market relevance of CDTs by creating demand for real-time, ODD-aware, infrastructure-supported decision systems. P3 states that actor-specific value propositions improve adoption potential more than generic smart-city positioning.

These propositions are not tested through a large sample. They are examined through literature, FRODDO documentation, project evidence, secondary cases and strategic analysis.

1.5 Relevance to Urban Innovation and Digital Transformation

Urban innovation is moving into a more difficult phase. Cities are no longer only experimenting with digital tools, they are being asked to govern complex digital infrastructures. DTs, AI systems, mobility data spaces and automated transport are part of that change. The EU Local Digital Twin Toolbox, for example, is presented as a modular and standards-based initiative to help cities simulate, analyse and plan urban environments, built around interoperability, openness and scalability [European Commission, Interoperable Europe Portal, 2025]. This shows that CDT adoption is becoming a European policy and implementation issue, not just a research topic.

The dissertation contributes in urban innovation by showing that CDT market readiness depends on institutional conditions. It is not only about better digital models. Cities need procurement pathways, governance structures, data-sharing rules, skills and evidence. The common European mobility data space points in a similar direction by promoting access, pooling and sharing of mobility and transport data across ecosystems [European Commission, 2025]. If mobility data remains fragmented, CCAM-oriented CDTs remain fragile.

At the same time, this dissertation is relevant for road operators and public authorities because CCAM deployment creates new responsibility. Authorities need to understand when the physical and digital road environment can support automated mobility. That requires tools for scenario testing, early warning, ODD-related assessment and infrastructure coordination. A FRODDO-type CDT can support that role, but only if it is trusted and usable.

The relevance is sharper for marketing managers and CDT developers. The dissertation argues against generic positioning. “Smart CDT” is too broad as a market message. The value proposition should be more concrete: CCAM operational readiness, ODD-aware decision support, secure data fusion, traffic-management intelligence, pilot-backed evidence. Emerging technology value propositions often move from vision to network value and then to usage-specific value [Nussipova, 2022]. CDT marketing must make that move.

The dissertation also links digital transformation with trust and regulation making it relevant for policymakers as well. The AI Act establishes a harmonised framework for AI systems in the EU oriented toward human-centric and trustworthy AI [European Parliament &

Council of the European Union, 2024]. The Data Act sets harmonised rules on fair access to and use of data [European Parliament & Council of the European Union, 2023]. These frameworks do not only constrain CDT markets. They shape what trustworthy adoption looks like.

The broader relevance is this: cities need digital tools that are not only innovative, but adoptable. FRODDO offers a strong context to study this because it connects DT architecture, CCAM, data governance, pilots and exploitation planning. This dissertation therefore treats market readiness as a strategic bridge between technical progress and urban deployment.

1.6 Structure of the Dissertation

The remainder of this dissertation is structured as follows:

- Chapter 2 reviews theoretical models of innovation diffusion, technology readiness, and strategic marketing relevant to CDT and CCAM ecosystems.
- Chapter 3 outlines the conceptual framework and methodological approach, combining literature-based analysis with the FRODDO case synthesis.
- Chapter 4 applies the framework to assess market readiness factors across technological, organizational, and policy dimensions, using evidence from FRODDO deliverables and related initiatives.
- Chapter 5 concludes with strategic implications, offering recommendations for stakeholders seeking to accelerate CDT commercialization and adoption in smart cities.

2 Theoretical Background and Literature Review

This chapter builds the theoretical base for the dissertation. It does not try to cover all DT literature. That would be too wide and not very useful here. The focus is narrower: CDTs, smart city ecosystems, CCAM, innovation adoption, technology readiness, value co-creation, and strategic marketing for high-tech B2G markets. The point is to prepare one argument. CDT market readiness is not the same as technical maturity.

2.1 Defining CDT and Smart City Ecosystems

A CDT is not just a 3D model of a city with better graphics. It is closer to a living digital environment, connected to physical urban systems through data, models, simulations, interfaces and decision processes. The basic idea is simple: represent the city digitally so that planners, operators, firms and sometimes citizens can understand what is happening, test what may happen next, and act with less guesswork. But the practice is not simple. Data comes from many places, in different formats, with different owners. The city does not behave like a machine.

Recent literature treats CDTs as part of the wider family of Urban Digital Twins (UDTs), where geospatial models, IoT data, simulation, analytics and visual interfaces are combined to support urban planning and management [Mazzetto, 2024]. Mazzetto's review also shows that integration, interoperability, governance, data quality and scalability remain persistent problems, even when the technical promise is strong.

Still, the boundaries are fuzzy. Some systems called CDTs are mainly City Information Models (CIMs). They organise spatial data, support visualisation, perhaps help planning. Useful, yes. But not full twins. Cureton and Hartley distinguish CIMs from UDTs and argue that CIMs can act as precursors when they start to include richer data practices, training, licensing, system management and stakeholder engagement [Cureton & Hartley, 2023]. A CDT for CCAM must go further. It must support operational decisions in changing mobility conditions, not only display city layers.

Smart city ecosystems add the second layer. A smart city is not only sensors and platforms. It is a network of public authorities, infrastructure owners, technology vendors, transport operators, data providers, researchers, regulators, citizens and users. These actors do not always have the same priorities. Some want efficiency. Some want safety. Some want control over data, others want open access. Some just want the system not to fail.

Calzati notes that CDTs are no longer pure hype, but they are not yet mainstream either, partly because technical progress runs ahead of governance, public value and organisational embedding [Calzati, 2023]. That is the core tension. CDTs promise integration, yet cities are fragmented. They promise prediction, yet urban life is full of exceptions. They promise better decisions, but decisions are political too.

For this dissertation, CDT is therefore defined as a data-driven, model-supported and decision-oriented digital representation of urban systems, able to update, simulate and support action. In the FRODDO context, the definition is narrowed further: the CDT is treated as a federated, AI-assisted environment for CCAM, linking real-time data, predictive analytics, simulation, dashboards and physical-digital infrastructure cooperation [European Commision, CORDIS, 2026]. So the CDT becomes less of a smart-city showcase and more of an operational layer.

2.2 Evolution of Digital Twin Concepts

DT thinking did not start from cities. It came from product lifecycle management, manufacturing, aerospace-style monitoring and then wider cyber-physical systems. The early idea was clean: a physical object has a digital counterpart, fed by data, used for monitoring, prediction and testing. Over time the concept became less object-centred. It expanded from machine or product to process, factory, transport system, neighbourhood and city. As a result, the scale grew larger, more actors became relevant, the quality of data worsened and politics came into play.

Recent reviews show this shift clearly. DTs are now described not only as virtual replicas, but as adaptive systems that combine data, models, analytics, simulation and feedback loops across the lifecycle of a physical or socio-technical system [Semeraro et al., 2021]. That definition is useful because it keeps the twin alive. A static 3D model or a dashboard are not enough.The “twin” starts when the digital side can update, represent behaviour, test scenarios and support decisions.

The transition to smart cities changed the concept again. UDTs added geospatial data, IoT streams, environmental models, mobility flows, planning tools and stakeholder interfaces.

The object was no longer a turbine or vehicle part. It became a neighbourhood, a corridor, a city service, sometimes a whole city. This makes the twin harder to define. It also makes it harder to sell, because the buyer may not know what problem is being solved.

There is also the issue of maturity. Cureton and Hartley's CIM-to-UDT distinction helps avoid inflation [Cureton & Hartley, 2023]. Not every city model is a twin. Some are only maps with layers which might be usefull but still not "twins". Market claims become weak when the concept is stretched too far.

For CCAM, the evolution becomes sharper again. A DT cannot only support planning; it must help manage dynamic mobility conditions, infrastructure status, hazards, traffic states and automated-vehicle limits. FRODDO follows that newer logic. Its DT is defined as dynamic, federated and AI-assisted, integrating real-time data, predictive analytics and simulation to support automated vehicles across different environments [Europoean Commision CORDIS, 2026]. So the concept has moved again: from product mirror, to urban model, to operational intelligence layer.

And the evolution is unfinished. That is the point.

2.3 Cooperative, Connected and Automated Mobility (CCAM) as a Catalyst for CDT Market Development

CCAM changes the market meaning of CDTs. Without CCAM, a CDT can remain a planning tool: useful for simulation, urban monitoring, policy testing. With CCAM, the twin becomes more operational. It has to supδport movement, risk, automation limits, infrastructure status, traffic behavior and data exchange. The safety layer is considerably stronger.

The reason is ODD. Automated vehicles do not operate safely under all conditions. They operate inside defined Operational Design Domains: road type, weather, visibility, connectivity, traffic complexity, infrastructure support, and other limits. CCAM pushes cities and road operators to understand these limits in real time, not as static documents. The CCAM Partnership frames automated mobility as a European agenda for safe, inclusive and sustainable road transport through coordinated research, validation and deployment activity [CCAM Association, 2023].

This is where CDTs become more than urban data platforms. They become instruments for coordinated deployment. A city or road operator does not need a CDT only to “see” the city. It needs to assess whether a road context is fit for connected and automated mobility, which data flows are missing, which infrastructure conditions matter, where risk is rising.

FRODDO makes this link explicit. Its project logic concerns broader ODDs that safely cooperate with Physical and Digital Infrastructure, using advanced sensing, machine learning, hybrid AI and simulation to improve CCAM-enabled infrastructure management [FRODDO Consortium, 2024a]. This is a strong market signal. If cities must host automated mobility, they need tools that show whether the environment is ready. The CDT becomes part of that readiness. In Figure 1, the results of a survey conducted among CCAM stakeholders, in FRODDO, show that they consider “Enhanced safety of Autonomou Driving in urban areas” the most important benefit of analyzing the physical an digital infrastructure in a holistic way.

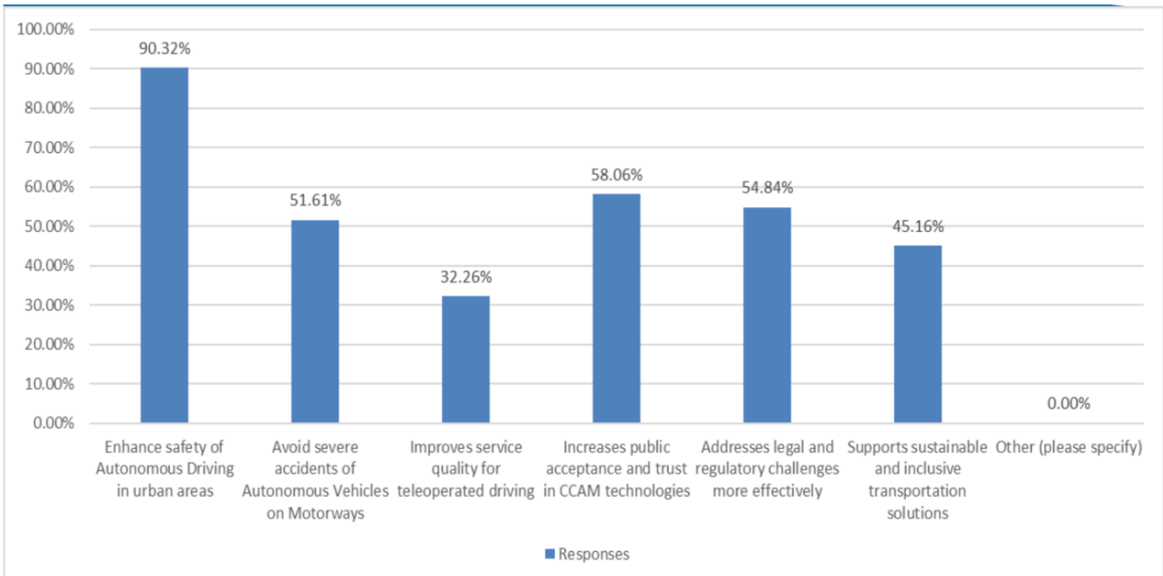

Figure 1: The most important benefits of analysing the physical and digital infrastructure in a holistic way according to FRODDO survey (source: FRODDO Consortium, 2025c)

There is also a data reason. CCAM depends on vehicle-to-everything communication, infrastructure perception, positioning, traffic-state prediction and secure exchange between actors. A normal traffic dashboard cannot easily handle this. FRODDO’s DT is designed to integrate real-time data, predictive analytics and simulation for safe automated-vehicle operation [FRODDO Consortium, 2025a]. That makes the CDT a coordination system, not only a map.

The market logic follows. Traffic management centres may need scenario testing. Road operators may need early warnings. Cities may need evidence before opening corridors to automated services. Technology providers may need test environments for integration. Citizens may need trust that automated mobility is not being pushed blindly.

CCAM also exposes the weakness of many smart city markets: pilots often stop before procurement. The technology is shown, but the business case stays vague. FRODDO's stakeholder work points to this directly, with interoperability, public trust, inclusive governance, harmonised strategies, structured partnerships and real-time data-sharing platforms named as priorities for deployment [FRODDO Consortium, 2025c]. In market terms, these are not background conditions. They are adoption conditions.

So CCAM acts as a catalyst because it gives CDTs a more challenging task and a clearer buyer problem. The city twin is no longer just helping a city see itself. It helps decide whether automated mobility can safely, lawfully and usefully operate there.

2.4 Theoretical Models of Innovation Diffusion and Market Adoption

The adoption problem needs a solid theoretical background. Rogers' diffusion logic [Rogers, 2003], technology readiness, TAM and value co-creation are used here as tools. They help explain why a technically advanced CDT may still fail to spread. They also help connect market readiness with stakeholder behaviour, procurement, trialability and trust. This section frames the theory withing the CDT/CCAM problem.

2.4.1 Rogers' Diffusion of Innovation Theory

Rogers' diffusion theory [Rogers, 2003] is useful here, but not as a history lesson. It works as a filter for why CDTs may spread, stall or stay trapped in pilot form. Recent diffusion work still keeps the main adoption attributes alive: relative advantage, compatibility, complexity, trialability, observability and sometimes reinvention [Overbye-Thompson & Hamilton, 2025]. For CDT and CCAM, these words are not abstract. They describe the market's pain points.

Relative advantage is built by answering whether the CDT is clearly better than current tools. A city already has GIS layers, traffic dashboards, spreadsheets, simulation models, consultants and control rooms. So the CDT must show more than elegance. It must reduce uncertainty around CCAM deployment, improve situational awareness, support ODD-related decisions or make infrastructure planning safer. If this advantage is not highlighted, adoption slows.

Compatibility is harder. A CDT must fit public-sector routines, procurement rules, legacy traffic systems, data-sharing limits and the daily logic of operators. Call and Herber argue that perceived innovation attributes can shape adoption speed in complex engineering contexts, especially when new model-based methods disrupt existing workflows [Call & Herber, 2022]. Same problem here. A technically strong CDT may still be rejected if it feels like another system that nobody has time to absorb.

Complexity works against diffusion. CDTs are complex by nature: real-time data, AI models, simulation, APIs, dashboards, cybersecurity, governance. But complexity can be managed if the user experience is clear and the offer is modular. FRODDO's federated structure, Data Fusion Bus and dashboard logic try to manage this complexity by separating integration, intelligence and user-facing decision support [FRODDO Consortium, 2025a; FRODDO Consortium, 2025e].

Trialability is crucial in B2G markets. Cities do not adopt high-risk systems only by reading claims. They pilot, test, and ask what fails. FRODDO's pilot framework creates this trial space across several CCAM settings [FRODDO Consortium, 2025f]. Observability closes the loop. Benefits must be visible to non-technical decision makers, not only to engineers. Safer operations, better warnings and clearer scenarios need to be seen, not promised.

So diffusion theory helps define the adoption test: CDTs spread when they look useful, fit existing systems, feel manageable, can be tried, and show results. Otherwise, they remain impressive prototypes.

2.4.2 Technology Readiness and Acceptance Models (TAM, TRL)

Technology readiness and acceptance do different work. On one hand, Technology Readiness Level (TRL) asks whether the system is technically mature. On the other hand, Technology Acceptance Model (TAM) asks whether people, organisations or users are likely to accept and use it. For CDTs in CCAM, both are necessary and neither is enough on its own.

TRL is useful because it gives a shared maturity language: early concept, validated prototype, demonstration and operational proof. It helps projects avoid vague claims about "advanced" technology. Salazar and Russi-Vigoya argue that TRL remains useful for judging maturity and risk, but it is technology-centred and weak on human readiness, usability or organisational fit [Salazar & Russi-Vigoya, 2021]. That is the gap. A CDT may reach a convincing technical level and still be hard to use, hard to procure, or hard to trust.

FRODDO shows this split clearly. TRL progress is defined for several components, including Data Fusion Bus, Digital-Twin-as-a-Service, AI-assisted traffic simulation, decision support, early warning and behavioural models [FRODDO Consortium, 2024a] creating a technical ladder which is good, but it does not prove market adoption.

TAM plays a role from the acceptance perspective. Recent automated-vehicle work still uses TAM because perceived usefulness, ease of use, trust and intention to use remain important when people face automated systems [Hickerson & Lee, 2022]. In CCAM, acceptance is not only passenger acceptance. Operators must accept dashboard outputs. Cities must accept legal and procurement risk. Road authorities must accept shared data. Different acceptance points, same system.

Finally, trust complicates the model. If the CDT connects infrastructure, traffic, vehicle and user data, then cybersecurity and data governance become part of perceived usefulness. A system that looks technically powerful but legally or operationally risky may be rejected. This is why FRODDO's data-management and ethical-legal layers are not side documents; they are part of its acceptance logic [FRODDO Consortium, 2024c; FRODDO Consortium, 2025b].

So this dissertation treats TRL as the maturity floor and TAM as the adoption filter. A FRODDO-type CDT must be technically validated, but also useful, understandable, trusted, secure and institutionally acceptable. Otherwise it is ready only in the lab sense, but not in the market sense.

2.4.3 Value Co-Creation and Stakeholder Ecosystems in Emerging Tech Markets

Value co-creation matters because a CDT does not create value alone. It is not a stand-alone product sitting on a shelf. Its value appears when data owners share usable data, operators act on outputs, public authorities allow governance space, suppliers integrate services, citizens accept the system. No single actor holds the whole value chain.

Recent value co-creation literature has moved toward a stakeholder view. Value is produced through resource integration across many actors, not only through a firm-customer exchange [Bal et al., 2023]. This fits emerging CDT markets. A vendor may build the platform, yes, but the city supplies context, operators supply operational knowledge, infrastructure owners supply access, regulators define limits. The "customer" is plural, and has a multi-modal nature.

In smart city ecosystems this becomes even more visible. Digital platforms need a stakeholder value proposition that is meaningful for urban actors, not only profitable for the platform owner [Carrasco-Farré et al., 2022]. A CDT for CCAM must therefore explain different forms of value: safer traffic decisions for operators, better policy evidence for cities, integration opportunities for technology providers, trust and clarity for users. Same infrastructure, different reasons to care.

But co-creation can be weak if it stays at workshop level. It needs roles, data rules, decision rights and follow-up. Smart city capability is built through multi-level coordination across organisations, resources and institutions [Gupta et al., 2023]. This is why stakeholder ecosystems are not just "engagement". They are market infrastructure. Without them, adoption becomes fragile; the pilot works, the market does not.

FRODDO shows this clearly. Its stakeholder work identifies interoperability, public trust, inclusive governance, harmonised strategies, structured partnerships and real-time data-sharing platforms as priorities for CCAM deployment [FRODDO Consortium, 2025c]. Although these aspects are often considered soft social points, in this case, they are conditions for market entry. If actors cannot share data, agree on responsibilities or trust the system, the CDT remains technically interesting but commercially weak.

So value co-creation is not an optional theory layer. It explains how CDT markets form. The product is built technically, but the market is built socially, institutionally, through partnerships and use, which sometimes is a slow process but still we are not aware of any way to avoid it.

2.5 Strategic Marketing Frameworks for High-Tech and B2G (Business-to-Government) Innovation

Strategic marketing for CDTs in CCAM is not mainly about promotion. It is about making a complex, risky, public-sector technology understandable enough to buy. High-tech B2G markets are slow, rule-heavy, often fragmented. The user, buyer, funder, regulator and beneficiary may be different actors. A traffic operator may need the system daily; a municipality may pay; citizens may carry the consequences. The market is neither smooth, nor uniform and full of irregularities.

For emerging technologies, the value proposition usually changes over time. Nussipova shows that early value propositions often move from broad vision, to network value, then to concrete usage value as the market learns what the technology actually does [Nussipova, 2022]. This is directly applicable to CDT commercialisation. At first the vision is “smart city transformation”. Then it becomes ecosystem value: data, infrastructure, operators, vehicles. Finally it should become usage value: safer CCAM corridors, better traffic decisions, ODD-aware planning, fewer blind spots. That is the level where commercialization is mature.

In B2G markets, risk reduction matters as much as benefit creation. Public buyers must justify procurement, comply with rules, avoid lock-in, protect data and show public value. OECD work on innovation procurement stresses that public procurement can support innovation, but public managers still face barriers when trying to bring new solutions and processes into government organisations [Monteiro et al., 2024]. So CDT marketing must include procurement language from the start. What is being bought. Who owns data. How it integrates. What evidence exists. What happens after the pilot.

GovTech logic reinforces this. OECD frames GovTech as collaboration between public bodies, innovators, start-ups, intrapreneurs and academia, supported by enabling conditions such as funding, procurement mechanisms, skills, data governance and implementation capacity [OECD, 202f4]. For CDT market entry, this means the “customer” is not only an individual city department. It is a capability environment. If the city cannot experiment, procure, govern data or train staff, the offer remains interesting but not adoptable.

FRODDO's exploitation work already points to this multi-market problem. It identifies connected vehicles, DTs, mobility data platforms and traffic management centres as relevant market spaces [FRODDO Consortium, 2025g]. The strategic marketing task is to convert these spaces into precise market-entry packages. Not one giant CDT product. Several focused offers: decision support for traffic centres, secure data-fusion layer for CCAM actors, simulation service for ODD planning, trust dashboard for AV pilots.

B2G customer strategy also needs patience. Yan, Lee and Josephson show that acquisition performance in business-to-government markets depends on how firms manage government customer assets, including expansion into new government customers [Yan et al., 2024]. For CDT providers this suggests a practical route: use pilots as references, then replicate across comparable cities or road authorities.

So the framework is simple and specific: (i) segmentation by actor and decision problem, (ii) positioning around risk reduction and operational value, (iii) building procurement-ready evidence, (iv) use of partnerships to cross the public-private boundary, and (v) avoid selling the DT as magic, through big promises of extraordinary results but rather through clearly described technologies with specific, quantified and demonstrated results.

2.6 Synthesis: The Market Readiness Gap in Smart CDT Deployment

The literature points to a clear gap. CDTs are becoming technically credible faster than they are becoming market-ready. The tools are improving: real-time data, simulation, urban models, AI analytics, dashboards, sometimes federated architectures. But the market conditions around them are thinner. Procurement is unclear, governance is uneven, data rights are complex, next to trust problems that do not disappear because the model looks impressive.

UDT work keeps returning to the same blockages: interoperability, data integration, governance, privacy, scalability, validation and the difficulty of connecting different urban systems into something usable [Mazzetto, 2024]. Although these seem like purely technical gaps, eventually the become market gaps. If a city cannot integrate the twin with existing systems, cannot govern the data or cannot explain who is accountable, then the CDT is not ready for adoption. The pilot demonstration might still be very good but that is a different thing.

The comparative literature says the same in a more direct way. CDTs are not considered impressive anymore, although they still remain not mainstream, partly because technical promises run ahead of sociotechnical reality [Calzati, 2023]. CDT development has reached a serious stage, yet routine deployment is still rare. The missing layer is not only better software, but institutional absorption.

FRODDO makes the gap visible in a CCAM setting. Its DT is dynamic, federated and AI-assisted, using real-time data, predictive analytics and simulation to support automated-vehicle operations [FRODDO Consortium, 2025a]. This might be a strong technical base, but CCAM raises the adoption threshold. A CDT must support ODD-related decisions, secure data exchange, infrastructure cooperation, human-facing dashboards and trust, which is far more demanding than normal urban planning use.

The stakeholder evidence confirms it. FRODDO's co-creation work identifies interoperability, public trust, inclusive governance, harmonised strategies, structured partnerships and real-time data-sharing platforms as core priorities [FRODDO Consortium, 2025c]. These are now actual adoption conditions, not "nice-to-have" optional features.

The market-readiness gap is therefore the distance between a technically functional CDT and a CDT that can be procured, governed, trusted, operated and scaled inside real smart-city and CCAM ecosystems. Looks like technical maturity is the floor and market readiness is the harder layer above it.

3 Conceptual Framework and Methodological Approach

This chapter explains how this dissertation is built. It defines the research design, the literature-based case synthesis method, the conceptual framework, the case selection, the data sources and the analytical procedure. FRODDO is not treated as a distant example observed from outside. It is the primary research context in which the author participates as a consortium member and researcher. That position gives direct access to project logic, documents, technical choices, stakeholder outputs and exploitation thinking. It also means the analysis is written from inside the project's development process, not after it has finished.

3.1 Research Design and Rationale

This study uses a qualitative, exploratory design. It does not try to measure the CDT market through sales data, procurement statistics or adoption rates, because the market for CCAM-oriented CDTs is still forming and it might be early for clean measurement as there are still too many evolving conditions. The useful question is not how large this market already is, but what conditions make such systems more likely to become market-ready.

The design follows a literature-based case synthesis. Recent methodological guidance treats literature reviews as valid research when they organise, compare and extend existing knowledge rather than only summarising it [Kraus et al., 2022]. This dissertation uses that logic, next to embedded project evidence from FRODDO. So the study sits between review, conceptual framework development and case-based interpretation. It is neither a detached survey, nor a technical evaluation report.

The rationale is practical. CDTs for CCAM sit between urban innovation, automated mobility, public procurement, data governance and infrastructure safety. A single lens would flatten them. Creswell and Creswell describe research design as the plan connecting assumptions, evidence, methods and interpretation [Creswell & Creswell, 2023]. Here, the assumption is simple: market readiness is multi-layered. It cannot be read from TRL alone, nor from stakeholder interest alone, nor from market forecasts.

FRODDO fits the design because it combines the layers under study. The project develops a federated DT environment for CCAM, using advanced sensing, machine learning, hybrid

AI and simulation to support adaptable ODDs in changing road contexts [FRODDO Consortium, 2024a]. Its DT work presents a dynamic, federated and AI-assisted platform using real-time data, predictive analytics and simulation for automated-vehicle operation [FRODDO Consortium, 2025a]. That makes FRODDO a live research setting where the dissertation’s concepts can be examined while the project is still evolving and is analytically rich.

3.2 Methodological Approach: Literature-Based Case Synthesis

The methodological approach is literature-based case synthesis. It combines recent academic literature, EU policy and market-facing material, FRODDO deliverables and selected secondary CDT/CCAM cases. The point is not to produce a full systematic review. The point is to build a structured argument about market readiness, using sources that speak to the same problem from different sides.

The review logic is selective but disciplined. Paul and colleagues’ SPAR-4-SLR framework is useful because it separates assembling, arranging and assessing sources, so the review process becomes more traceable [Paul et al., 2021]. This study does not follow SPAR-4-SLR as a strict protocol. It borrows the principle. Sources are assembled around the research question, arranged by analytical role, then assessed for what they add to the framework.

The academic material covers CDTs, UDTs, CCAM, innovation diffusion, TRL, technology acceptance, value co-creation, GovTech, public procurement and B2G marketing. The collaboration and interaction of these fields is still far from being clear and transparent and that is we have included a chapter dedicated to the synthesis of the literature. The CDT literature explains the technical and governance challenge. Adoption theory explains diffusion and acceptance. Strategic marketing explains market entry, value proposition, procurement and buyer risk.

FRODDO documents form the main project evidence. D4.1 is used for DT architecture and technological maturity [FRODDO Consortium, 2025a]. D2.1 is used for stakeholder requirements, co-creation and adoption conditions [FRODDO Consortium, 2025c]. D1.3 supports the data-governance and compliance layer [FRODDO Consortium, 2025b]. D7.3 supports exploitation and market-context analysis [FRODDO Consortium, 2025g]. Other deliverables are used where they clarify pilots, ODD continuity or decision support.

Analysis is thematic. Braun and Clarke describe thematic analysis as an interpretive method for identifying patterns of meaning rather than mechanically counting terms [Braun & Clarke, 2021]. This applies in our work as welle, "Interoperability" is not important only because it appears often. It matters because it links technical architecture, data exchange, procurement confidence and scaling exactly the same with trust and with governance.

The synthesis therefore works through comparison. Literature gives concepts. FRODDO gives embedded project evidence. Secondary cases provide contrast. Where these sources converge, the issue is treated as central to market readiness. Where they diverge, the gap is kept visible.

3.3 Conceptual Framework: Integrating Innovation Diffusion and Strategic Marketing Models

The conceptual framework joins two fields that are often separated. Innovation diffusion asks how a technology spreads, how uncertainty falls, and why adoption may stall. Strategic marketing asks how a technology is positioned, justified, packaged and made buyable. For

Table 1: Traceability Matrix- CCAM Cooperation Requirements in the FRODDO project (source: FRODDO Consortium 2025c)

ID	Requirement	How will be Addressed in the FRODDO Project
R1	**Clear Strategic Coordination Across Sectors** A coordinated approach across different CCAM stakeholders is needed to improve efficiency and reduce fragmentation.	Cross-sectoral cooperation models and formal collaboration roles based on co-creation outcomes, feeding into infrastructure and pilot design. Cross-sectoral engagement mechanisms to enable ongoing collaboration.
R2	**Regulatory Compliance and Harmonised Standards** Compliance with GDPR, safety regulations, and interoperability standards is essential for trust and deployment.	The infrastructure and simulation components include GDPR-compliant practices, ethical data use, and alignment with sectoral and EU-level standardisation efforts.
R3	**Shared Competence and Knowledge Exchange** Effective collaboration requires mutual understanding and capacity-building across professional domains.	Stakeholder-informed interfaces and tools that support knowledge sharing and cross-disciplinary usability.

R5	**User-Centred and Inclusive System Design** CCAM systems should accommodate diverse user needs, particularly for older people and people with disabilities.	Inclusive design principles and user profiles derived from stakeholder engagement inform infrastructure design and pilot scenarios.
R6	**Common Vision and Aligned Values** Collaboration must be guided by shared values, collective goals, and trust-building mechanisms.	Stakeholder expectations and collaboration principles captured in D2.1 inform the governance model and system-level design logic.
R7	**System Interoperability and Compatibility** Stakeholders highlighted the need for seamless integration between CCAM technologies and legacy systems.	Harmonised technical specifications and procedures, validated in pilots for compatibility across vehicles, infrastructure, and digital services.
R8	**Public Trust and Demonstrable Safety** Adoption depends on perceived safety, validated performance, and transparent system behaviour.	Pilots will incorporate stakeholder feedback and define KPIs to assess public trust, safety perception, and usability.

CCAM-oriented CDTs, both are needed. A technically mature system may still be hard to procure. A strong value proposition may still fail if the platform is not validated.

The framework uses three linked dimensions: technology maturity, market readiness and value proposition. They are treated as separate, but not independent. Technology maturity is the floor. Market readiness is the adoption condition. Value proposition is the translation layer.

3.3.1 Technology Maturity

Technology maturity asks whether the CDT system is still a concept, a prototype, a tested platform or something close to operational use. For CCAM, maturity means more than software functioning. It means data flows, AI models, simulation, dashboards, cybersecurity, interoperability and pilot testing are developed enough to support real mobility decisions.

TRL is useful because it gives a shared maturity language. Salazar and Russi-Vigoya argue that TRL remains helpful for judging technical maturity and risk, but is weak on human readiness and organisational fit [Salazar & Russi-Vigoya, 2021]. This distinction matters. A CDT can be technically mature but still not market-ready.

FRODDO has a clear technical maturity path. The Grant Agreement defines TRL movement for components such as the Data Fusion Bus, Digital-Twin-as-a-Service, AI-assisted traffic simulation, Decision Support Dashboard, Early Warning services and behavioural models [FRODDO Consortium, 2024a]. This gives the study measurable technical evidence. Still, TRL numbers are not enough. Integration and pilot performance are the real test.

AI maturity adds uncertainty. AI Watch notes that AI readiness assessment becomes harder when systems are context-dependent or embedded in wider socio-technical environments [Martínez-Plumed et al., 2022]. FRODDO fits this condition. A model can work in one pilot and behave differently with another data stream, another road setting, another operator need.

So the framework reads technology maturity through architecture, AI/data readiness, ODD relevance and pilot validation. The CDT must be able to work, but also to work under changing CCAM conditions.

3.3.2 Market Readiness

Market readiness asks a harder question: can the CDT move from project output to adoptable market offer? Not just can it be demonstrated. Can it be bought, governed, used, trusted, maintained and scaled.

This is especially important in B2G settings. Public procurement for innovation can support new public-sector solutions, but public managers and innovators still face barriers in accessing and using innovation procurement pathways [Monteiro et al., 2024]. A FRODDO-type CDT may be technically strong, yet still difficult to specify in a tender as definitions are still being formed. Is it software, infrastructure intelligence, decision support, data service, simulation platform? Maybe all, but this creates friction.

In this framework, market readiness is assessed through buyer clarity, institutional fit, data governance, stakeholder value, procurement logic and repeatability. FRODDO's exploitation work already identifies connected vehicles, DTs, mobility data platforms and traffic management centres as relevant market spaces [FRODDO Consortium, 2025g]. Useful, but still broad. A market space is not yet a buyer. A buyer is not yet a procurement route.

GovTech literature reinforces this. The OECD GovTech framework stresses funding, procurement mechanisms, data governance, skills and implementation capacity as conditions for digital innovation in government [OECD, 2024]. So the buyer must also be ready and this is a side of CDT adoption not always highlighted.

In the framework, market readiness is the bridge between technical promise and actual uptake. It is where the pilot becomes, or fails to become, a market offer.

3.3.3 Value Proposition

Value proposition is the third layer. It asks what the CDT promises, to whom, and why that promise is strong enough to justify adoption.

Emerging technologies rarely start with stable value propositions. Nussipova shows that value propositions in emerging B2B technologies can shift from broad vision, to network value, to usage-specific value as markets learn [Nussipova, 2022]. FRODDO needs this movement. “Smart mobility DT” is too wide. “ODD-aware decision support for CCAM operations” is sharper.

The framework treats value as actor-specific. A road operator may value early warnings and situational awareness. A city may value safer pilots and better evidence for infrastructure investment. A technology provider may value integration routes. A passenger may value clear trust and discomfort information. Same system, different value.

Urban platform research supports this view. Carrasco-Farré and colleagues argue that digital platforms in urban ecosystems need stakeholder value propositions that are meaningful for different urban actors [Carrasco-Farré et al., 2022]. Bal and colleagues also frame value co-creation as a stakeholder process, where expected and realised value emerge through collaboration [Bal et al., 2023]. For FRODDO, this means the value proposition depends on actors staying connected: data owners, operators, public authorities, technical partners, users.

The value proposition layer therefore translates maturity and readiness into a market argument. If each actor cannot see its own value, adoption remains fragile.

3.4 Case Selection and Data Sources

The case selection is purposive. FRODDO is the primary research context because the author is part of the consortium and because the project combines the main objects of this dissertation: CDTs, CCAM, ODD continuity, data exchange, decision support, pilots, stakeholder cooperation and exploitation. Secondary cases are used only for comparison. They help test whether the identified readiness issues appear beyond FRODDO.

The data sources are documentary and analytical. They include FRODDO deliverables, recent academic literature, EU policy material, project websites and selected public documentation from related CDT and CCAM initiatives.

3.4.1 Horizon Europe CCAM projects

Horizon Europe CCAM projects are relevant because they are not positioned neither in pure theory nor in full commercial deployment but rather between research and market. This middle zone is where market readiness usually forms: pilots, demonstrations, standards, stakeholder work, exploitation planning and policy alignment.

The wider frame is the European CCAM Partnership. Its Strategic Research and Innovation Agenda presents CCAM as a European effort to support safer, inclusive and sustainable mobility through coordinated research, validation and deployment-oriented innovation [CCAM Association, 2023]. FRODDO belongs to this field. It is not developing a DT outside the European CCAM agenda; it works inside that agenda.

FRODDO is selected because it fits the research problem tightly. It is defined around broader ODDs, cooperation with Physical and Digital Infrastructure, fail-safe design, advanced sensing, machine learning, hybrid AI and simulation [FRODDO Consortium, 2024a] while the work is structured within a 36-month Innovation Action [FRODDO Consortium, 2024b].

The case is also rich because it contains both technical development and market-facing activity. It includes DT architecture, stakeholder requirements, data management, pilots and exploitation planning. This is valuable for market-readiness analysis. A project with only technical architecture would be too narrow and a project with only policy material would be too weak, but FRODDO has both.

3.4.2 Secondary cases

Secondary cases are used as contrast points. They are not equal empirical cases. They help test whether the FRODDO-based framework is too narrow, and whether similar readiness issues appear in other CDT contexts.

Calzati's study of Dublin, Helsinki and Rotterdam is useful because it argues that CDTs are no longer pure hype, yet not mainstream either [Calzati, 2023]. This supports the dissertation's central point: technical promise does not automatically create adoption.

Lancaster adds a second comparison. Cureton and Hartley distinguish City Information Models from Urban UDTs, showing that CIMs may become precursors when they include training, data acquisition, licensing, management and stakeholder engagement [Cureton & Hartley, 2023]. This helps avoid conceptual inflation. Not every digital city model is a CDT.

The EU Local Digital Twin Toolbox provides the policy-infrastructure comparison. It is a modular, standards-based set of tools for cities, built around interoperability, openness and scalability [European Commission, Interoperable Europe Portal, 2025]. This shows where the broader CDT market is moving: reusable public-sector building blocks, not isolated prototypes.

Together, the secondary cases provide a compact comparison frame. Governance, model-to-twin maturity, standardisation and scaling return as repeated issues. FRODDO is then read against these signals, not alone.

3.5 Data Collection and Analysis Procedures

Data collection is documentary. The material is collected from recent academic literature, FRODDO project documentation, EU policy sources and secondary CDT/CCAM cases. The selection follows relevance to the research question: market readiness of CDTs for CCAM.

Part of the FRODDO documentation used in this study includes project work to which the author contributed during the preparation period of the dissertation, particularly in relation to the design and development of the FRODDO Decision Support System, pilot setup, quality management and clustering activities with other CCAM EC-funded projects. These contributions are treated here as part of the project documentary corpus, not as a separate primary dataset. Their relevance lies in the direct connection between project implementation work and the market-readiness questions examined in the dissertation, especially the translation of technical outputs into decision-support functionality, pilot validation logic and potential adoption pathways.

The first step was concept collection. Literature on CDT, CCAM, adoption, TRL, TAM, value co-creation, GovTech, innovation procurement and B2G marketing was reviewed to define the analytical lens. The second step was project evidence collection. FRODDO documents were grouped by role: technical maturity, stakeholder needs, data governance, pilot logic and exploitation.

The third step was thematic coding. Initial themes came from the conceptual framework: technology maturity, market readiness, value proposition. Sub-themes emerged while reading: interoperability, ODD continuity, public-sector procurement, skills, trust, data governance, dashboard usability and ecosystem orchestration. The coding process was not intended to produce quantitative frequencies. Its purpose was to organise the evidence into analytically meaningful categories and to connect the source material with the research questions (*Table 2*). Each theme was reviewed across multiple types of sources where possible, so that the analysis did not rely only on project documentation or on isolated literature claims.

The final step was synthesis. Evidence from literature, FRODDO and secondary cases was compared. If an issue appeared across all three, it was treated as a strong readiness condition. If it appeared only inside FRODDO, it was treated as project-specific. If it appeared in literature but not yet in the FRODDO documents, it was treated as a possible gap.

This procedure fits the purpose. The study does not claim to measure market readiness statistically but is building an analytical reading of it.

Table 2: Thematic coding structure used in the analysis

Main theme	Sub-theme	Type of evidence used	Inclusion rule	Example source
Technology maturity	CDT architecture and system integration	FRODDO deliverables, academic literature, technical/policy sources	Evidence was included when it described the technical design, maturity, integration logic or operational capability of CDT components.	FRODDO DT architecture material; Digital Twin literature; EU Local Digital Twin sources

Interoperability	Data exchange, standards and integration between systems	Academic literature, EU policy documents, FRODDO technical documents	Evidence was included when it referred to compatibility between platforms, data formats, APIs, infrastructure layers or mobility systems.	Digital Twin Consortium model; EU data-space policy; FRODDO Data Fusion Bus documentation
Data governance and compliance	Data access, privacy, security, ethical and legal requirements	EU regulatory documents, project data-management material, academic sources	Evidence was included when it addressed how data is collected, shared, protected, governed or made legally usable.	GDPR, AI Act, Data Act, FRODDO Data Management Plan
Market readiness	Movement from demonstrator to adoptable solution	Literature on innovation adoption, GovTech and smart-city implementation	Evidence was included when it explained whether a CDT solution could move beyond pilot status toward procurement, adoption or scaling.	OECD GovTech sources; smart-city adoption literature; FRODDO exploitation material
Public-sector procurement	Buyer clarity, procurement logic and institutional fit	Policy sources, B2G marketing literature, project exploitation documents	Evidence was included when it referred to the ability of cities, road operators or public authorities to define, purchase and operate CDT solutions.	GovTech literature; B2G innovation sources; FRODDO stakeholder and exploitation documents
Stakeholder trust	Trust, legitimacy, perceived usefulness and acceptance	Technology acceptance literature, policy sources, stakeholder-related project evidence	Evidence was included when it addressed confidence in CDT outputs, trust in automated mobility, perceived usefulness or acceptance by public and private actors.	TAM literature; CCAM policy sources; FRODDO stakeholder evidence
Institutional capacity	Skills, governance structures and organisational readiness	Academic literature, public-sector innovation sources, FRODDO case material	Evidence was included when it showed whether adopting organisations had the skills, processes, governance capacity or resources to use CDT solutions effectively.	Smart-city governance literature; OECD GovTech work; FRODDO project material
Adoption barriers	Technical, organisational, regulatory	Academic sources, policy reports, comparative	Evidence was included when it identified factors that could delay, prevent	CDT literature; CCAM ecosystem sources;

	and socio-political obstacles	cases, FRODDO evidence	or weaken CDT adoption.	comparative smart-city cases
Value proposition clarity	Actor-specific benefits and strategic positioning	Strategic marketing literature, value co-creation theory, FRODDO exploitation material	Evidence was included when it explained what value different actors receive from a CDT and how that value can be communicated.	Strategic marketing frameworks; value co-creation literature; FRODDO market-readiness analysis
Scalability	Replication across cities, pilots and operational contexts	Academic literature, EU project documents, comparative cases	Evidence was included when it discussed whether CDT solutions could be transferred, expanded or adapted beyond a single pilot environment.	EU smart-city policy sources; CDT implementation literature; FRODDO pilot framework

3.6 Trustworthiness, Researcher Reflexivity and Validation Measures

This dissertation follows a qualitative and exploratory design. Its quality therefore depends less on statistical testing and more on the clarity, consistency and credibility of the analytical process. The main concern is simple: the evidence must not appear as a loose description of the FRODDO project, but as a structured interpretation supported by literature, policy sources, project material and comparative examples.

A central issue is the author’s direct involvement in FRODDO. This position offers clear advantages. It provides access to project logic, design choices, deliverables, pilot planning and exploitation discussions that would be difficult for an external researcher to observe. At the same time, it creates a risk of bias. The author may interpret project evidence through prior knowledge, professional commitment or familiarity with the consortium’s objectives.

For this reason, the study adopts a reflexive position. FRODDO is not treated as neutral proof of market readiness. It is treated as an embedded case through which market-readiness conditions can be examined. Project documents are therefore read critically and compared with independent academic, policy and regulatory sources. This triangulation helps separate project ambition from broader evidence.

The analysis was also guided by the conceptual framework developed in this chapter. Evidence was organised around recurring themes such as technology maturity, interoperability, data governance, procurement, stakeholder trust, institutional capacity, adoption barriers, value proposition clarity and scalability. These themes helped keep the analysis focused and reduced the risk of selecting only favourable evidence.

Since this is a single-researcher qualitative study, formal inter-coder reliability was not applicable. Instead, reliability was strengthened through repeated reading of the material, consistent thematic coding, comparison across source types and clear links between evidence, themes and research questions. Evidence supported by both FRODDO material and external sources is treated as stronger than evidence based only on project documentation.

The study also has limits. It does not include primary interviews, surveys or direct observation of real procurement decisions by cities or road operators. Its findings should therefore be understood as an exploratory and conceptually grounded synthesis, not as a final empirical validation of CDT market adoption. Future research could test the framework through interviews with public authorities, traffic-management centres, technology providers, procurement officers and CCAM stakeholders.

4 Market Readiness Analysis

This chapter applies the conceptual framework to FRODDO. The focus is not to praise the project or judge it as finished. It is to read it as a live market-readiness case: a Horizon Europe CCAM action where DT architecture, ODD continuity, pilots, stakeholder cooperation, legal compliance and exploitation planning are being built at the same time. That is exactly where readiness becomes visible and also where it becomes fragile.

4.1 Overview of the FRODDO Project and its Strategic Relevance

FRODDO is strategically relevant because it treats CCAM as an infrastructure and ecosystem problem, not only as an automated-vehicle problem. Its full title, Federated cybeR-physical infrastructure for ODD cOntinuity, already signals this. The focus is on making automated mobility safer and more continuous through cooperation between vehicles, Physical and Digital Infrastructure, authorities, road operators, data systems and users [FRODDO Consortium, 2024a].

The project fits the CDT market-readiness question because its DT is not framed as a generic city model. It is a federated operational environment for CCAM. This matters. A normal smart city platform may support planning; FRODDO followes a harder path as it tries to support the road context in which automated mobility can work safely.

It also sits inside the European CCAM policy field. The CCAM Partnership's SRIA frames automated mobility as a coordinated European research and deployment agenda for safe, inclusive and sustainable road transport [CCAM Association, 2023]. FRODDO works inside that agenda, next to digitalisation, automation, infrastructure cooperation and public-sector mobility transformation.

4.1.1 Vision and Objectives (based on Grant Agreement and project summary)

FRODDO's vision starts from a clear operational problem. Automated vehicles operate within an Operational Design Domain, but the road environment is dynamic: weather changes, infrastructure conditions vary, connectivity can fail, traffic behaves unpredictably, and public authorities do not always have access to vehicle-specific ODD information. So the project asks how ODD continuity can be supported by the surrounding physical and digital environment [FRODDO Consortium, 2024a].

The objective is not to make vehicles autonomous in isolation. It is to develop methods and tools that allow broader, safer ODDs through cooperation with Physical and Digital Infrastructure. FRODDO uses advanced sensing, machine learning, hybrid AI and simulation in a federated DT environment to improve adaptability in complex road contexts [FRODDO Consortium, 2024b]. This moves the project into the market space of infrastructure-enabled CCAM.

The practical objectives include safer CCAM operations, better data-information-decision flows, improved positioning and connectivity, predictive analytics, traffic-agent models, decision support, and pilot validation. The vision is broad, but the market relevance is specific. FRODDO addresses a real future buyer problem: how can cities, road operators and mobility actors know whether a CCAM service can safely operate in a given context?

That is where the DT becomes strategic.

4.1.2 FRODDO's Federated Digital Twin Framework for CCAM

FRODDO's DT framework is built around federation. It does not assume that all data, models and services sit inside one closed platform. Instead, it connects heterogeneous sources, modules and users through shared data exchange and service layers. This is important for CCAM, because automated mobility depends on many actors and systems that were not designed as one machine.

D4.1 describes the FRODDO DT as dynamic, federated and AI-assisted, integrating real-time data, predictive analytics and simulation to support automated-vehicle operations across diverse environments [FRODDO Consortium, 2025a]. The technical logic is clear: the DT must represent the transport environment, connect live and historical data, support simulation, and provide outputs to decision-support and early-warning services.

The Data Fusion Bus (DFB) is the central connector. It enables data exchange between the DT, decision-support services, early-warning services, simulations, pilots and other mobility systems [FRODDO Consortium, 2025a]. In market terms, this matters because a CDT product cannot scale if each deployment requires custom integration from zero. The DFB gives FRODDO at least a tehnical route toward repeatability.

The Decision Support Dashboards (DSDs) add the user-facing layer. D4.6 distinguishes between expert dashboards for operators and planners, and mobile passenger-facing dashboards focused on trust and discomfort information [FRODDO Consortium, 2025e]. This split is useful. Operators need situational awareness, warnings, predictions, layers, KPIs. Passengers need simpler signals. The same platform includes different user value.

The framework therefore combines representation, prediction, simulation, secure exchange and human-facing decision support. It is not a complete market product yet, but it has a plausible product architecture.

4.2 Technological Maturity Assessment

Technological maturity is assessed through architecture, integration, data governance, AI/prediction, security and pilot validation. FRODDO is still an ongoing Innovation Action, so the assessment must stay cautious. The project is technically credible. Full maturity depends on operational evidence from pilots and later iterations.

4.2.1 FRODDO DT architecture (D4.1) and alignment with the Digital Twin Consortium model

FRODDO's DT architecture aligns with the Digital Twin Consortium's platform-stack logic. The DTC Platform Stack Architectural Framework presents DT systems through layers such as real-world data sources, IT/OT foundations, virtual representation, service interfaces, applications, security and trustworthiness [Digital Twin Consortium, 2023]. FRODDO's D4.1 uses a similar structure: physical and external data sources, a Data Fusion Bus, identity and access management, GIS and database services, interoperability services, simulation tools, decision support and dashboards [FRODDO Consortium, 2025a].

This alignment strengthens the maturity argument. It shows that the FRODDO DT is not a loose dashboard. It has a recognisable digital-twin architecture: assets and entities, geospatial models, data history, service interfaces, security roles and applications. The architecture also uses the Crimson DT platform as a modular and scalable base [FRODDO Consortium, 2025a]. So the design has an underlying platform logic, not just pilot-specific coding.

The strongest maturity signal is integration. FRODDO links the DT with the Early Warning System, Decision Support System and traffic-management simulations through the Data

Fusion Bus [FRODDO Consortium, 2025a]. This is where market relevance starts. A city or road operator will not buy separate research modules. They need connected functions: data ingestion, warnings, predictions, interface, governance.

Nevertheless maturity remains uneven as a federated architecture can be well designed while still depending on live data quality, latency, interoperability with local systems, and operational usability. The pilot framework is therefore essential. D5.1 defines the structure for testing FRODDO across Ljubljana, Athens, Modena and Bursa, using different CCAM scenarios and local architectures [FRODDO Consortium, 2025f]. This variation helps test whether the architecture can be replicable and scalable.

Table 3: FRODDO Pilot Testing Framework (source: FRODDO Consortium, 2025f)

Framework Element	Description
Standardized Testing Protocols	Harmonised procedures for scenario design, data collection, and system validation; ensures methodological consistency across all pilots.
Harmonised Metrics	Core KPIs for efficiency, sustainability, autonomy, and user experience, complemented by pilot-specific metrics.
Positioning & PNT Technologies	GNSS, INS, 5G, UWB, LiDAR/vision-based SLAM integrated to assess localisation performance in varied environments.
User-Centric Evaluation	Combination of questionnaires, physiological monitoring, and stakeholder feedback to assess usability, trust, and acceptance.
Safety, Efficiency, and Sustainability Indicators	Quantitative and qualitative indicators for hazard detection, system reliability, resource use, and environmental impact.
Risk Management & Mitigation	Identification of technical, operational, and regulatory risks; contingency planning embedded in pilot design.
Data Governance & Compliance	GDPR-compliant handling of personal and operational data, aligned with D1.2 and D6.2 guidelines.
Interoperability & Modularity	Framework designed for adaptability to diverse CCAM technologies, infrastructures, and regulatory settings.

The assessment is positive but not final. FRODDO's DT architecture is mature enough to support market-oriented analysis. It is not yet mature enough to be treated as a fully validated commercial product.

4.2.2 Data management and ethical compliance

Data management is a core maturity factor in FRODDO. The CDT depends on data from vehicles, infrastructure, sensors, pilots, software modules, surveys, dashboards and metadata. If these data flows are weak or unlawful, the system cannot scale. No trust, no market.

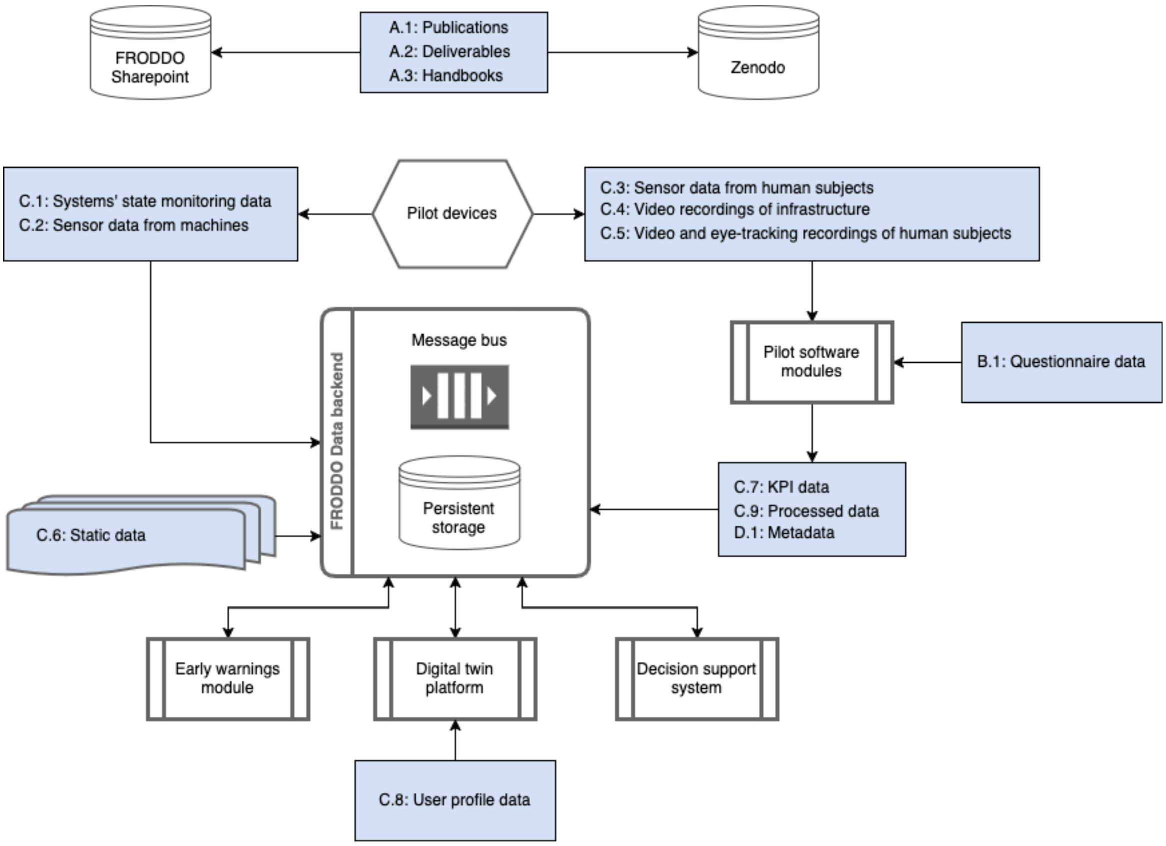

Figure 2: Data flow in the FRODDO framework (source: FRODDO Consortium, 2024c)

D1.3 presents the updated Data Management Plan and treats data as a full lifecycle issue: creation, storage, processing, sharing, protection, retention and documentation [FRODDO Consortium, 2025b]. It identifies several data categories, including survey data, system-state monitoring data, sensor data, video and eye-tracking data, infrastructure data, KPI data, user-profile data, processed data and metadata [FRODDO Consortium, 2025b]. This is a complex data mixture as some data is technical, some may be personal or sensitive and some becomes sensitive by context.

The DMP applies FAIR principles, GDPR-related procedures, data minimisation, consent where needed, anonymisation, pseudonymisation, access control, encryption, logging and auditing [FRODDO Consortium, 2025b]. These are not only compliance tools. They are adoption enablers. Public buyers need to know how data is handled before they adopt a CCAM DT.

The ethical and legal framework adds another layer. D6.2 addresses GDPR, AI-related obligations, pilot ethics, participant protection, transparency and accountability [FRODDO Consortium, 2024c]. This matters because AI and data use in CCAM can affect safety, privacy and public trust. The AI Act now provides a harmonised EU framework for AI systems, built around trustworthy and human-centric AI [European Parliament & Council of the European Union, 2024]. FRODDO's alignment with that regulatory direction improves its market credibility.

The conclusion is simple: FRODDO's data and ethics governance are strong readiness assets. The remaining test is operational. Controls written in documents must work during pilot execution, data exchange and future replication.

4.3 Market Context: Smart City and CCAM Ecosystems

The market context is not a single buyer market. It is a CCAM and smart city ecosystem. That means different actors hold different parts of the value: cities, road operators, public authorities, infrastructure owners, OEMs, software providers, data platforms, researchers, regulators and citizens. The CDT must create value across that network.

4.3.1 Stakeholder mapping

FRODDO's stakeholder landscape is broad because CCAM itself is broad. D2.1 maps the ecosystem across industry, service providers, transport and mobility operators, public administration, research, legal and regulatory bodies, civil society and end users [FRODDO Consortium, 2025c]. These groups do not play the same role in adoption. Some build. Some buy. Some operate. Some regulate. Some legitimise or resist.

Industry actors and technology providers are important because they turn project results into platforms, services or integrations. They care about interoperability, scalability, validation environments and future commercial positioning. Mobility operators and traffic management centres are closer to day-to-day use. They need dashboards, alerts, scenario testing, situational awareness and operational confidence.

Public authorities have a different role. They may buy, regulate, fund, approve or block deployment. Their adoption logic includes procurement, legal safety, public value, political exposure and long-term maintenance. The same CDT value proposition will not work for all these actors.

Researchers and validation partners provide credibility. Regulators and legal experts define what can be deployed. Citizens and passengers affect legitimacy. FRODDO's passenger-facing dashboard logic is relevant here, because trust is not only an operator issue [FRODDO Consortium, 2025e]. Users need understandable signals, not just technical proof.

So stakeholder mapping is not a communication exercise. It is market analysis. If the CDT cannot explain its value to each major actor group, it remains a pilot system with limited adoption power.

4.3.2 Market demand, regulation, and policy context

Demand for FRODDO-type CDT solutions is pulled by several adjacent markets. D7.3 identifies connected vehicles, DTs, mobility data platforms and traffic management centres as relevant market spaces for FRODDO exploitation [FRODDO Consortium, 2025g]. This is useful, but it also shows the difficulty. The product category is not clean. A FRODDO result may be positioned as CCAM infrastructure intelligence, traffic-management support, ODD-continuity tooling, data-fusion service or Digital-Twin-as-a-Service.

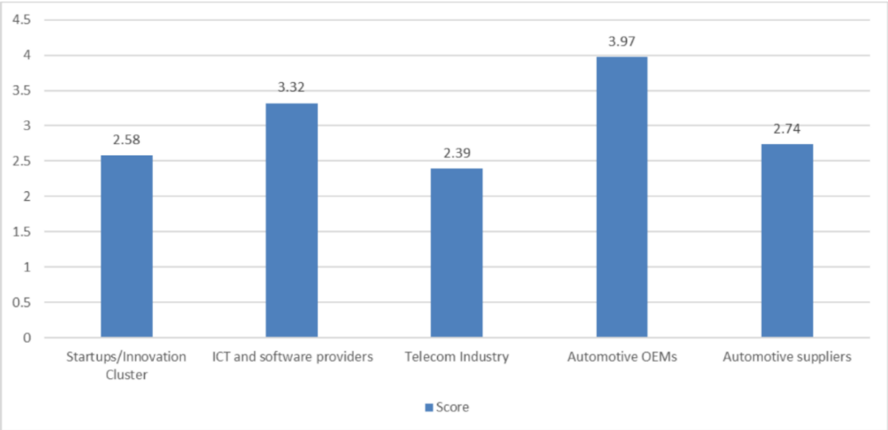

Figure 3: Market Segments which will bring CCAM to the market. Note: Scores are based on a 1–5 scale, with 5 indicating the highest level of perceived importance (source: FRODDO Consortium, 2025c)

The policy context helps. The CCAM SRIA gives automated mobility a European deployment frame, with safe and sustainable road transport through automation as the strategic direction [CCAM Association, 2023]. This supports FRODDO because the project is aligned with a recognised EU mobility agenda.

The data-policy context also matters. The common European mobility data space is intended to facilitate access, pooling and sharing of mobility and transport data from existing and future sources [European Commission, 2025a]. This fits FRODDO's federated data-exchange logic. A CCAM DT will struggle if mobility data remains trapped in isolated systems.

Regulation creates pressure but also trust. The Data Act sets harmonised rules on fair access to and use of data [European Parliament & Council of the European Union, 2023]. The AI Act sets rules for AI systems and their safe, rights-compatible use [European Parliament & Council of the European Union, 2024]. For a CDT built on data exchange, prediction and decision support, these are not background laws. They shape adoption.

Table 4: Summary of FRODDO PEST analysis (source: FRODDO Consortium, 2025g)

Result Name	Description
Political	1.New Horizon Europe to enable further adoption of project's results 2. Commercialisation gap signals need to prioritise on regional expertise 3. Geopolitical Instability 4. Legislation highlights opportunities and challenges
Economic	1.Less intense effects of tariffs in the EU GDP 2.Labour productivity is smaller than the US 3.More conservative investors in the short-term
Social	1.Ageing population is expected to create gaps in jobs 2.Shortage of skill in new technologies mandating upskilling regimes 3.Ethical considerations during the period where conventional and connected environments will co-exist
Technological	1.Relative DTs will reach productivity levels by 2029-2034 2.V2X communications and automotive cybersecurity are at a more mature state

The Local DT policy context is also relevant. The EU Local Digital Twin Toolbox is presented as a set of tools for smarter, data-driven urban planning [European Commission, Interoperable Europe Portal, 2025]. This indicates a wider European movement toward standardised local twin infrastructure. FRODDO is more specialised because it focuses on CCAM and ODD continuity, but it benefits from this wider CDT market formation.

The market is therefore promising but not easy. Demand exists. Policy is supportive. Regulation is becoming clearer. But buyers will still ask: who pays, who operates, who owns the data, who is liable, what proof exists, and what happens after the project?

4.4 Adoption Drivers and Barriers

Adoption depends on technical, organisational and socio-political factors. FRODDO has drivers in all three layers. It also faces barriers in all three. The market-readiness question is whether the drivers become strong enough to overcome the friction.

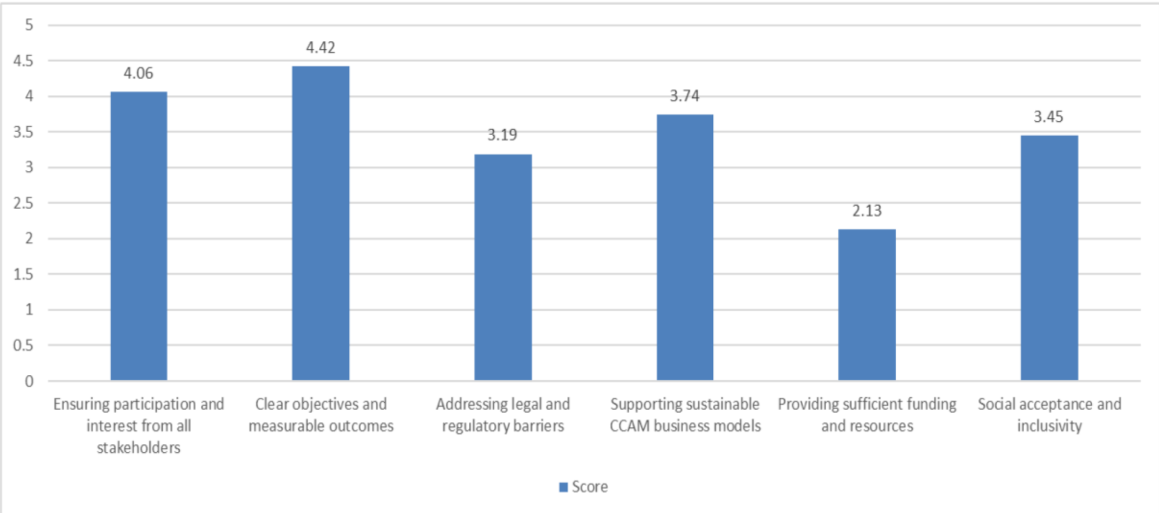

Figure 4: : Areas that FRODDO and its holistic CCAM design studying simultaneously physical (road) and digital (data) infrastructure will overcome market barriers most (source: FRODDO Consortium, 2025b)

4.4.1 Technical: interoperability, data security, scalability

Interoperability is the strongest technical driver. It is also the strongest technical barrier. FRODDO must connect vehicles, infrastructure, DT services, DSS, EWS, simulation tools, pilot systems and third-party data. D4.1 treats openness and interoperability as high-level requirements, including APIs and standard data formats [FRODDO Consortium, 2025a]. That is essential. A CDT that cannot connect to local systems will not be adopted.

The Data Fusion Bus is the main technical enabler. It supports secure and scalable data exchange across FRODDO components [FRODDO Consortium, 2025a]. In market terms, this is important because it makes the system less dependent on one-off integrations. Both reuse but, more importantly, replication matter most.

Data security is the second driver. FRODDO’s DMP describes encryption, access control, anonymisation, pseudonymisation, logging, auditing and secure transfer procedures [FRODDO Consortium, 2025b]. This directly supports adoption, because public actors need confidence in how mobility, infrastructure and possible personal data are handled.

Scalability remains less proven. The architecture is designed as modular and federated, but scaling must be tested in practice. D5.1 provides the route through pilots in different contexts [FRODDO Consortium, 2025f]. Yet pilot success is not the same as market-scale operation. The technical gap is not that FRODDO lacks a scalability logic. The gap is that scalability evidence is still emerging.

4.4.2 Organizational: procurement, skills, governance

The Organisational barriers may be harder than technical ones. Public actors may support CCAM in principle, but still lack a procurement pathway for a federated CDT. Is it software? Infrastructure? Safety support? Data service? Simulation platform? This ambiguity slows adoption.

FRODDO’s exploitation report identifies several market spaces, but also shows that future uptake will depend on turning project results into exploitable packages [FRODDO Consortium, 2025g]. This is where procurement matters. Public-sector buyers need clear specifications, responsibilities, maintenance arrangements and evidence. Without this, the offer stays vague.

Skills are another barrier. A CCAM DT requires staff who understand mobility operations, digital infrastructure, data governance, AI outputs, dashboards and public accountability. D2.1 points to knowledge exchange, shared competence and cross-sector cooperation as important conditions for CCAM deployment [FRODDO Consortium, 2025c]. That is a market issue. A city cannot adopt what it cannot operate.

Governance sits across everything. FRODDO has internal project governance through work packages, coordination, quality processes, ethics/legal support and exploitation planning [FRODDO Consortium, 2024b]. But future adopters need their own governance model: data ownership, user access, operational responsibility, response to warnings, model updates, supplier roles. This is where pilot-to-market transfer often breaks.

The organisational adoption picture is therefore cautious. FRODDO builds many of the right conditions, but public-sector absorption remains uncertain.

4.4.3 Socio-political: trust, ethics, and regulatory alignment

Trust is the socio-political core of CDT adoption. A CCAM DT may be technically accurate, but if operators, authorities or users do not trust it, adoption stays shallow. D2.1 identifies public trust, inclusive governance, interoperability and harmonised strategies as key priorities for CCAM deployment [FRODDO Consortium, 2025c]. These are not soft themes. They are adoption conditions.

Ethics is part of the same issue. FRODDO handles data-intensive mobility contexts, including pilot data and potentially human-related data [FRODDO Consortium, 2025b]. D6.2 provides the ethical and legal framework, including GDPR alignment, participant protection and AI-related attention [FRODDO Consortium, 2024c]. That makes compliance part of the value proposition.

Regulatory alignment can be a barrier because it adds obligations. But it can also be a market asset. A CDT that can show AI Act awareness, GDPR-grade data governance, Data Act awareness and secure data flows will be easier for public authorities to justify. The AI Act and Data Act do not just constrain the market; they also make trust more structured [European Parliament & Council of the European Union, 2023; European Parliament & Council of the European Union, 2024].

User-facing trust also matters. D4.6 includes passenger-oriented dashboard elements around trust and discomfort [FRODDO Consortium, 2025e]. This is strategically useful. Trust must be designed into interfaces, not only stated in project language.

So the socio-political picture is mixed. FRODDO has strong safeguards, but trust will only become adoption power if pilots show clear, understandable and publicly defensible results.

4.5 Comparative Case Insights

Secondary cases show that FRODDO is part of a wider CDT market pattern. DUET is useful because it framed Local DTs as tools for evidence-based policymaking, using digital models to support better public decisions before policy roll-out [European Commission, 2021]. The insight for FRODDO is direct: a twin becomes market-relevant when it reduces decision risk.

Calzati's study of Dublin, Helsinki and Rotterdam is more cautious. It argues that CDTs are no longer pure hype, but not yet mainstream [Calzati, 2023]. This fits FRODDO's position. The project is technically credible, but mainstream adoption needs governance, public value and institutional embedding.

Lancaster adds the model-to-twin warning. Cureton and Hartley distinguish City Information Models from UDTs and highlight training, data acquisition, licensing, system management and stakeholder engagement as transition issues [Cureton & Hartley, 2023]. This protects the analysis from overclaiming. Not every city model is a CDT; not every CDT is market-ready.

DTUMOS adds the mobility-scale comparison. Yeon and colleagues present an urban mobility DT framework validated with real-world data and large-scale vehicle scenarios [Yeon et al., 2023]. The lesson is scale. FRODDO's pilots are necessary, but future market uptake will depend on whether its services can move beyond pilot-specific settings.

The EU Local Digital Twin Toolbox shows another direction: standardisation and reusable public-sector tools [European Commission, Interoperable Europe Portal, 2025]. This is important because FRODDO's future market context may expect openness, modularity and interoperability by default.

The comparison is not about ranking. FRODDO is stronger where CCAM, ODD continuity and federated infrastructure are concerned. Other cases show the same general market gap: data, governance, scale, stakeholder fit, and adoption beyond demonstration.

4.6 Synthesis: Readiness Level and Market Gaps

FRODDO can be assessed as technically credible, market-oriented and still pilot-dependent. That is the most accurate readiness judgement. The project has a strong technical base: federated DT architecture, Data Fusion Bus, decision-support layer, early-warning integration, data governance, ethical/legal framework and pilot structure [FRODDO Consortium, 2025a; FRODDO Consortium, 2025b; FRODDO Consortium, 2025f].

Technology readiness is the strongest layer. The Grant Agreement sets TRL movement for key components, including the Data Fusion Bus, Digital-Twin-as-a-Service, AI-assisted traffic simulation, decision-support dashboards and early-warning services [FRODDO Consortium, 2024a]. The architecture then supports this with a modular, federated and AI-assisted DT design [FRODDO Consortium, 2025a]. This gives FRODDO a credible technological maturity trajectory.

Market readiness is weaker, but not absent. D7.3 identifies exploitation routes and market spaces around connected vehicles, DTs, mobility data platforms and traffic management centres [FRODDO Consortium, 2025g]. That shows market orientation. Yet market spaces need to become buyer-specific offers. A traffic management centre does not buy the same thing as a city authority or a technology provider.

The first market gap is product definition. FRODDO outputs can be framed as a DT platform, ODD-continuity layer, data-fusion infrastructure, traffic-management support system, early-warning service or CCAM safety tool. This flexibility is useful, but it may confuse procurement. The market offer needs sharper packaging.

The second gap is operational proof. D5.1 defines strong pilots, but final pilot evidence is needed before adoption claims become solid [FRODDO Consortium, 2025f]. Buyers will need evidence on usability, data reliability, safety contribution, integration cost and transferability.

The third gap is procurement and ownership. Public-sector buyers need clear procurement language, business models, responsibility allocation and maintenance logic. Without this, technical results may remain project outputs.

The fourth gap is ecosystem readiness. D2.1 shows that stakeholders prioritise interoperability, public trust, inclusive governance, structured partnerships and real-time data sharing [FRODDO Consortium, 2025c]. These are not solved by technology alone. They require sustained coordination.

The final gap is transferability. FRODDO’s architecture is federated and scalable by design, but replication beyond pilot sites has to be demonstrated. This is where comparison with EU LDT efforts and mobility digital-twin cases becomes useful.

So the conclusion is clear. FRODDO is not blocked by lack of technological promise. Its real market-readiness challenge is translation: turning architecture, data governance, pilot outputs and stakeholder cooperation into a clear, trusted and procurable offer for CCAM and smart-city actors.

5 Strategic Implications and Conclusions

The analysis ends with a simple finding. FRODDO-type CDTs for CCAM are not blocked mainly by lack of technological promise. The harder problem is translation: turning federated architecture, data governance, pilot evidence and stakeholder cooperation into a clear, trusted and procurable offer. That is the market-readiness challenge. Technical credibility exists, but it has to become buyer logic.

5.1 Strategic Recommendations for CDT Market Entry and Scaling

The recommendations focus on market entry and scaling, not on adding more technical ambition. FRODDO already has a strong technical base: a federated DT, Data Fusion Bus, decision-support dashboards, early-warning logic, data governance and pilot framework [FRODDO Consortium, 2025a; FRODDO Consortium, 2025c; FRODDO Consortium, 2025f]. The next strategic task is sharper: define the offer, organise the ecosystem, and make trust visible.

The recommendations below are therefore practical. They concern positioning, partnerships and policy alignment.

5.1.1 Positioning and value proposition design

The first recommendation is to stop positioning FRODDO-type outputs as a generic “CDT”. Too broad. Too easy to misunderstand. A city may hear 3D model. A traffic centre may hear dashboard. A technology provider may hear integration platform. None of these is fully wrong, but none is enough.

The stronger positioning is CCAM operational readiness. More specifically: a federated DT environment that helps cities, road operators and mobility actors understand whether automated mobility can operate safely under changing road, traffic, infrastructure and connectivity conditions. This fits FRODDO’s actual design. D4.1 describes the FRODDO DT as dynamic, federated and AI-assisted, integrating real-time data, predictive analytics and simulation to support automated-vehicle operations [FRODDO Consortium, 2025a]. That is not just a smart-city visualisation tool. It is operational infrastructure.

The value proposition should also be actor-specific. For traffic management centres, the offer is early warning, situational awareness, scenario testing and decision support. For public authorities, it is safer CCAM deployment, evidence for infrastructure choices, and lower uncertainty before scaling. For technology providers, it is a federated architecture and data-fusion route. For passengers or users, it is trust, comfort and understandable information. One system. Several value logics.

This fits the wider literature. Emerging technology value propositions often shift from broad vision to network framing, then to concrete use value as the market learns what the technology can actually do [Nussipova, 2022]. FRODDO should move fast toward the third stage. Less “future mobility ecosystem”. More “ODD-aware traffic decision support for CCAM corridors”.

Pilot evidence must then be attached to each value claim. FRODDO’s pilot framework covers different CCAM contexts in Ljubljana, Athens, Modena and Bursa [FRODDO Consortium, 2025f]. These pilots should not only validate technical performance. They should produce market-facing evidence: what improves, for whom, under which conditions, and how repeatable it is. Claims without proof will not survive public procurement.

5.1.2 Partnerships and ecosystem orchestration

The second recommendation is to treat partnerships as part of the market offer. A CCAM DT cannot scale through one actor. It needs data owners, traffic managers, infrastructure operators, public authorities, technology providers, legal and ethics support, research validation, plus user-facing organisations. Without that network the CDT becomes a good platform looking for a system that does not exist.

FRODDO already shows this. D2.1 identifies interoperability, public trust, inclusive governance, harmonised strategies, structured partnerships and real-time data-sharing platforms as core priorities for CCAM deployment [FRODDO Consortium, 2025c]. These are not dissemination topics. They are market infrastructure. If the actors cannot cooperate, the product cannot fully work.

The recommendation is to build market-entry packages around anchor partners. A traffic-management package needs a road operator or traffic centre as anchor. A secure data-fusion package needs a platform or systems integrator. An ODD-continuity offer needs public authorities next to infrastructure actors. A passenger-trust dashboard needs an AV pilot or mobility service operator. The anchor partner makes the value concrete. Otherwise the offer floats.

The same logic appears in stakeholder value literature. Urban digital platforms need value propositions that make sense across the ecosystem, not only for the platform owner [Carrasco-Farré et al., 2022]. Value co-creation also depends on resource integration across stakeholders, not only on a firm selling to one customer [Bal et al., 2023]. For FRODDO this means the route to market should be orchestrated, not merely promoted.

The clustering role is also important. FRODDO’s position in CCAM project networks can support replication, comparison and visibility across EU-funded initiatives. This should be used strategically: not only to share results, but to identify early adopters, align terminology, test value propositions and connect with complementary projects. Scaling will probably not happen as one big commercial jump. More likely, it will happen through pilots, references, partner networks, and selective uptake. It is probably a slower procedure, but also a more realistic one.

5.1.3 Policy alignment and trust-building mechanisms

The third recommendation is to turn policy alignment into an adoption asset. For CCAM DTs, compliance is not only a legal burden. It is part of market trust. Public authorities need to know whether the system handles data lawfully, whether AI use is explainable enough, whether cybersecurity is credible, and whether accountability is clear.

FRODDO has a solid legal and ethical base. The updated Data Management Plan covers FAIR principles, GDPR-related procedures, DPIA logic, access control, anonymisation, pseudonymisation, encryption, logging and auditing [FRODDO Consortium, 2025b]. The ethical and legal framework addresses legal monitoring, pilot ethics, participant protection, AI-related obligations and accountability [FRODDO Consortium, 2024c]. This is important for the market story and should be made visible so buyers should not have to search for assurance.

The AI Act matters here because FRODDO-type systems use AI-assisted analytics, prediction, decision support and user-facing outputs. The regulation establishes harmonised rules for AI systems in the EU and aims to support human-centric, trustworthy AI [European Parliament & Council of the European Union, 2024]. The Data Act matters too, because CDT systems depend on fair access to and use of data from connected products, services and infrastructures [European Parliament & Council of the European Union, 2023]. These frameworks shape market expectations and they also create a language for trust.

Trust should also be designed into interfaces. FRODDO’s D4.6 distinguishes expert dashboards from passenger-facing mobile dashboards and includes trust/discomfort-related information for AV users [FRODDO Consortium, 2025e]. This is strategically useful because trust cannot only be a statement in a deliverable. It is also what the user sees, understands, and can act on.

The practical mechanism is simple: every future CDT offer should include a short trust file acting as a buyer-readable assurance layer, directly answering clear questions. What data is used. Who controls access. What AI functions exist. What human oversight is present. What evidence came from pilots. What risks remain.

5.2 Implications for Marketing Managers and Policymakers

For marketing managers, the implication is direct: do not sell the DT as a technology category. Sell the problem it solves. Public buyers do not wake up needing a federated CDT. They face traffic uncertainty, fragmented data, CCAM safety concerns, pressure to modernise infrastructure, regulatory complexity and public scrutiny. The product must be translated into these pains.

That means segmentation must follow decision roles. “Smart cities” is not a useful segment. Traffic management centres, road authorities, CCAM pilot operators, infrastructure managers and mobility-data platforms are clearer. FRODDO’s exploitation report already identifies connected vehicles, DTs, mobility data platforms and traffic management centres as relevant market spaces [FRODDO Consortium, 2025g]. Marketing managers should now convert these spaces into buying situations: who pays, who uses, who blocks, who benefits.

They should also treat pilots as sales evidence, not only research validation. The question is not simply whether the system worked. It is whether the pilot produced evidence that a buyer can use: reliability, usability, integration effort, data quality, governance clarity, safety contribution, user trust. This is the bridge from demonstration to adoption.

For policymakers, the implication is different. Their role is to create conditions under which useful CDT systems can be procured, tested and scaled without locking cities into opaque or fragile arrangements. OECD work on innovation procurement shows that procurement can support public-sector innovation, but innovators and public managers still face barriers in accessing and using innovation procurement routes [Monteiro et al., 2024]. This applies strongly to FRODDO-type CDT solutions. They do not fit old procurement categories easily.

Policymakers should therefore support functional procurement language. Instead of asking for a “DT platform”, calls and tenders could specify interoperable data exchange, ODD-aware decision support, simulation-backed traffic management, secure dashboarding, auditability, human oversight and post-deployment maintenance. Functional specifications in procurement language would point to the direction of more complete, market-ready products.

They should also support data-sharing governance. The common European mobility data space is moving in this direction by promoting mobility and transport data sharing across ecosystems [European Commission, 2025]. A CCAM CDT cannot work if data remains locked in silos. Policy can reduce that friction through standards, shared rules and trusted data spaces.

The shared implication is this: market readiness is co-produced. Marketing managers must make the offer specific and evidence-based. Policymakers must make the adoption environment clearer, lawful and interoperable. If either side fails, the CDT remains a strong pilot with weak market pull.

5.3 Contributions to Theory and Practice

The main theoretical contribution is the separation of technology readiness from market readiness. In CDT literature these are often blurred. A system is technically demonstrated, then described as “ready”. This dissertation argues that readiness has more layers: technical maturity, market readiness, value proposition, trust, procurement and ecosystem coordination. This approach might be less elegant, but it is significantly more accurate.

The study also contributes by linking innovation diffusion and strategic marketing in a CCAM DT context. Diffusion theory helps explain adoption conditions: usefulness, compatibility, complexity, trialability and observability. Strategic marketing adds positioning, buyer clarity, value proposition and route-to-market logic. Together they explain why a technically credible CDT may still struggle to scale.

For practice, the contribution is a market-readiness reading of FRODDO. The analysis shows that FRODDO is technically credible and market-oriented, but still pilot-dependent. Its strengths are the federated DT architecture, Data Fusion Bus, decision-support layer, data governance, stakeholder co-creation and EU policy alignment [FRODDO Consortium, 2025a; FRODDO Consortium, 2025c; FRODDO Consortium, 2025g]. Its gaps are product definition, procurement pathway, operational proof, buyer clarity and transferability beyond pilot sites.

This dissertation also aims to give a practical diagnostic. CDT developers can ask: is the offer actor-specific? Is the data governance explainable? Are pilots generating buyer-ready evidence? Is there an anchor partner? Is the product procurable? Are trust mechanisms visible? These questions are simple and they cut through vague, smart-city language.

The contribution is not a final model of the CDT market, as it is probably too early for this. It is a working framework for seeing the gap between pilot and product.

5.4 Limitations and Future Research Directions

This study has certain limitations. The first concerns timing. FRODDO is still an ongoing project. D4.1 presents the first version of the Digital Twin, while later versions and pilot results will provide stronger evidence on operational performance, user experience and deployment potential [FRODDO Consortium, 2025a]. D5.1 defines the pilot framework, but the final validation results are not yet available as the full basis for this analysis [FRODDO Consortium, 2025f]. For this reason, the market-readiness judgement offered in this dissertation should be read as provisional. It captures a specific stage in the movement from technical development to market preparation, not the final commercial position of the project.

A second limitation concerns the market itself. City Digital Twins, CCAM services, mobility data platforms, traffic-management systems and digital infrastructure solutions increasingly overlap, but they do not yet form one stable and mature product category. This makes the boundaries of the market difficult to define. It also makes the value proposition harder to fix. A CDT may be presented as infrastructure intelligence, simulation capacity, decision support, data integration, safety support or GovTech innovation. These are related, but not identical. As a result, the analysis remains sensitive to future changes in regulation, procurement practice, public-sector digital capacity, data-space development and the results of large-scale pilots.

A third limitation concerns researcher positionality. The author is directly involved in the FRODDO project. This provides a richer understanding of the case, because it gives access to project logic, deliverables, pilot planning, internal assumptions and exploitation discussions. At the same time, it may also influence interpretation. An embedded researcher may understand the case in depth, but may also be closer to the project's own expectations, language and strategic ambitions. This limitation was addressed through reflexivity and triangulation, as explained in Chapter 3. FRODDO material was not treated as neutral proof of market readiness. It was compared with academic literature, policy sources, regulatory material and secondary cases. Still, the findings should be understood as the analysis of an informed participant, not as the judgement of a fully external evaluator.

Another limitation is the absence of primary fieldwork with external buyers and users. The dissertation uses literature, policy documents, project material and secondary cases, but it does not include interviews or surveys with city authorities, traffic-management centres, road operators, procurement officers, technology providers or end users. This means that the study can identify likely adoption conditions, barriers and value propositions, but it cannot claim to measure actual buyer intention or procurement readiness. The market perspective is therefore analytical and interpretive rather than directly empirical.

Future research should move in three directions. First, it should use the final FRODDO pilot results to test the proposed market-readiness framework against operational evidence. This would make it possible to examine whether the identified adoption drivers, barriers and value propositions are confirmed once the system is tested in real or near-real conditions.

Second, future research should collect buyer-side evidence. Interviews with municipalities, road operators, transport authorities, procurement departments and traffic-management organisations would help clarify what these actors actually need before adopting a CDT solution. This would also make it possible to test whether the proposed value propositions are clear, credible and procurement-relevant.

Third, the framework could be applied comparatively to other CDT and CCAM initiatives in Europe. A broader comparison would show which market-readiness conditions are specific to FRODDO and which are more general across the sector. This would strengthen the external validity of the study and could support the development of a more mature market-readiness assessment model for City Digital Twins.

Those limitations do not weaken the central argument of the dissertation. They define its scope. This study does not claim to prove that FRODDO, or any CDT solution, is already market-ready. It argues that market readiness must be understood as more than technical progress. It depends on evidence, governance, trust, procurement clarity, institutional capacity and actor-specific value. The next step is therefore empirical validation: testing the framework with pilot outcomes and with the organisations that may eventually buy, operate or regulate these systems.

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Appendix A: Summary of FRODDO Project Documents Used in the Dissertation

This Appendix summarises the FRODDO project documents used as the main evidence base for the dissertation. The documents are not treated as background material only. They support the dissertation's core argument: FRODDO is a CCAM-oriented CDT project moving from technical development toward market readiness, but still dependent on pilot evidence, stakeholder uptake, governance and exploitation pathways.

The Grant Agreement is the strategic and contractual base of the project. It defines FRODDO as Federated cybeR-physical infrastructure for ODD cOntinuity, funded under Horizon Europe and focused on CCAM safety through cooperation between automated vehicles, Operational Design Domains, Physical and Digital Infrastructure, road operators, authorities and data systems [FRODDO Consortium, 2024a]. The Grant Agreement is especially important for Chapter 1 and Chapter 4 because it explains why FRODDO matters: the project does not treat automated mobility as a vehicle-only problαδαΔΔεem. It treats it as an infrastructure and ecosystem problem. This is exactly where the CDT market-readiness issue begins.

D1.1, the Project Manual, gives the operational frame. It describes the work-package structure, governance arrangements, project coordination, reporting logic, quality management and risk-control processes [FRODDO Consortium, 2024b]. For this dissertation, D1.1 supports the understanding of FRODDO as a structured Innovation Action, not a loose technical experiment. It also shows the project's internal architecture: coordination, CCAM cooperation, cyber-physical infrastructure, federated DTs, pilots, legal/ethical/data-security work, and impact creation. Not glamorous, but necessary. Market readiness needs execution discipline before market claims can be taken seriously.

D6.2, the Ethical and Legal Framework, supports the regulatory and trust layer. It addresses ethical and legal monitoring, GDPR-related principles, participant protection, pilot ethics, transparency, accountability and the emerging AI regulatory context [FRODDO Consortium, 2024c]. In the dissertation, this deliverable is used mainly in Chapters 4 and 5, where trust, ethics and policy alignment are treated as market-readiness conditions. A CCAM-oriented CDT cannot be marketed only as a technical platform. It must also show that data, users, AI outputs and pilot activities are handled in a legally and socially acceptable way.

D4.1 is one of the central technical sources. It presents the first version of the FRODDO Digital Twin for transport management and describes it as a dynamic, federated and AI-assisted platform integrating real-time data, predictive analytics and simulation to support automated-vehicle operations [FRODDO Consortium, 2025a]. This deliverable is the basis for the technological maturity analysis. It explains the architecture, the Crimson DT platform, the Data Fusion Bus, the integration with decision support and early warning functions, plus the wider logic of interoperability and federation. For the dissertation, D4.1 is evidence that FRODDO's CDT is not merely a visual city model. It is an operational CCAM support environment.

D1.3, the updated Data Management Plan, provides the data-governance basis. It describes FRODDO's data lifecycle, including collection, storage, processing, sharing, protection, documentation and retention [FRODDO Consortium, 2025b]. It also identifies the main data categories: project reports, survey responses, system and module data, sensor data, video and eye-tracking recordings, infrastructure data, KPI data, user-profile data, processed data and metadata [FRODDO Consortium, 2025b]. In the dissertation, D1.3 is used to show that data governance is not a side issue. It is part of CDT market readiness. If data flows are not lawful, secure, documented and reusable, the DT cannot scale.

D2.1, Co-creation outcomes and User requirements, gives the stakeholder and adoption evidence. It reports FRODDO's early co-creation work and expert input, identifying interoperability, public trust, inclusive governance, harmonised strategies, structured partnerships and real-time data-sharing platforms as important conditions for CCAM deployment [FRODDO Consortium, 2025c]. This deliverable is central for Chapters 2, 3 and 4. It supports the dissertation's claim that the market for CCAM-oriented CDTs is not shaped only by technology. It is shaped by actors, shared rules, trust, data exchange and governance. A messy market. But real.

D3.1, the Dynamic ODD Extension Framework with Predictive Analytics, connects FRODDO's technical logic with the CCAM problem. It examines how Operational Design Domains can be extended or supported through predictive analytics, improved positioning, connectivity, behavioural modelling, infrastructure data and DT-based testing [FRODDO

Consortium, 2025d]. This is important because ODD continuity is one of FRODDO's strongest market-relevant claims. A CDT becomes valuable when it helps cities and road operators understand whether automated mobility can operate safely in a given road context. D3.1 supports that argument directly.

D4.6, Decision Support Dashboards - first version, gives the user-facing layer. It explains how predictive analytics, early warnings and contextual data are translated into dashboards for operators, planners, analysts and AV passengers [FRODDO Consortium, 2025e]. It distinguishes the expert dashboard integrated with the DT from the passenger-facing mobile dashboard, including trust and discomfort information. For the dissertation, this is important because market readiness depends on usability and interpretation. Operators do not adopt an architecture. They adopt tools they can read and act on. Users need something even simpler.

D5.1, the Pilot Testing Framework, provides the bridge between design and validation. It defines how FRODDO pilots are planned, structured and evaluated across different contexts, including Ljubljana, Athens, Modena and Bursa [FRODDO Consortium, 2025f]. This deliverable supports the dissertation's repeated point that FRODDO is technically credible, but still pilot-dependent. The framework is strong evidence of validation planning. It is not yet final proof of adoption. That distinction matters. Market-readiness claims become stronger only when pilot results show reliability, usefulness, transferability and stakeholder acceptance.

D7.3, the Interim Exploitation Report, is the main market-facing source. It identifies exploitation activities, emerging project results, joint exploitable results, key exploitable results and relevant market spaces such as connected vehicles, DTs, mobility data platforms and traffic management centres [FRODDO Consortium, 2025g]. In the dissertation, D7.3 is used to connect FRODDO's technical outputs with commercialisation and scaling. It also shows the central challenge: FRODDO has several possible market routes, but these need clearer product definition, buyer logic, evidence and post-project uptake pathways.

Together, these documents form the evidence spine of the study. The Grant Agreement and D1.1 explain why FRODDO exists and how it is organised. D4.1 and D3.1 explain the technical and ODD-related logic. D1.3 and D6.2 explain data, ethics and compliance. D2.1 explains stakeholder needs and adoption conditions. D4.6 shows how intelligence becomes user-facing decision support. D5.1 defines the pilot route. D7.3 connects the project to exploitation and market spaces.

FRODDO is not simply a DT project, nor only a CCAM project. It is a federated CCAM DT effort where technology maturity, data governance, stakeholder value, pilots and exploitation are developed together. That is why it was selected as the embedded research context for analysing CDT market readiness.

Appendix B: Overview of EU Regulatory Framework for CDT and CCAM Market Readiness

This Appendix summarises the EU regulatory framework most relevant to the dissertation's market-readiness analysis. The focus is not legal detail for its own sake. The focus is adoption. A CCAM-oriented CDT may be technically mature, but if it cannot explain how it handles AI, data, cybersecurity and accountability, public-sector uptake becomes difficult. Maybe impossible.

The AI Act is the central EU framework for AI-based systems. It sets harmonised rules for AI development, placement on the market, deployment and use, with an emphasis on human-centric and trustworthy AI, next to protection of health, safety and fundamental rights [European Parliament & Council of the European Union, 2024]. For FRODDO-type CDT solutions this is directly relevant because the platform logic includes AI-assisted prediction, simulation, decision support, early warning and user-facing outputs. The system does not merely display data. It interprets conditions and supports decisions. Different risk level.

In practical terms, the AI Act means that CDT developers and adopters must be able to describe what AI components are used, what role human oversight plays, what data supports the models, how outputs are presented, and what risks remain. FRODDO's Ethical and Legal Framework already moves in this direction by addressing ethical and legal monitoring, participant protection, transparency, accountability and the emerging AI regulatory context [FRODDO Consortium, 2024c]. This matters for market readiness because buyers do not only need performance but they also need assurance.

GDPR remains the core framework for personal data protection in the EU, even though the original regulation predates the five-year citation window. For that reason, this appendix refers to the European Commission's 2024 second report on GDPR application, which confirms the continuing centrality of GDPR enforcement, consistency, rights protection and compliance challenges [European Commission, 2024]. In a CCAM/CDT setting, GDPR becomes relevant whenever data relates to identifiable or potentially identifiable persons: passengers, drivers, participants in pilots, survey respondents, pedestrians captured in video, location traces, user profiles, behavioural indicators. Sometimes personal data is obvious while others it is hidden in metadata.

FRODDO's updated Data Management Plan is relevant here because it treats data as a lifecycle issue: collection, storage, processing, sharing, documentation, access control and retention [FRODDO Consortium, 2025b]. It also refers to data minimisation, anonymisation, pseudonymisation, encryption, access control, logging and auditing [FRODDO Consortium, 2025b]. For market readiness, this is not administrative background. It is part of trust. A public authority will not easily adopt a data-intensive CDT if the data logic is unclear.

The Data Act adds another layer. It sets harmonised rules on fair access to and use of data in the EU [European Parliament & Council of the European Union, 2023]. This matters because CDT systems depend on data access across connected infrastructure, vehicles, platforms, public authorities and service providers. A CDT cannot work well if relevant data remains locked inside isolated systems or controlled through unclear agreements. The market issue is plain: data access is not only a legal condition. It is a scaling condition.

For FRODDO-type solutions, the Data Act is especially relevant because market entry may involve several actors: road operators, technology providers, public authorities, traffic management centres, infrastructure owners and mobility services. Each actor may hold part of the data needed for operational value. The Data Act does not solve every governance question, but it pushes the market toward clearer rules for data sharing, access and reuse. That direction fits the dissertation's argument about federated CDT market readiness.

NIS2 provides the cybersecurity frame. The directive aims to achieve a high common level of cybersecurity across the Union and expands the EU cybersecurity regime beyond the earlier NIS framework [European Parliament & Council of the European Union, 2022]. For CCAM-oriented CDTs, cybersecurity is not a technical afterthought. The system may connect infrastructure data, mobility services, dashboards, APIs, identity management, prediction layers and operational warnings. A weak cyber posture would damage trust immediately.

NIS2 is also relevant because transport and digital infrastructure are close to its logic of essential and important entities, depending on the specific organisation and national implementation. A CDT deployed with a city or traffic authority would need strong risk-management procedures, incident handling, supplier awareness, secure access, and resilience. FRODDO’s data-management and security measures, including encryption, secure transfer, access control and auditing, support this direction [FRODDO Consortium, 2025b]. Not enough by itself for certification or compliance, but a useful readiness base.

Together, these frameworks create a regulatory trust triangle, plus one data-market layer. The AI Act asks whether AI functions are safe, transparent, supervised and rights-compatible. GDPR asks whether personal data is processed lawfully and protected. NIS2 asks whether the networked system is cyber-resilient. The Data Act asks whether data access and use can be organised fairly across actors. For CCAM DTs, all four questions meet in the same place.

So the regulatory conclusion is simple. Compliance is not only a brake on innovation. It is also a market condition. A FRODDO-type CDT that can show AI Act awareness, GDPR-grade data governance, Data Act compatibility and NIS2-style cybersecurity maturity will be easier to trust, procure and scale. A CDT that cannot explain these issues may still be technically interesting. Commercially fragile though.

Declaration on the Use of Artificial Intelligence:

During the preparation of this dissertation, ChatGPT (OpenAI) was used to support the organisation of ideas and the revision of language, clarity and structure. AI-assisted material was critically reviewed and revised by the author, and factual statements and references were checked against the original sources. The author exercised independent judgement in selecting and incorporating suggestions and in determining the research approach, interpretation and conclusions. The author accepts full responsibility for the final dissertation, including its accuracy, originality, appropriate attribution and academic integrity.

Author’s Statement:

I hereby declare that, in accordance with dissertation 8 of Law 1599/1986 and dissertation 2.4.6 par. 3 of Law 1256/1982, this thesis/dissertation is solely a product of personal work and does not infringe any intellectual property rights of third parties and is not the product of a partial or total plagiarism, and the sources used are strictly limited to the bibliographic references.