



**Politecnico
di Torino**

Politecnico di Torino

Master's Degree in Engineering and Management

Master's thesis:

Optimizing CCAM Deployment through the GUEST-SI Methodology:

A Stakeholder-Centric Approach within the Sinfonica Framework

Relator:

Prof. Guido Perboli

Prof. Francesca Merlo

Candidate:

Samaneh Oroujalian Mashhadi

Academic Year 2024/2025

Contents

Abstract.....	5
Chapter 1: Foundations of CCAM Deployment.....	6
1.1 Understanding CCAM.....	6
1.1.1 Overview of Connected, Cooperative, and Automated Mobility	6
1.1.2 Inclusivity and Human-Centric Mobility in CCAM.....	7
1.1.3 Institutional Roles and Deployment Readiness	8
1.2 The Evolution of Mobility Systems.....	8
1.2.1 From Traditional Transport to Intelligent Automation	8
1.2.2 Key Enablers and Barriers of CCAM Integration.....	9
1.2.3 From Vehicles to Ecosystems: The Emerging Paradigm.....	10
1.3 The CCAM Deployment Process	11
1.3.1 From Pilot to Scale: Phased Implementation of CCAM.....	11
1.3.2 Strategic Enablers: Policy, Infrastructure, and Technological Adaptation.....	12
1.4 Business and Operational Models for CCAM	14
1.4.1 Structuring Cooperation Between Public and Private Stakeholders	14
1.4.2 Innovation Models for CCAM: Business Agility, Experimentation, and Transformation.....	15
CHAPTER 2: The Sinfonica Framework – A Coordinated Approach to CCAM.....	17
2.1 Introduction to SINFONICA	17
2.1.1 What is SINFONICA?	17
2.1.2 Objectives of SINFONICA as a European Framework.....	18
2.1.3 How SINFONICA Aligns with CCAM Deployment Strategies	18
2.2 Collaborative Governance Models for Mobility Integration.....	20
2.2.1 Technical, Economic, and Regulatory Coordination	21
2.2.2 Stakeholder Engagement and the Role of Public-Private Partnerships.....	24
2.3 SINFONICA’s Role in CCAM Implementation.....	26
2.3.1 Providing Interoperability Guidelines for CCAM Systems	26
2.3.2 Supporting Standardization of Automated Mobility Solutions	28
2.3.3 Enhancing Cross-Border Deployment Efforts.....	30
CHAPTER 3: Challenges and Requirements in CCAM Deployment.....	32
3.1 The CCAM Ecosystem.....	32
3.1.1 Key Stakeholders in CCAM	32
3.1.2 Collaborative Frameworks for CCAM Deployment.....	33
3.2 Barriers to Effective CCAM Implementation	35
3.2.1 Regulatory Hurdles and Standardization Issues	35

3.2.2 Infrastructure Readiness and Digital Connectivity Challenges	36
3.2.3 Public Acceptance and Behavioral Adaptation to Automated Mobility	38
3.3 The Role of SINFONICA in CCAM Coordination	40
3.3.1 Policy and Technical Integration	40
3.3.2 Stakeholder Cooperation and Participatory Engagement	41
3.3.3 Decision Support Tools for Strategic Alignment	41
Chapter 4: The GUEST-SI Framework for CCAM Deployment.....	42
4.1 Lessons from Past Mobility Initiatives	42
4.1.1 Reviewing European Mobility Projects and Their Impact on CCAM	42
4.1.2 Lessons on Stakeholder Engagement and Public Acceptance.....	43
4.1.3 Technological Readiness and Infrastructure Gaps	44
4.1.4: Economic and Policy Implications for CCAM Scaling.....	46
4.2 The GUEST-SI Framework	47
4.2.1 Enhancing Systematic Stakeholder Engagement in CCAM Planning	48
4.2.2 Aligning Technical, Economic, and Regulatory Aspects of CCAM Deployment	49
4.3.1 Urban Mobility Management Systems	51
4.3.2 Automated Freight Logistics and Transport Corridors	53
4.3.3 Multi-Modal Connectivity Solutions	54
5: Implementation of the GUEST-SI Methodology.....	56
5.1 Operationalizing the GUEST-SI Methodology in CCAM Contexts	56
5.1.1 Application of Structured Decision-Making Models.....	56
5.2 Stakeholder-Centered Tools in GUST-SI.....	66
5.2.1 Actor ID: Mapping Stakeholder Roles and Influences	68
5.2.2 Value Ring: Aligning User Needs with Service Design	81
5.2.3 User Needs Matrix: Structuring Priorities by Actor Group	82
5.2.4 Enabling Knowledge Transfer and System Mapping	83
5.3 Implementation Results Across Pilot Cities	84
5.3.1 Trikala: Co-Creation and Rural Inclusion Strategies	85
5.3.2 Hamburg: Accessibility and Trust in Urban CCAM.....	87
5.3.3 Noord-Brabant: Mobility Equity and Digital Literacy.....	88
5.3.4 West Midlands: Institutional Trust and Participatory Pilots	90
5.4 Lessons Learned and Methodological Reflections	93
5.4.1 Strengths and Adaptability of GUEST-SI.....	94
5.4.2 Challenges in Cross-City Implementation	96
5.4.3 Alignment with EU CCAM, Digital Inclusion, and Mobility Policy Frameworks ..	97
5.4.2 Recommendations and Future Directions.....	98

CHAPTER 6: Business and Economic Models for CCAM Scalability	101
6.1 Stakeholder Roles in Value Generation and Funding	101
6.1.1 Collaborative Funding Mechanisms for CCAM	101
6.1.2 Economic Incentives for Public and Private Actors.....	102
6.2 Typologies of Business Models for CCAM Deployment	103
6.2.1 Infrastructure-Based CCAM Business Models	104
6.3 Economic and Social Evaluation of CCAM Scalability	108
6.3.1 Assessing Financial Viability and Return on Investment	108
6.3.2 Cost-Benefit and Equity Outcomes in Regional Mobility.....	109
Chapter 7: Conclusions.....	111
7.1 Summary of Research Objectives and Methodology	111
7.2 Key Findings and Contributions.....	112
7.3 Theoretical and Practical Implications	114
7.4 Policy Recommendations for Inclusive CCAM Deployment.....	116
7.5 Limitations of the Study	118
7.6 Future Research Directions.....	120
7.7 Final Reflection.....	122
References	124

Abstract

The deployment of Connected, Cooperative, and Automated Mobility (CCAM) in Europe presents a transformative opportunity to enhance urban transport systems, making them more inclusive, accessible, sustainable, and human-centric. However, aligning technical innovation with societal acceptance remains a major challenge. This thesis, developed within the framework of the SINFONICA project, investigates how stakeholder engagement and value co-creation can guide effective and inclusive CCAM deployment.

To address this, the study applies the GUEST-SI methodology, a structured stakeholder integration toolset that includes Actor ID Cards, Value Rings, and a User Needs Matrix. These tools were implemented using qualitative data gathered from focus groups and interviews in four European pilot regions: Hamburg, Noord-Brabant, Trikala, and the West Midlands. The findings highlight the diverse needs, expectations, and priorities of stakeholders—especially vulnerable and digitally excluded groups—and reveal key tensions between automation, affordability, data governance, and physical accessibility.

By translating these insights into actionable deployment strategies, the thesis proposes a participatory model that supports policy harmonization, ethical design, and equitable benefit distribution in CCAM ecosystems. The results underscore the importance of involving all actor groups early and continuously in the mobility innovation lifecycle, thereby fostering trust, legitimacy, and long-term adoption of CCAM solutions in Europe.

Keywords: CCAM, SINFONICA, GUEST-SI, stakeholder engagement, Actor ID, Value Ring, user needs, inclusive mobility, accessibility, policy, automation.

Chapter 1: Foundations of CCAM Deployment

1.1 Understanding CCAM

1.1.1 Overview of Connected, Cooperative, and Automated Mobility

Connected, Cooperative, and Automated Mobility (CCAM) refers to a transformative transport paradigm that converges real-time communication, intelligent cooperation, and automation technologies to create a safer, more sustainable, and user-centric mobility ecosystem. It moves beyond conventional transportation models by promoting machine-to-machine (M2M) communication, decentralized decision-making, and integrated mobility services.

Connected Mobility enables vehicles and infrastructure to exchange data via V2V (Vehicle-to-Vehicle), V2I (Vehicle-to-Infrastructure), and V2X (Vehicle-to-Everything) communication protocols. These technologies provide situational awareness, dynamic routing, and hazard anticipation (Ferreira, 2019). Advanced edge computing and multi-access edge networks further support low-latency data processing, which is essential for real-time operations in CCAM environments.

Cooperative Mobility fosters interaction and coordination among vehicles and infrastructure to enhance traffic efficiency and safety. This includes applications like platooning, intersection management, and lane merging, where automated agents act on shared intentions rather than isolated sensor inputs (Ferreira, 2019). Crucially, such cooperation hinges on ultra-reliable low-latency communications (URLLC) and synchronization frameworks that ensure seamless joint operations.

Automated Mobility leverages artificial intelligence, sensor fusion, and machine learning to support autonomy across all SAE levels. Full automation scenarios, such as Shared Automated Electric Mobility Systems (SAEMS), require intelligent planning across stakeholders to simulate complex trade-offs in urban space, energy, and equity (Yu & McKinley, 2024). Automation also introduces ethical and regulatory complexities, requiring trust frameworks and human-machine governance protocols.

A key enabler of CCAM's full potential lies in hybrid communication architectures that ensure reliability even in non-ideal deployment scenarios. For instance, the hybrid vehicular

network proposed by Amador Molina et al. (2022) utilizes LTE and DSRC (IEEE 802.11p) to alert drivers about vulnerable road users (VRUs), even when direct line-of-sight is obstructed. These safety innovations illustrate how CCAM integrates both emerging technologies and human-centered considerations.

Furthermore, as CCAM matures, ensuring **lightweight, scalable, and secure communication** becomes imperative. Boutahala et al. (2025) propose a “light security scheme” for CCAM in which one-time mutual authentication and behavioral consistency monitoring reduce the computational load while preserving trust, offering an efficient alternative to traditional cryptographic methods.

1.1.2 Inclusivity and Human-Centric Mobility in CCAM

While CCAM is technologically intensive, it must remain grounded in the everyday mobility needs of diverse user groups. Ringhand et al. (2024) emphasize the necessity of aligning CCAM services with complex and multidimensional mobility determinants—including socioeconomic status, physical ability, digital access, and spatial context. Their inclusive framework, applied in the SINFONICA project, outlines how CCAM can cater to users traditionally excluded from transport innovation.

This framework distinguishes three key dimensions:

- **Mobility Needs:** Shaped by psychological drivers (e.g., autonomy, competence), physical abilities, digital literacy, and contextual factors such as environment and trip purpose.
- **CCAM Design Requirements:** Systems must offer accessibility, affordability, availability, and acceptability—core principles for equitable deployment.
- **Behavioral Use Intention:** Based on the Theory of Planned Behavior (Ajzen, 1991), successful adoption requires aligning user attitudes, social norms, and perceived behavioral control with CCAM offerings.

Specific attention is given to user groups such as women, LGBTQIA+ individuals, migrants, rural residents, the elderly, and people with disabilities—all of whom may face unique access or interaction challenges (Ringhand et al., 2024). Addressing these needs requires participatory and iterative design processes.

To this end, **synthetic participatory planning**—as demonstrated by Yu & McKinley (2024)—offers a scalable method for including diverse stakeholder perspectives. Using digital avatars in structured simulations, planners can evaluate alternative CCAM systems across criteria like equity, infrastructure integration, and innovation, thereby identifying solutions that reflect public values without the logistical complexity of traditional focus groups.

1.1.3 Institutional Roles and Deployment Readiness

CCAM deployment is not solely a technological or market-driven challenge—it requires robust institutional commitment and multi-level governance. Fagerholt et al. (2023) show that in Norway, public agencies view their role in CCAM not merely as regulators but as **enablers**. Authorities can facilitate CCAM through intersectoral collaboration, investment in digital infrastructure, and shared learning ecosystems.

Their study identifies key drivers and barriers:

- **Drivers:** Interdisciplinary competence, trust-based collaboration, and adaptive regulation.
- **Barriers:** Resource constraints, lagging technological maturity (e.g., 5G positioning services), and the lack of strategic alignment between physical and digital infrastructure investment.

Importantly, CCAM progress depends on **coordinated national strategies**. These must designate lead agencies, incentivize data-sharing, and formalize learning pathways (Fagerholt et al., 2023). Failure to align strategic planning with technical capacity can result in fragmented rollouts and diminished public trust.

1.2 The Evolution of Mobility Systems

1.2.1 From Traditional Transport to Intelligent Automation

The evolution of mobility systems is characterized by the progressive layering of technological, social, and infrastructural innovations—from human-operated transport to intelligent, data-driven ecosystems. This transformation has occurred in four broad phases:

1. **Manual and Mechanized Transport:** Historically, mobility systems were dominated by human-operated, unconnected vehicles with minimal regulatory and planning frameworks. This phase prioritized mechanical advancement (e.g., combustion engines) but offered limited responsiveness to real-time travel conditions or user diversity.
2. **Digitally Connected Mobility:** The integration of GPS, telematics, and digital route planning laid the groundwork for today's connected transport systems. These tools enabled smarter traffic management, more informed decision-making, and eventually the integration of vehicle sensors into broader Intelligent Transportation Systems (ITS) (Ferreira, 2019).
3. **Automated and Cooperative Systems:** The current phase is defined by artificial intelligence, V2X communication, and automation across the transport stack. Vehicles and infrastructure can now engage in real-time coordination to optimize safety and efficiency, moving toward full autonomy.
4. **Participatory and Inclusive Planning Models:** The future of mobility lies not only in automation but in participatory and adaptive planning systems that integrate social, behavioral, and ethical dimensions. For instance, Synthetic Participatory Planning (SPP) frameworks simulate multi-stakeholder collaboration using AI-generated avatars to evaluate Shared Automated Electric Mobility Systems (SAEMS) over decades (Yu & McKinley, 2024). This method allows planners to account for equity, innovation, and infrastructure trade-offs in a scalable and evidence-based manner.

A key inflection point in this evolution is the shift from **infrastructure-centric design** to **user- and behavior-centric design**. This is supported by models that recognize not just travel demand but also user experience, digital inclusion, and environmental outcomes (Ringhand et al., 2024).

1.2.2 Key Enablers and Barriers of CCAM Integration

As mobility systems evolve into complex cyber-physical environments, several factors critically shape the successful integration of CCAM technologies:

A. Technological Maturity

Advances in sensors, communication protocols, and distributed AI are foundational. However, many CCAM services still face technical barriers—such as limited deployment

of 5G edge infrastructure, imprecise GPS in urban canyons, and interoperability gaps across V2X devices (Amador Molina et al., 2022; Boutahala et al., 2025). Security and scalability must also be addressed through lightweight, decentralized authentication systems that maintain trust without increasing latency (Boutahala et al., 2025).

B. Institutional Capacity and Governance

According to Fagerholt et al. (2023), public agencies play a crucial enabling role in CCAM by aligning technical development with infrastructure planning and inter-sectoral governance. In Norway, digital infrastructure is often underfunded relative to traditional road investments, limiting the real-time capacity required for CCAM applications. Furthermore, institutions must develop learning-oriented cultures that can adapt regulations as technologies mature.

C. Human and Social Factors

Public trust, digital literacy, and user behavior are essential for adoption. CCAM cannot succeed with a purely top-down technological approach. Ringhand et al. (2024) emphasize the importance of tailoring services to varied mobility needs—particularly for digitally excluded groups, low-income populations, the elderly, and disabled individuals. Behavioural models such as the Theory of Planned Behaviour and Self-Determination Theory explain how perceived control, social norms, and intrinsic motivation influence adoption.

D. Stakeholder Engagement and Design Co-Production

The evolution of mobility requires robust participatory methods. Traditional transport planning models often exclude vulnerable stakeholders from meaningful participation. Synthetic participatory methods offer a novel solution by simulating diverse perspectives in co-creating system goals and trade-offs (Yu & McKinley, 2024). This aligns with the broader CCAM objective of democratic innovation and inclusive mobility design.

1.2.3 From Vehicles to Ecosystems: The Emerging Paradigm

Mobility is no longer defined solely by vehicles or infrastructure but by dynamic interactions among users, services, and systems. As such, CCAM redefines mobility as a **multi-agent, interoperable ecosystem** with the following features:

- **Decentralized Control:** Vehicles operate semi-autonomously while exchanging data through shared standards.

- **Context-Aware Behavior:** Systems adjust based on real-time user profiles and urban conditions.
- **Multimodal Integration:** Automated shuttles, public transit, and micro-mobility converge under platforms like MaaS.
- **Socially Intelligent Design:** Interfaces and services adapt to user diversity and behavioral patterns.

This systems-level transformation requires cities and national governments to reimagine their roles—not just as regulators but as orchestrators of data governance, ethical frameworks, and public-private innovation coalitions.

1.3 The CCAM Deployment Process

1.3.1 From Pilot to Scale: Phased Implementation of CCAM

The deployment of Connected, Cooperative, and Automated Mobility (CCAM) systems follows a structured, multi-phase trajectory that progresses from small-scale research environments to large-scale, real-world implementations. This evolutionary pathway reflects the complexity of integrating novel technologies into socio-technical systems where safety, trust, regulatory readiness, and user acceptance are paramount.

Phase 1: Research and Development (R&D)

This phase involves technological feasibility assessments and concept validation. R&D activities include the design of communication protocols, simulation of autonomous driving scenarios, and laboratory testing of edge-computing architectures. Notably, Ferreira (2019) emphasizes that while connected vehicle functionalities are increasingly present in commercial models, true V2X-based cooperation remains largely underdeveloped and continues to be the subject of experimental research.

Phase 2: Pilot Testing in Controlled Environments

Next, technologies are introduced into closed testbeds or monitored environments. In Sweden, for example, Amador Molina et al. (2022) tested a hybrid vehicular network—combining LTE and DSRC—to protect Vulnerable Road Users (VRUs) such as pedestrians and cyclists. Their PoC system demonstrated the capacity to send alerts to vehicles within a

130-meter range, confirming its effectiveness in both urban and track environments. However, limitations such as GPS imprecision and cellular variability underscore the importance of this controlled phase for refining system robustness.

Phase 3: Field Operational Tests (FOTs)

FOTs mark the transition to real-world deployment. They evaluate CCAM performance under naturalistic driving conditions and in partnership with public authorities and private providers. These tests assess not only technical functionality but also behavioral dynamics and legal frameworks. Fagerholt et al. (2023) report that in Norway, real-world pilots involving the Norwegian Public Roads Administration faced challenges related to digital infrastructure maturity, indicating that scaling up requires more than functional technology—it demands system readiness across public institutions.

Phase 4: Pre-Commercial Deployment

At this stage, CCAM services are introduced in limited public markets or selected urban areas to gauge user adoption and operational feasibility. Yu & McKinley (2024) suggest that participatory planning frameworks—particularly those leveraging digital stakeholder simulations—can support decision-makers in evaluating the trade-offs of different deployment models (e.g., sustainability vs. innovation, or infrastructure vs. equity). Such structured foresight is crucial before scaling.

Phase 5: Full-Scale Integration

Full-scale deployment involves standardized integration of CCAM technologies across national and transnational transport systems. Interoperability becomes a central concern, especially across borders and vendors. As emphasized by Boutahala et al. (2025), communication overhead and cryptographic complexity must be reduced to maintain system efficiency and scalability. Their proposed light security scheme, which authenticates vehicles once and uses behavioral consistency monitoring for ongoing trust, offers one solution to this challenge.

1.3.2 Strategic Enablers: Policy, Infrastructure, and Technological Adaptation

Achieving scalable, inclusive CCAM deployment depends on more than technical maturation. It requires a convergence of strategic enablers that operate across policy, infrastructure, and technological domains.

A. Regulatory Readiness and Public Sector Enablement

Authorities must actively shape CCAM deployment by providing clear frameworks for liability, cybersecurity, and ethical standards. According to Fagerholt et al. (2023), Norwegian public agencies see themselves as **enablers** rather than passive regulators. Their strategy includes assigning coordinating institutions, expanding interdisciplinary collaboration, and embedding learning mechanisms within institutions. Such adaptive governance is crucial to guide CCAM development through uncertainty. Moreover, CCAM's inherent complexity demands cross-sector alignment—particularly between transportation, communications, and spatial planning authorities. Institutional silos remain a barrier, and aligning investment strategies for both digital and physical infrastructure is necessary to avoid mismatched deployment timelines.

B. Infrastructure Transformation

To support real-time decision-making, urban and interurban infrastructure must be upgraded with sensor networks, smart intersections, roadside units (RSUs), and cloud-edge systems. This includes:

- **Positioning Systems:** High-definition maps and sub-meter GPS accuracy are essential for AVs. However, Amador Molina et al. (2022) show that positioning inaccuracies remain a significant limitation in dense urban areas.
- **Communication Networks:** The implementation of ultra-reliable low-latency networks (URLLC) is fundamental to ensure the timing of cooperative manoeuvres. Cellular coverage variation, especially in mixed urban-suburban corridors, can lead to message delay or failure, reducing system safety and usability.
- **Redundancy and Resilience:** As Boutahala et al. (2025) demonstrate, relying on centralized security and communication brokers introduces potential points of failure. Future-ready infrastructure should support redundancy, decentralization, and fault tolerance at scale.

C. Technological Interoperability and Scalability

Achieving interoperability across CCAM platforms is a foundational requirement for deployment. Systems must communicate seamlessly across vehicle brands, jurisdictions, and service providers. Lightweight security protocols, such as the one proposed by Boutahala et al. (2025), reduce the overhead of continuous cryptographic validation, enabling wider scalability while preserving safety integrity.

Additionally, Yu & McKinley (2024) emphasize the importance of scenario-based evaluations in long-term planning. By simulating how CCAM systems perform under different stakeholder values and budget constraints, cities can prioritize configurations that optimize both technological and social performance (e.g., equity-focused vs. innovation-led deployments).

1.4 Business and Operational Models for CCAM

The sustainable deployment of Connected, Cooperative, and Automated Mobility (CCAM) systems requires not only technological readiness and regulatory support but also innovative business and operational models. These models must facilitate collaboration between public and private stakeholders, enable scalable funding mechanisms, and adapt to the uncertainty and complexity inherent in disruptive mobility innovation. In this context, CCAM is not simply a transportation reform—it is a platform for systemic business transformation.

1.4.1 Structuring Cooperation Between Public and Private Stakeholders

The successful realization of CCAM depends on multi-actor collaboration. Public authorities, infrastructure managers, mobility operators, and technology developers each hold vital roles across the CCAM value chain:

- **Public Sector Actors:** These include transport authorities, municipalities, and policy-makers who define regulatory frameworks, urban development goals, and inclusion standards. As shown in Norway’s experience, public actors often see themselves as enablers of CCAM through inter-agency collaboration and institutional learning structures (Fagerholt et al., 2023).
- **Technology Developers and OEMs:** These private actors drive innovation in AI, V2X communication, autonomous vehicle systems, and safety architectures. Startups and agile SMEs also contribute through iterative innovation processes, often using Lean Startup principles to develop minimum viable products (MVPs) and pivot according to real-world testing (Bocken & Snihur, 2019).
- **Mobility and Platform Operators:** Shared mobility services, MaaS providers, and logistics companies deploy CCAM-enabled services. They rely on robust data exchange and customer engagement strategies to manage fleet operations, user subscriptions, and pricing models. Many of these actors draw upon platform-based,

digitally intermediated business strategies akin to those seen in the broader digital entrepreneurship space (Ghezzi & Cavallo, 2018).

- **Infrastructure and Communication Providers:** These include telecommunications operators, smart city planners, and digital infrastructure firms responsible for deploying roadside units, 5G coverage, and data centers that enable real-time CCAM operation (Boutahala et al., 2025).

A key challenge is coordinating these stakeholders toward shared objectives. The synthesis of public value (e.g., safety, equity, sustainability) with private incentives (e.g., ROI, IP protection) requires hybrid governance and contractual models such as public-private partnerships (PPPs), open data standards, and incentive-aligned procurement frameworks.

1.4.2 Innovation Models for CCAM: Business Agility, Experimentation, and Transformation

CCAM development and deployment face high uncertainty, fragmented regulation, and evolving user expectations. In such conditions, traditional linear planning models are insufficient. Instead, adaptive and experimental frameworks are necessary to iterate on service models, validate user needs, and align infrastructure investment with evolving contexts.

A. Lean Startup Methodology and MVPs

Lean Startup is a strategic innovation framework designed for environments of high uncertainty, which aligns well with the dynamic landscape of CCAM. It emphasizes rapid experimentation, customer feedback, and MVPs to test assumptions before large-scale investment (Bortolini et al., 2018; Bocken & Snihur, 2019). In CCAM, this could translate into:

- Testing autonomous shuttle services in confined campuses or business parks before broader deployment.
- Experimenting with cooperative platooning for freight in designated logistics corridors.
- Deploying MaaS platforms in limited regions to validate pricing bundles and user experience before citywide scaling.

This iterative approach allows mobility operators and cities to refine both technology and business models in real-time, reducing the risk of costly failures or low adoption.

B. Business Model Innovation (BMI)

CCAM also calls for deep **Business Model Innovation (BMI)**—non-trivial reconfiguration of how value is created, delivered, and captured in mobility systems (Trimi & Berbegal-Mirabent, 2012). For instance:

- CCAM-enabled MaaS platforms shift value creation from infrastructure and vehicle ownership to service integration and personalization.
- Autonomous vehicle fleets challenge traditional car ownership and insurance models.
- Cooperative infrastructure may require subscription-based or tokenized access frameworks for interoperability.

These innovations are driven by digital platform design, modular service architectures, and API ecosystems—consistent with digital entrepreneurship and agile innovation practices (Ghezzi & Cavallo, 2018).

C. Disruptive Innovation and Strategic Ambidexterity

Disruptive innovation theory (Christensen et al., 2016) helps explain how CCAM can challenge existing mobility systems by introducing initially lower-performance but novel alternatives—such as small autonomous shuttles replacing high-capacity buses in certain contexts, or app-based micro-mobility platforms outcompeting legacy transit providers on short routes.

The risk, however, is that incumbent actors fail to adapt because they over-invest in existing models. Strategic ambidexterity—balancing exploitation of current assets with exploration of new models—is essential for both private firms and public agencies. Incumbents can create autonomous spin-offs or co-develop CCAM pilots with startups to diversify innovation risk while maintaining alignment with legacy operations.

CHAPTER 2: The Sinfonica Framework – A Coordinated Approach to CCAM

2.1 Introduction to SINFONICA

2.1.1 What is SINFONICA?

SINFONICA (*Social Innovation for Inclusive CCAM Deployment*) is a European Union-funded initiative under the Horizon Europe programme, established to develop a comprehensive framework for the ethical, inclusive, and coordinated deployment of Cooperative, Connected, and Automated Mobility (CCAM) across the continent. The project addresses the urgent need to align technical innovation in automated mobility with the values of social equity, user diversity, and institutional trust.

Unlike traditional CCAM deployments that are driven primarily by technological feasibility, SINFONICA adopts a **human-centric and stakeholder-driven approach**, integrating interdisciplinary insights from transport engineering, social psychology, digital ethics, and participatory governance (Ringhand et al., 2024; Grandsart et al., 2025). Its primary focus lies in co-creating mobility solutions with all societal groups—particularly vulnerable road users—while ensuring that CCAM infrastructures are interoperable, trusted, and harmonized across European borders.

The framework is operationalized through a combination of technical standardization, inclusive design tools, stakeholder engagement mechanisms, and decision support systems. It serves as both a methodological guide and a policy-shaping tool for regions, cities, and transport authorities aiming to implement CCAM in a socially sustainable manner.

Definition: *SINFONICA is a human-centric, stakeholder-driven, and digitally integrated framework for the inclusive, interoperable, and ethical deployment of CCAM systems in Europe. It integrates technical coordination, participatory engagement, and policy harmonization to ensure equitable access to automated mobility.*

2.1.2 Objectives of SINFONICA as a European Framework

SINFONICA’s mission aligns with the European Green Deal, Vision Zero, and the EU Smart Mobility Strategy by supporting CCAM technologies that are not only intelligent and efficient, but also accessible, inclusive, and trusted. Its objectives span five interlinked dimensions:

1. **Enhancing Social Acceptance and Trust:** By applying the Theory of Planned Behavior and Self-Determination Theory, SINFONICA identifies psychological and social factors that shape CCAM adoption across user groups (Ringhand et al., 2024).
2. **Ensuring Inclusivity for Vulnerable Groups:** The project prioritizes underrepresented populations through inclusive co-design and participatory planning (Grandsart et al., 2025; Pangbourne et al., 2020).
3. **Developing Tools for Stakeholder Engagement:** Practical instruments like the Actor ID Card, Stakeholder Analysis Matrix, and co-creation workshops enable structured, continuous engagement of relevant actors (Grandsart et al., 2025; SINFONICA D4.1, 2024).
4. **Advancing Technical and Data Interoperability:** SINFONICA supports alignment with European efforts in V2X, 5G, and AI-powered CCAM by advocating for interoperable and privacy-respecting system design (Ferreira, 2019; Santa et al., 2022).
5. **Supporting Evidence-Based Policy and Regulation:** Through the development of knowledge maps and policy briefs, SINFONICA empowers policymakers to draft inclusive, harmonized CCAM regulations (Fagerholt et al., 2023).

Together, these dimensions position SINFONICA as a key enabler in Europe’s transition toward connected, equitable, and sustainable mobility systems.

2.1.3 How SINFONICA Aligns with CCAM Deployment Strategies

SINFONICA strategically aligns with the European vision for Cooperative, Connected, and Automated Mobility (CCAM) by operationalizing inclusive, participatory, and data-driven mechanisms for mobility innovation. A central pillar of this alignment is SINFONICA’s user-centric methodology. The project integrates behavioral, psychological, and contextual dimensions of mobility needs—particularly for vulnerable road users (VRUs)—into the design and assessment of CCAM solutions (Ringhand et al., 2024). This inclusion is

implemented through structured tools such as the Actor ID Card, Stakeholder Analysis Matrix, and participatory workshops, which specifically address the priorities of underrepresented groups including people with disabilities, low-income populations, rural residents, and the elderly.

Additionally, SINFONICA addresses key technical and infrastructural prerequisites for CCAM deployment by supporting the harmonization of communication standards such as Vehicle-to-Everything (V2X) and by promoting robust, ethics-oriented data governance. These efforts align with broader EU objectives around interoperability, standardization, and secure data exchange across mobility ecosystems (Ferreira, 2019). By integrating principles of ethical AI and privacy-by-design, SINFONICA contributes to building trusted digital infrastructures that are essential for the cross-border scalability of automated mobility services.

Crucially, the project complements the technological domain with rigorous social engagement mechanisms. Drawing from methodologies piloted in SHOW and supported by stakeholder engagement literature, SINFONICA applies participatory mechanisms—such as Ideathons, MAMCA workshops, and hackathons—to co-create service models and refine deployment scenarios (Grandsart et al., 2025). These formats enable iterative design processes that align with local governance structures and public expectations, mitigating the risk of socio-technical misalignment that can hinder CCAM acceptance (Hutahaeen, 2017).

Moreover, SINFONICA facilitates the systemic inclusion of CCAM into multimodal urban transport ecosystems through integration with Mobility-as-a-Service (MaaS) paradigms. Its emphasis on accessibility, affordability, and seamless cross-border interoperability addresses concerns about exclusion and fragmentation in current automated transport models (Lyons et al., 2020; Pangbourne et al., 2020). For instance, its efforts to standardize fare integration and digital infrastructure align with broader goals of reducing cognitive load and increasing behavioral adoption of CCAM services (Ringhand et al., 2024).

On a governance level, SINFONICA adopts a collaborative, multilevel coordination strategy that aligns with principles emphasized in Scandinavian deployments and anticipatory governance models (Fagerholt et al., 2023). This approach fosters intersectoral collaboration between infrastructure agencies, digital communication regulators, and public mobility

operators—key to overcoming fragmented decision-making and advancing cohesive, cross-border regulatory readiness.

2.2 Core Components of SINFONICA

2.2.1 Collaborative Governance Models for Mobility Integration

A defining feature of the SINFONICA framework is its emphasis on collaborative, multi-level governance models that bridge institutional, technological, and societal domains to ensure equitable CCAM (Cooperative, Connected, and Automated Mobility) deployment. In contrast to top-down, techno-centric strategies, SINFONICA fosters co-governance by engaging diverse stakeholders—public authorities, technology developers, citizens, and advocacy groups—across local, regional, and European scales.

This governance model builds on the recognition that CCAM implementation is not solely a technical or infrastructural challenge, but a socio-political transformation requiring democratic legitimacy, procedural equity, and dynamic coordination. Research from the SHOW project, which tested various participatory formats such as Ideathons, Hackathons, and MAMCA stakeholder workshops, illustrates how iterative engagement throughout the CCAM innovation cycle enhances both the design and societal acceptance of automated mobility (Grandsart et al., 2025).

SINFONICA integrates such methods into its operational governance strategy by aligning them with structured tools like the Actor ID Card and Stakeholder Analysis Matrix. These tools not only identify and map stakeholder influence and interest but also tailor engagement strategies to reflect each actor's role in shaping CCAM ecosystems (Ringhand et al., 2024).

In terms of institutional structure, SINFONICA embraces a multi-actor, cross-sectoral approach that brings together government bodies, industry stakeholders, and academic institutions to foster synergies in planning, research, and deployment. This approach conceptually aligns with the **Triple Helix model of innovation governance**, which emphasizes the dynamic interactions between academia, industry, and government to drive systemic innovation (Etzkowitz & Leydesdorff, 2000). This is further operationalized through partnerships with local municipalities, transit operators, research institutions, and community organizations, enabling context-specific governance arrangements that address the unique mobility needs of urban, peri-urban, and rural areas.

Furthermore, SINFONICA’s governance model proactively mitigates regulatory and infrastructural fragmentation by promoting harmonized standards and interoperability frameworks across European regions. Central to this effort is the integration of shared data platforms and AI-driven decision support tools—such as the Knowledge Map Explorer—which facilitate not only technical coherence but also enhance transparency and accountability in policy development and implementation (SINFONICA D4.1, 2024).

An additional layer of innovation in governance comes from SINFONICA’s attention to social equity. It incorporates procedural fairness by explicitly involving underrepresented groups—such as low-income residents, persons with disabilities, elderly populations, and digitally excluded individuals—in decision-making processes (Ringhand et al., 2024; Pangbourne et al., 2020). This stands in contrast to conventional planning models where such populations are often treated as passive beneficiaries rather than active co-creators.

Finally, the integration of digital tools—such as interactive feedback platforms, stakeholder-responsive dashboards, and knowledge-sharing systems—ensures that SINFONICA’s governance model remains adaptive, evidence-based, and citizen-responsive. These elements support learning-oriented governance, as emphasized in Norwegian CCAM policy studies (Fagerholt et al., 2023), where institutional feedback loops facilitate long-term innovation, risk mitigation, and trust-building. In conclusion, SINFONICA’s collaborative governance framework not only enhances multi-stakeholder coordination but also institutionalizes democratic and inclusive planning practices critical to CCAM deployment in Europe. By embedding deliberative, data-driven, and co-creative processes, the project ensures that mobility integration simultaneously advances technological innovation and social equity.

2.2.2 Technical, Economic, and Regulatory Coordination

Effective deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems hinges on the coherent integration of technical infrastructure, viable economic frameworks, and harmonized regulatory standards. SINFONICA contributes significantly to this integration by fostering structured, multi-actor collaboration, ensuring that innovation is socially inclusive, financially sustainable, and institutionally aligned.

Technical Coordination

SINFONICA promotes technological interoperability and resilience through the standardization of protocols and integration of emerging digital technologies. At its core,

the project builds on the premise that seamless CCAM deployment requires consistent communication standards and secure data flows across regions and platforms.

- **Standardization of CCAM Technologies:** In alignment with broader EU strategies, SINFONICA supports the adoption of interoperable V2X communication standards, such as DSRC and C-V2X, to enable reliable interaction among vehicles, roadside infrastructure, and mobility services (Ferreira, 2019). Harmonized protocols are essential for realizing real-time responsiveness and cooperative driving functions.
- **Integration of AI and 5G Technologies:** SINFONICA aligns with ongoing European efforts to integrate 5G networks and AI applications into CCAM systems, recognizing their potential to enhance safety, efficiency, and responsiveness in automated mobility. These technologies enable low-latency communication, distributed edge computing, and predictive traffic management (Attaran & Attaran, 2020; Ferreira, 2019), supporting high-demand applications such as remote driving, autonomous platooning, and real-time hazard detection.
- **Cybersecurity and Data Privacy:** Recognizing the vulnerability of connected vehicles and digital infrastructures, SINFONICA emphasizes the importance of secure and trustworthy data ecosystems in CCAM governance. While not developing technical protocols directly, the project contributes to frameworks that support data integrity and user protection. Related innovations, such as hybrid vehicular networks and real-time consistency checks, have been demonstrated in European research (Amador Molina et al., 2022) as vital enablers of trust in CCAM systems.

Economic Coordination

The sustainability of CCAM solutions also depends on viable funding models and strategic investments in enabling infrastructure. SINFONICA supports economic coordination through partnerships and mechanisms that prioritize long-term service viability and equitable access.

- **Public-Private Partnerships (PPPs) and Business Models:** SINFONICA fosters inclusive economic coordination by promoting collaboration among public authorities, private operators, and community actors to ensure that CCAM services are viable and equitably accessible. While the project does not prescribe specific funding structures, its governance tools support business models that align

technological deployment with social objectives—avoiding market-driven exclusion and reinforcing public trust (Grandsart et al., 2025; Hutahaeen, 2017).

- **Investment in Smart Infrastructure:** As demonstrated in studies on 5G-enabled port and mobility ecosystems, digital transformation requires synchronized investments in cyber-physical systems, real-time sensing, and digital twins (Ahokangas et al., 2020). While SINFONICA does not directly invest in infrastructure, it supports strategic coordination across sectors to anticipate and align infrastructure needs—such as data-sharing frameworks and digital governance tools—necessary for inclusive and scalable CCAM deployment.
- **Affordability through MaaS and Usage-Based Pricing:** The integration of CCAM into Mobility-as-a-Service (MaaS) ecosystems enables flexible pricing models that reflect user behavior and regional affordability. SINFONICA aligns with research highlighting that equitable access depends on pay-per-use models, subscription packages, and public subsidies—particularly for marginalized groups (Lyons et al., 2020; Pangbourne et al., 2020).

Regulatory Coordination

SINFONICA recognizes that regulatory fragmentation poses a major barrier to the cross-border deployment of CCAM systems. It actively promotes policy harmonization, legal clarity, and ethical frameworks to ensure CCAM implementation is both scalable and socially accountable.

- **Standardized European Regulations:** The SINFONICA framework contributes to the alignment of CCAM deployment with EU-wide legal and technical standards by supporting stakeholder-informed policy development on safety, automation protocols, and ethical implementation. While it does not draft regulations, SINFONICA’s emphasis on governance harmonization and inclusive design aligns closely with European transport objectives and the strategic priorities of the ERTRAC CCAM roadmap. These efforts also resonate with findings from Scandinavian CCAM governance studies, which highlight the importance of anticipatory coordination, liability clarity, and institutional preparedness for cross-border automated mobility (Fagerholt et al., 2023; ERTRAC, 2022).
- **Ethical and Accessibility Guidelines:** Informed by behavioral and sociotechnical research, SINFONICA embeds ethical considerations into deployment plans. This

includes ensuring that CCAM systems accommodate people with disabilities, the elderly, and digitally excluded individuals through inclusive design and participatory co-creation processes (Ringhand et al., 2024; Grandsart et al., 2025).

- **Liability and Insurance Considerations:** While legal uncertainties surrounding CCAM—such as accident attribution and software accountability—remain a challenge, current research emphasizes the importance of adaptive regulatory frameworks and dynamic risk assessment in facilitating market acceptance. Although SINFONICA does not directly develop insurance models, it contributes to the broader discussion by informing policy through participatory governance and ethical design (Ringhand et al., 2024).

By coordinating technical, economic, and regulatory pathways, SINFONICA acts as a foundational enabler for the real-world implementation of CCAM systems. Its integrative approach ensures that automated mobility is not only technologically viable but also inclusive, equitable, and institutionally embedded across European mobility ecosystems.

2.2.3 Stakeholder Engagement and the Role of Public-Private Partnerships

Stakeholder engagement is a foundational principle of the SINFONICA framework, grounded in the conviction that inclusive, transparent, and participatory governance is essential to the successful deployment of Cooperative, Connected, and Automated Mobility (CCAM). By systematically involving public authorities, industry actors, civil society organizations, and underrepresented communities, SINFONICA ensures that CCAM systems reflect a broad spectrum of social needs, values, and expectations (Ringhand et al., 2024; Grandsart et al., 2025).

Multi-Dimensional Stakeholder Engagement

SINFONICA adopts a layered engagement model rooted in practice-oriented research on participatory innovation and stakeholder co-production. This model incorporates structured instruments such as Actor ID Cards and Stakeholder Analysis Matrices, which classify stakeholders by interest and influence to enable targeted engagement strategies (Ringhand et al., 2024). It also includes deliberative formats like ideathons, hackathons, and Multi-Actor Multi-Criteria Analysis (MAMCA) workshops, as tested in EU projects such as SHOW, to collaboratively generate solutions and validate CCAM deployment scenarios (Grandsart et al., 2025). These participatory processes allow stakeholders not only to

contribute technical or operational knowledge but also to share experiential insights on accessibility, digital inclusion, and public trust. The **MAMCA methodology**, in particular, emphasizes multi-criteria decision-making and democratic consensus-building by involving diverse actors in scenario assessment (Grandsart et al., 2025).

Moreover, SINFONICA emphasizes the inclusion of marginalized groups such as the elderly, people with disabilities, migrants, low-income residents, and digitally excluded individuals. These users are often excluded from automated transport design due to systemic biases or accessibility gaps. SINFONICA actively mitigates this by incorporating mobility needs grounded in the **Self-Determination Theory** and **Theory of Planned Behavior**, which account for competence, autonomy, and perceived behavioral control (Ringhand et al., 2024).

Public-Private Partnerships (PPPs) as CCAM Enablers

To move from pilot-stage CCAM deployments toward real-world implementation, collaborative governance models such as public-private partnerships (PPPs) offer a valuable framework. These partnerships—where public authorities and private stakeholders co-invest in infrastructure, platforms, and services—have proven effective in related domains such as 5G-enabled ports and digital mobility ecosystems (Ahokangas et al., 2020). While SINFONICA does not prescribe specific funding structures, its emphasis on multi-actor coordination, stakeholder engagement, and institutional alignment supports the kind of cross-sector collaboration that PPPs exemplify.

Effective CCAM deployment can be advanced through the joint facilitation of testbeds and pilot zones for autonomous mobility, particularly in underrepresented or rural areas; support for co-investment strategies in digital platforms such as real-time traffic management systems and multimodal routing services (Attaran & Attaran, 2020); and the co-creation of user-centric solutions that actively involve cities, technology providers, and citizens in designing inclusive mobility features (Grandsart et al., 2025).

Such partnerships enable agile innovation while safeguarding public accountability and aligning with environmental and social equity goals. As noted in broader infrastructure governance research, PPPs offer a mechanism to bridge investment gaps by pooling resources and aligning stakeholder incentives (Hutahaeen, 2017).

Challenges and Safeguards

While stakeholder engagement and public-private partnerships (PPPs) offer significant benefits for CCAM development, they also entail risks if not carefully managed. Research highlights concerns such as elite capture and the exclusion of vulnerable voices (Hutahaeen, 2017), the dominance of commercial interests in data governance and service design (Pangbourne et al., 2020), and the prevalence of short-term private sector investments that may conflict with long-term public mobility objectives (Lyons et al., 2020).

To mitigate these risks, SINFONICA integrates principles of fairness, accountability, and transparency throughout the project cycle by applying stakeholder analysis matrices to map actor influence and interest, ensuring balanced participation across sectors. It also maintains open communication channels and iterative feedback mechanisms through workshops, focus groups, and co-creation activities, while embedding ethical principles into CCAM planning—emphasizing accessibility, social inclusion, and informed consent, particularly for vulnerable and digitally excluded groups (Ringhand et al., 2024).

Toward a Co-Governance Model

Ultimately, SINFONICA envisions a co-governance model where public institutions retain oversight but collaborate closely with private entities, researchers, and civil society organizations. This hybrid governance structure ensures that CCAM systems are not only technologically advanced but also socially responsive and democratically legitimate. As emphasized in stakeholder engagement literature and validated through participatory planning experiments in projects like SHOW, such an approach is essential for building public trust, improving deployment readiness, and mitigating social resistance to automation (Grandsart et al., 2025; Ringhand et al., 2024).

2.3 SINFONICA's Role in CCAM Implementation

2.3.1 Providing Interoperability Guidelines for CCAM Systems

Interoperability is a cornerstone of Cooperative, Connected, and Automated Mobility (CCAM), enabling seamless communication, coordination, and service integration across geographies, transport systems, and digital platforms. While SINFONICA does not produce technical standards itself, it supports this critical objective by facilitating multi-stakeholder coordination and aligning governance strategies with European regulatory frameworks. Through tools like the Knowledge Map Explorer and Stakeholder Analysis Matrix, the

project contributes to the cross-border and cross-sector compatibility essential for inclusive and scalable CCAM deployment

At the technical level, SINFONICA supports interoperability in CCAM by aligning governance models and stakeholder strategies with ongoing standardization efforts in Europe. Although it does not directly define V2X communication protocols, the project recognizes the importance of harmonized message formats such as CAM and DENM in enabling real-time interaction between vehicles, infrastructure, and users. Empirical studies of hybrid vehicular networks combining LTE and DSRC (802.11p) technologies demonstrate how such systems can effectively integrate vulnerable road user data and vehicular alerts (Amador Molina et al., 2022). These findings underscore the need for cross-domain coordination to ensure responsive, inclusive, and reliable CCAM services in complex urban environments.

To foster trust and digital inclusion, SINFONICA emphasizes ethical data governance and transparency rather than direct technical cybersecurity solutions. While it does not implement authentication protocols, the project supports secure and inclusive CCAM deployment through participatory engagement, stakeholder-informed governance, and alignment with European data protection norms.

Beyond technical communication protocols, interoperability in CCAM also involves integration across mobility platforms and service layers. SINFONICA supports this broader perspective by aligning stakeholder governance and user needs with emerging multimodal transport ecosystems, including public transport, ride-sharing, and automated services. Although the project does not design APIs or ticketing systems, it aligns with policy goals that emphasize the need for unified digital frameworks to ensure service continuity and user accessibility (Lyons et al., 2020).

From a **governance and policy** standpoint, SINFONICA supports the standardization of operational definitions, data formats, and safety protocols across European borders. This addresses a core challenge identified in CCAM research: regulatory heterogeneity often undermines system-wide performance and legal clarity (Fagerholt et al., 2023). SINFONICA's guidelines thus advocate for alignment with existing EU frameworks, including GDPR for data protection and the ITS Directive for cooperative system deployment.

A novel contribution of SINFONICA is its integration of **inclusive interoperability criteria**—ensuring that digital and automated mobility systems remain accessible to all user groups, including those with limited digital literacy or connectivity. This aligns with human-centered CCAM design frameworks that account for psychological, socioeconomic, and situational mobility barriers (Ringhand et al., 2024). Interoperability is therefore not only a technical concern but also a **social requirement** for equitable mobility.

Additionally, the 5G-MOBIX initiative offers valuable insights that complement SINFONICA’s approach. Real-world testing across national borders demonstrated that achieving interoperability requires harmonized Quality of Service (QoS) standards, low-latency 5G infrastructure, and advanced edge computing capabilities (Santa et al., 2022). While SINFONICA does not directly address these technical components, its emphasis on governance alignment and cross-border coordination contributes to creating the policy and stakeholder readiness needed to support such pan-European digital infrastructures.

2.3.2 Supporting Standardization of Automated Mobility Solutions

Standardization is a foundational requirement for the successful and scalable deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems. The SINFONICA framework contributes to this goal by supporting the harmonization of operational, regulatory, and social processes in alignment with European standards. Rather than treating standardization as a purely technical endeavor, SINFONICA frames it as a multi-dimensional process that must integrate engineering, legal, ethical, and accessibility considerations to ensure equitable and effective CCAM implementation across the European Union.

Technical and Operational Standardization

SINFONICA aligns with the objectives of initiatives such as 5G-MOBIX and the C-ITS platform by supporting cross-border and cross-operator coordination for CCAM interoperability. These efforts include awareness of V2X communication requirements and performance considerations such as latency, safety alerts, and handover quality. Insights from trials by Santa et al. (2022), conducted at the Spanish–Portuguese border, show that metrics like mobility interruption time and handover success rate are essential for seamless interoperability. While SINFONICA does not set these technical benchmarks, its

governance framework facilitates alignment with such standards. Additionally, SINFONICA references safety frameworks established in EU General Safety Regulations (GSR) and SAE automation levels to ensure consistency in stakeholder understanding of autonomous vehicle operations across diverse use cases (Ferreira, 2019).

Legal and Regulatory Standardization

From a legal standpoint, SINFONICA supports the harmonization of regulatory frameworks essential for CCAM deployment. This includes alignment with GDPR for ethical data governance and user rights protection. While the project does not define liability or insurance standards, it addresses stakeholder concerns related to accountability and cross-border legal clarity. *Fagerholt et al. (2023)* emphasize the importance of proactive, multi-agency approaches to CCAM regulation. SINFONICA's participatory tools and focus on policy convergence reflect these institutional priorities by promoting shared operational understandings and fostering alignment across member states.

Inclusion and Accessibility in Standardization

A unique contribution of SINFONICA lies in its commitment to inclusive standardization, moving beyond the assumption of a “universal user” by explicitly incorporating the needs of people with physical or cognitive impairments, digitally excluded individuals, older adults, and rural residents. As Ringhand et al. (2024) emphasize, equitable standardization must account for contextual, behavioral, and psychological variables. Accordingly, the SINFONICA framework advocates for human-machine interface (HMI) standards that are intuitive, accessible, and adaptable to diverse user capabilities and environmental conditions. Moreover, tools such as the Actor ID Card and participatory scenario evaluation formats (e.g., MAMCA) are employed to ensure that the **standardization process itself** is co-designed and democratically validated (Grandsart et al., 2025).

Platform and Infrastructure Standards

The advancement of digital twins, edge computing, and Mobility-as-a-Service (MaaS) platforms demands that backend infrastructure and software systems adhere to standard protocols for data interoperability, secure system updates, and predictive analytics integration. While SINFONICA does not develop infrastructure standards directly, its governance and coordination strategies align with emerging best practices for modular, open, and cross-sector digital architectures. These principles are echoed in infrastructure

research such as Ahokangas et al. (2020), which demonstrates how flexible and scalable design approaches support long-term integration across digitally connected ecosystems.

2.3.3 Enhancing Cross-Border Deployment Efforts

One of the most significant barriers to widespread Cooperative, Connected, and Automated Mobility (CCAM) adoption across Europe is the fragmentation of regulatory frameworks, digital infrastructure, and interoperability standards between countries. SINFONICA directly addresses this challenge by promoting **harmonized, cross-border deployment strategies** that ensure automated mobility systems can operate seamlessly across national jurisdictions, technical ecosystems, and administrative regimes.

Regulatory Harmonization Across Borders

SINFONICA contributes to the development of a pan-European regulatory environment for CCAM by fostering the alignment of legal definitions and governance frameworks across EU member states. This effort includes promoting stakeholder awareness and strategic coordination on key regulatory domains such as autonomous driving classifications (e.g., SAE levels), safety and liability considerations for automated vehicle operations, cross-border recognition of licensing and insurance frameworks, and the implementation of GDPR-compliant protocols for ethical data sharing.

In line with findings from Fagerholt et al. (2023), successful cross-border deployment of CCAM requires proactive coordination among transport authorities, mapping and communication agencies, and technology developers. Their study in Norway underscores the importance of inter-agency collaboration and multi-sectoral leadership to harmonize deployment strategies across diverse legal and infrastructural contexts. SINFONICA reflects these priorities through its emphasis on stakeholder co-creation, institutional convergence, and regulatory preparedness across the European Union.

Infrastructure Interoperability Through Digital Twins and 5G Corridors

SINFONICA aligns with insights from cross-border CCAM initiatives such as 5G-MOBIX, which have demonstrated the value of digital twin infrastructure in simulating and optimizing automated mobility performance prior to physical deployment. As shown in Santa et al. (2022), digital twins support the modeling of latency, safety events, and

interoperability scenarios across diverse legal and network environments. In addition, 5G-enabled corridors—where automated handovers between mobile network operators are executed with minimal latency—play a critical role in enabling seamless AV operations across borders. These testbeds have highlighted recurring performance bottlenecks during transitions between regulatory and network zones. While SINFONICA does not conduct such trials, it reinforces the need for joint infrastructure coordination and shared performance benchmarks to support consistent and scalable CCAM deployment across Europe.

Standardized Cross-Border Ticketing and Payment Systems

SINFONICA also acknowledges that technical interoperability must encompass user-facing services such as ticketing, identity verification, and multimodal integration. As Lyons et al. (2020) emphasize, effective cross-border Mobility-as-a-Service (MaaS) requires standardization in fare integration, unified subscription models, and common APIs for mobility apps and services, ensuring seamless and inclusive user experiences across different national and regional systems.

Such service-level interoperability enhances the user experience, reduces the cognitive burden of switching systems between countries, and improves accessibility for digitally or socially marginalized users—core goals of the SINFONICA framework (Ringhand et al., 2024).

Joint Cross-Border Pilots and Stakeholder Engagement

Building on participatory approaches trialed in the SHOW and SINFONICA projects, the framework facilitates the co-design of cross-border testbeds that engage a diverse range of stakeholders, including local authorities, public transport operators, technology providers, and civil society organizations. These pilot initiatives serve not only to validate technical systems in real-life conditions but also to assess policy impacts and behavioral responses across cultural contexts. As highlighted by Grandsart et al. (2025), collaborative methods such as MAMCA workshops and hackathons have demonstrated effectiveness in producing user-informed CCAM scenarios that respect local priorities while remaining consistent with broader EU standards.

SINFONICA supports cross-border CCAM deployment by harmonizing regulations (Fagerholt et al., 2023), enabling 5G and digital twins (Santa et al., 2022), standardizing user

services (Lyons et al., 2020), and advancing joint pilots with participatory governance (Grandsart et al., 2025). These efforts ensure a socially inclusive, interoperable, and coordinated rollout across the EU.

CHAPTER 3: Challenges and Requirements in CCAM Deployment

3.1 The CCAM Ecosystem

The deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems involves a complex and interdependent ecosystem composed of diverse stakeholders, technical systems, and policy frameworks. A successful CCAM deployment requires systemic coordination among public authorities, mobility operators, technology providers, and end-users. Each of these actors plays a critical role in shaping the design, acceptance, and sustainability of automated mobility solutions.

3.1.1 Key Stakeholders in CCAM

Stakeholder involvement is central to the inclusive development of CCAM services. A stakeholder, as defined by Freeman (1984), is any actor that can affect or is affected by the realization of mobility innovations. Within the CCAM ecosystem, the principal stakeholders include:

- a. **Government and Policymakers:** Governments at local, regional, and national levels play key roles as regulators, funders, and infrastructure providers. Their responsibilities include enforcing EU and national regulations on transport, safety, and data; investing in intelligent transport systems like V2X and smart roads; funding research and inclusive mobility programs under EU initiatives such as Horizon Europe (Fagerholt et al., 2023); and fostering collaboration through platforms like SINFONICA and the ERTRAC CCAM roadmap (ERTRAC, 2022).
- b. **Mobility Operators:** Mobility operators—such as public transport authorities, MaaS providers, and shared mobility platforms—are responsible for integrating CCAM into multimodal networks, managing operations and cybersecurity, and ensuring inclusive access

for underserved groups (Zhao & Malikopoulos, 2020). Key challenges include high automation costs, legacy system integration, and building user trust and acceptance.

c. **Technology Providers:** Technology providers are key to enabling CCAM through the development of autonomous systems, digital infrastructure like V2X and edge computing (Ferreira, 2019), and cybersecurity frameworks that ensure trust and interoperability (Boutahala et al., 2025). Their main challenges involve standardization, advancing technology readiness, and ensuring cross-border compatibility (Santa et al., 2022).

d. **End Users (Citizens and Communities):** End users are both the primary beneficiaries and essential evaluators of Connected, Cooperative, and Automated Mobility (CCAM) solutions. Their diverse mobility needs—shaped by age, disability, income, digital literacy, and geographic context—must inform every stage of service design and deployment. According to Ringhand et al. (2024), truly inclusive CCAM requires affordability and accessibility through subsidized pricing, universal design, and multimodal integration; trust and control via transparent algorithms, clear safety standards, and participatory feedback mechanisms; and behavioural adaptation supported by digital literacy initiatives and public education. Participatory approaches, as implemented in the SHOW and SINFONICA projects, are vital to addressing user concerns, co-developing solutions, and securing societal legitimacy (Grandsart et al., 2025).

3.1.2 Collaborative Frameworks for CCAM Deployment

The deployment and maintenance of Cooperative, Connected, and Automated Mobility (CCAM) systems require strategic collaboration among stakeholders across the public, private, and civic sectors. Given the multi-level governance and technological interdependence of CCAM solutions, collaborative frameworks play a critical role in aligning objectives, ensuring interoperability, and integrating user needs into design and decision-making processes.

In the European context, projects such as **SINFONICA** and **SHOW** have developed participatory and technical coordination models to facilitate multi-actor cooperation. These frameworks not only support real-time planning and feedback loops but also enable inclusive innovation cycles that consider the perspectives of vulnerable user groups and diverse institutional actors (Ringhand et al., 2024; Grandsart et al., 2025).

a. Actor ID Cards for Stakeholder Profiling

The Actor ID Card methodology, developed under the SINFONICA framework, offers a structured approach to mapping and profiling stakeholders in CCAM systems based on their influence, technical roles, and levels of interest. This tool supports project planners in identifying high-impact stakeholders such as transport authorities, regional planners, and AV developers; evaluating key enablers and barriers to effective engagement; and customizing inclusive strategies for vulnerable or underrepresented groups, including elderly users and digitally excluded individuals (Ringhand et al., 2024). By enabling a comprehensive understanding of stakeholder dynamics, the methodology ensures that strategic decisions align with societal priorities and fosters balanced co-creation across both technical and policy domains.

b. Social Business Network (SBN) for Visualizing Interdependencies

The Social Business Network (SBN) tool conceptualizes CCAM stakeholder ecosystems as dynamic interaction networks by visualizing relationships among key actors—such as municipalities, telecommunication providers, vehicle manufacturers, and citizens—to detect structural gaps and silos in coordination, identify central actors and potential innovation facilitators, and build coalitions for joint CCAM deployment efforts (GUEST Methodology, 2017; Grandsart et al., 2025). This network-based modeling enhances collaborative alignment and transparency, supporting more inclusive governance and informed decision-making processes.

c. Knowledge Map Explorer for Data-Driven Coordination

The Knowledge Map Explorer, as applied in SINFONICA, functions as a decision-support tool that consolidates stakeholder feedback, policy frameworks, and technological trends to guide strategic planning in CCAM. It enables municipalities and transport agencies to anticipate regulatory or infrastructural needs, allows private sector actors to align innovation roadmaps with real-world constraints, and helps researchers and funders prioritize key areas for CCAM research and investment (Ringhand et al., 2024). By facilitating foresight and participatory assessment, the tool enhances the legitimacy, responsiveness, and adaptability of CCAM strategies.

d. Participatory Formats for Co-Creation

Participatory approaches—such as Ideathons, Hackathons, and Multi-Actor Multi-Criteria Analysis (MAMCA) workshops—have proven effective in integrating user and stakeholder input into the design and deployment of CCAM solutions. As demonstrated in the SHOW project, Ideathons help generate early-stage ideas for integrating automated vehicles with

existing infrastructure, Hackathons translate these ideas into functional service prototypes, and MAMCA workshops validate policy and deployment scenarios through structured stakeholder deliberation (Grandsart et al., 2025). These participatory formats bridge the gap between technical feasibility and social acceptability, ensuring that CCAM solutions are both innovative and contextually grounded in public needs and expectations.

3.2 Barriers to Effective CCAM Implementation

3.2.1 Regulatory Hurdles and Standardization Issues

Despite its transformative potential, the large-scale deployment of Cooperative, Connected, and Automated Mobility (CCAM) remains constrained by persistent regulatory and standardization barriers. These obstacles affect legal certainty, market scalability, cross-border operability, and public trust, all of which are essential for an integrated CCAM ecosystem across Europe.

a. Fragmented Legal Frameworks

The lack of harmonized legislation for CCAM across European Union (EU) Member States results in fragmented regulatory environments. Different national interpretations of liability, traffic law, insurance policies, and data protection significantly hinder cross-border deployment and fleet interoperability. These inconsistencies complicate the certification and validation of autonomous vehicle functions and delay transnational pilot initiatives (Fagerholt et al., 2023; ERTRAC, 2022).

Without a unified legal framework, automated vehicles face uncertainties regarding **who holds responsibility** in the event of an accident—drivers, manufacturers, or software providers—thereby impeding insurance processes and risk-sharing mechanisms (Boutahala et al., 2025).

b. Data Privacy and Security Concerns

CCAM systems heavily depend on real-time data exchange between vehicles (V2V), infrastructure (V2I), and users (V2X). This reliance introduces legal challenges related to compliance with the **General Data Protection Regulation (GDPR)**. Issues such as informed consent, anonymization of mobility data, and data ownership remain unresolved in many pilot deployments (Ringhand et al., 2024; Ferreira, 2019).

Furthermore, the increased use of cloud platforms and AI-based decision-making systems raises **cybersecurity vulnerabilities**. As noted in recent studies, current frameworks do not sufficiently address proactive risk mitigation, cryptographic authentication, or fail-safe protocols for AV communication networks (Boutahala et al., 2025).

c. Lack of Interoperability and Technical Standardization

CCAM deployment is further delayed by the absence of consistent standards for communication protocols, software updates, and hardware configurations. Manufacturers and operators currently use **non-uniform standards** for V2X communication (e.g., ITS-G5 vs. C-V2X), creating compatibility issues between different platforms (Santa et al., 2022).

Moreover, **technology readiness levels (TRLs)** vary significantly across stakeholders and countries, resulting in inconsistent performance expectations and certification procedures (Bakke, 2017). This variation affects both the safety validation and the legal acceptance of automated driving systems in public environments.

d. Delays in Policy Adaptation and Institutional Readiness

Rapid technological advances in CCAM outpace regulatory adaptation. Legislative inertia, lengthy consultation processes, and unclear institutional mandates slow the integration of CCAM considerations into urban planning, traffic law, and procurement policies (Fagerholt et al., 2023). This institutional lag prevents agile governance, which is essential for experimentation, scaling, and innovation transfer in CCAM ecosystems.

3.2.2 Infrastructure Readiness and Digital Connectivity Challenges

The successful deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems depends not only on vehicle technologies but also on the robustness of physical and digital infrastructures. Despite ongoing investments, most urban and rural areas in Europe lack the necessary infrastructure to support safe, efficient, and inclusive CCAM operations. This section identifies three critical infrastructure-related challenges: outdated transport infrastructure, insufficient digital and network connectivity, and the high costs of upgrades.

a. Outdated Transport Infrastructure

Many existing transport networks across Europe were not designed with automated and connected mobility in mind. Essential elements such as intelligent traffic signals, connected

roadside units (RSUs), digital signage, and adaptive road markings are often absent or outdated. This limits the ability of autonomous vehicles to safely interpret and respond to their environment, especially in mixed-traffic scenarios (Fagerholt et al., 2023; Ringhand et al., 2024). Bridges, tunnels, and intersections may lack the spatial or structural capacity to accommodate large fleets of connected and automated vehicles (CAVs), and retrofitting these assets requires significant public investment. In rural or peri-urban regions, poor road quality and limited maintenance further constrain the feasibility of CCAM services (Grandsart et al., 2025).

b. Insufficient Digital and Network Connectivity

CCAM systems require seamless, low-latency data exchange through 5G, Wi-Fi, or dedicated short-range communication (DSRC). However, network coverage in many regions remains patchy or insufficiently robust to support real-time vehicle-to-everything (V2X) communication. As highlighted in 5G-MOBIX trials, handovers between networks or cross-border connectivity can introduce latency spikes, jeopardizing the stability of automated driving functions (Santa et al., 2022). In rural and low-income areas, digital exclusion—defined as a lack of access to high-speed internet and advanced digital services—can create a structural disadvantage for CCAM deployment. This exacerbates spatial inequality and undermines the principle of inclusive mobility (Ringhand et al., 2024).

Moreover, centralized AI processing in CCAM fleets is highly sensitive to bandwidth and latency. High latency or packet loss during edge-cloud interactions can compromise safety-critical decisions such as obstacle avoidance or rerouting during emergencies (Boutahala et al., 2025).

c. High Costs and Uncertain Return on Investment

Upgrading infrastructure to CCAM-ready standards involves considerable capital expenditure. Intelligent road equipment—such as LIDAR-based traffic lights, RSUs, edge-computing nodes, and secure communication backbones—requires not only initial investment but also continuous maintenance and cybersecurity upgrades. These costs are particularly challenging for local governments with constrained budgets and uncertain revenue models for automated mobility (Fagerholt et al., 2023; Ferreira, 2019).

Public-private partnerships (PPPs) have been proposed to share investment risks, but their effectiveness is limited by unclear benefit-sharing schemes and lack of standardized business models. In many cases, the potential long-term societal benefits of CCAM (e.g., reduced emissions, enhanced accessibility) are not easily quantifiable in economic terms, making it difficult to justify large infrastructure investments (Grandsart et al., 2025).

3.2.3 Public Acceptance and Behavioral Adaptation to Automated Mobility

Technological readiness and infrastructure deployment alone are insufficient to ensure the success of Cooperative, Connected, and Automated Mobility (CCAM). Widespread adoption ultimately depends on public trust, perceived safety, and behavioral willingness to transition from conventional transport modes to automated systems. Human factors—including risk perception, digital competence, and value alignment—must be addressed systematically to achieve user-centered CCAM deployment.

a. Trust and Safety Perceptions

Public skepticism regarding the safety of automated vehicles remains one of the most persistent barriers to CCAM acceptance. Surveys and user studies across Europe reveal that many individuals express concern about the reliability of autonomous decision-making systems, particularly in complex or uncertain traffic environments (Ringhand et al., 2024). These concerns are especially pronounced among vulnerable road users such as pedestrians, cyclists, and older adults, who may fear being overlooked by algorithmically driven vehicles (Whelan et al., 2006).

In addition to concerns about technical failure, users are wary of cybersecurity risks, including hacking and data breaches that could compromise not only privacy but also physical safety. The opacity of AI algorithms and the absence of human oversight during fully automated operations further fuel public anxiety, particularly in emergency scenarios where ethical decision-making becomes ambiguous (Boutahala et al., 2025).

b. Workforce Disruptions and Economic Resistance

The anticipated displacement of professional drivers, including taxi operators, logistics workers, and bus drivers, has contributed to social resistance against automation. Labor

unions and transport associations have raised concerns about job loss, wage suppression, and the erosion of employment protections in an increasingly automated mobility ecosystem (Fagerholt et al., 2023).

Beyond direct job loss, broader economic concerns also emerge regarding access to retraining and the risk of digital exclusion among low-income populations. Individuals lacking the digital literacy to navigate app-based mobility services may be left behind in systems that assume universal access to smartphones and online platforms (Ringhand et al., 2024).

c. Behavioral Adaptation and Information Asymmetry

Behavioral inertia—rooted in habit, familiarity, and perceived control—poses another barrier to CCAM uptake. Even when services are available, users may be reluctant to switch from private vehicles to shared autonomous modes due to uncertainty, lack of knowledge, or preference for established travel routines. This effect is compounded by limited public awareness about how CCAM systems function and how to interact with them safely (Lyons et al., 2020).

Moreover, trust in institutions responsible for deploying CCAM—such as local authorities or technology providers—significantly influences acceptance. When deployment is perceived as top-down or profit-driven, citizens may resist adoption on normative or political grounds. Conversely, co-created services, participatory demonstrations, and transparent governance can improve behavioral willingness to engage with CCAM (Grandsart et al., 2025).

d. Engagement Strategies and Demonstration Projects

Real-world pilot projects, such as those conducted within the SHOW and SINFONICA frameworks, demonstrate the efficacy of participatory engagement in improving public trust and behavioral adaptation. Interactive demonstrations, test rides, and ideation workshops have helped demystify autonomous systems and provided users with agency in the design process (Grandsart et al., 2025).

Information campaigns that explain technical capabilities, safety protocols, and ethical design choices have also shown promise in counteracting fear and misinformation. Especially when targeting vulnerable or hesitant populations, these efforts must go beyond digital communication and include in-person outreach and experiential learning opportunities (Ringhand et al., 2024).

3.3 The Role of SINFONICA in CCAM Coordination

The SINFONICA project plays a central role in addressing the systemic coordination challenges associated with Cooperative, Connected, and Automated Mobility (CCAM). As an EU-funded initiative, SINFONICA provides a multilevel framework to align policy, stakeholder engagement, and technical integration across European mobility systems. Its primary objective is to ensure that CCAM deployment is inclusive, human-centric, and adaptable to evolving technological and societal contexts.

3.3.1 Policy and Technical Integration

SINFONICA facilitates the harmonization of CCAM policy frameworks across Europe by creating knowledge-sharing structures between municipalities, national transport agencies, and European-level regulators. This helps reduce fragmentation in legal interpretation, deployment strategies, and ethical standards related to CCAM (Ringhand et al., 2024). The project supports the definition of best practices for regulation and interoperability, particularly in relation to liability, safety certification, and data governance.

SINFONICA also addresses the challenge of technological fragmentation by promoting the adoption of shared technical standards, including communication protocols for vehicle-to-everything (V2X) connectivity. These efforts contribute to improving interoperability between vehicles, infrastructure, and digital systems, particularly across borders and operator networks (Grandsart et al., 2025).

Furthermore, the project supports the integration of AI-driven tools—such as autonomous decision systems, route optimization engines, and real-time data platforms—into public transport infrastructures, aligning emerging technologies with societal needs and public value frameworks (Boutahala et al., 2025).

3.3.2 Stakeholder Cooperation and Participatory Engagement

SINFONICA adopts a structured approach to stakeholder engagement through instruments such as the **Actor ID Card** and **Stakeholder Analysis Matrix**. These tools allow for the systematic profiling of actors based on influence, interest, and vulnerability, ensuring that underrepresented groups—such as older adults, migrants, women, and those with disabilities—are not overlooked in the CCAM design process (Ringhand et al., 2024).

The project promotes cross-sectoral collaboration through working groups, participatory workshops, and thematic focus groups. These formats facilitate deliberation among diverse actors, including local governments, transport providers, civil society, and private sector developers. By emphasizing co-creation, SINFONICA contributes to building legitimacy and trust in automated mobility systems (Grandsart et al., 2025).

In addition to participatory formats, the project supports continuous feedback loops between users and planners through digital platforms and real-world pilots. These loops are essential for aligning CCAM services with real-life behaviors, preferences, and concerns, and for iteratively improving design and deployment.

3.3.3 Decision Support Tools for Strategic Alignment

SINFONICA incorporates advanced decision-support systems to enhance coordination across governance levels and technical domains. One key tool is the **Knowledge Map Explorer**, a platform that consolidates stakeholder feedback, policy priorities, market trends, and technological constraints. It enables mobility planners, technology developers, and regulators to visualize interdependencies and anticipate risks (Ringhand et al., 2024).

Another innovation is the structured use of **Actor ID Cards**, which classify stakeholders based on power dynamics, technical roles, and expected impacts. This allows project leaders to identify strategic leverage points and develop tailored engagement strategies. These tools contribute not only to equitable planning but also to increased transparency and efficiency in CCAM policy-making.

Through these instruments, SINFONICA supports the development of inclusive, evidence-based CCAM roadmaps that reflect both top-down policy goals and bottom-up user needs. This dual alignment improves the coherence of deployment strategies and fosters resilience in the face of uncertainty and technological disruption.

Chapter 4: The GUEST-SI Framework for CCAM Deployment

4.1 Lessons from Past Mobility Initiatives

4.1.1 Reviewing European Mobility Projects and Their Impact on CCAM

The evolution of Cooperative, Connected, and Automated Mobility (CCAM) in Europe has been significantly informed by a series of EU-funded mobility initiatives, including projects under Horizon 2020 and the European Green Deal. These initiatives laid the groundwork for CCAM by testing emerging technologies, deploying pilot programs, and cultivating stakeholder collaboration across diverse mobility ecosystems.

Key insights from these projects converge on the critical importance of integrating CCAM solutions into the broader context of urban and regional mobility planning. For instance, projects such as SHOW, INCIT-EV, and the SINFONICA initiative have emphasized the necessity of aligning technological innovation with user-centric design, regulatory harmonization, and long-term economic sustainability (Ringhand et al., 2024; Zhao & Malikopoulos, 2020).

A common feature among successful initiatives has been their systemic approach to real-world complexity. This includes addressing infrastructural readiness, testing automation in mixed traffic environments, and engaging vulnerable populations in co-design processes. Notably, the SHOW project demonstrated the efficacy of participatory formats such as Ideathons, Hackathons, and multi-criteria evaluation workshops (MAMCA) in shaping inclusive CCAM strategies that reflect local priorities (Grandsart et al., 2025).

Furthermore, insights from shared autonomous vehicle (SAV) studies underscore the operational and social dimensions of automation. Agent-based simulations and scenario planning techniques have revealed that while SAV systems offer congestion and emission

reductions, they may also exacerbate vehicle miles traveled (VMT) without robust integration with public transport (Zhao & Malikopoulos, 2020). These findings are vital for CCAM policy architects to consider in balancing automation with sustainability goals.

From a governance and infrastructure perspective, the 5G-MOBIX and Port of Oulu studies illustrate how next-generation connectivity platforms and smart infrastructure ecosystems enable real-time data exchange and situational awareness—both essential for CCAM safety and coordination. However, they also reveal challenges related to latency, inter-operator handovers, and the need for secure, decentralized architectures (Santa et al., 2022; Ahokangas et al., 2020).

In sum, past mobility initiatives have contributed a multi-dimensional understanding of what it takes to implement CCAM: a combination of technical robustness, stakeholder co-creation, and policy foresight. Embedding these learnings into the GUEST-SI framework will strengthen the planning and deployment of CCAM services in ways that are inclusive, interoperable, and scalable.

4.1.2 Lessons on Stakeholder Engagement and Public Acceptance

Stakeholder engagement and public acceptance have consistently emerged as decisive factors in the success or failure of CCAM initiatives. Past mobility projects across Europe highlight that without structured and inclusive stakeholder participation, even the most technologically advanced mobility solutions face social resistance, limited uptake, or political pushback.

A review of engagement mechanisms in the SHOW project revealed the strategic value of participatory tools such as ideathons, hackathons, and multi-criteria stakeholder workshops. These formats not only generate creative mobility solutions but also serve as democratic platforms that integrate the voices of users, operators, and public authorities into service design and evaluation (Grandsart et al., 2025). For example, ideathons conducted in Austria led to the conceptualization of inclusive services like DigiStop and App2Anywhere, while hackathons in Greece and workshops in Finland validated these ideas with real-world stakeholders, including people with reduced mobility.

Public acceptance of CCAM systems is significantly influenced by trust, transparency, and perceptions of fairness. Research shows that many users remain skeptical of autonomous

systems due to concerns over safety, data privacy, and affordability (Ringhand et al., 2024; Ferreira, 2019). Successful projects addressed these challenges through transparent communication and pilot demonstrations that allowed citizens to directly interact with automated vehicles in controlled environments, thereby demystifying automation and building behavioral familiarity.

Moreover, inclusivity in design is crucial. The SINFONICA framework incorporates tools such as the Actor ID Card and Stakeholder Analysis Matrix to identify underrepresented groups and ensure their needs shape the deployment of CCAM services. This is particularly relevant for populations at risk of digital exclusion, including the elderly, migrants, low-income individuals, and residents in rural areas (Ringhand et al., 2024). The literature underscores that inclusive co-design—especially with marginalized communities—is essential to mitigate structural mobility barriers and promote widespread adoption.

From a theoretical perspective, stakeholder engagement strategies are most effective when treated not just as procedural requirements but as dynamic practices. Knox et al. (2025) describe engagement-as-practice as involving relational, procedural, cognitive, and material actions. This understanding broadens the scope of engagement from tokenistic consultation to meaningful collaboration, ensuring that CCAM systems are both technically sound and socially legitimate.

In sum, the lessons from past CCAM and mobility projects confirm that participatory, inclusive, and transparent engagement processes are foundational for public acceptance. Embedding these practices into CCAM deployment strategies—especially through the GUEST-SI framework—enhances trust, reduces resistance, and ensures that automated mobility evolves as a public good.

4.1.3 Technological Readiness and Infrastructure Gaps

The transition from research prototypes to real-world deployment of Cooperative, Connected, and Automated Mobility (CCAM) requires a high level of technological maturity across both digital and physical infrastructures. However, a critical lesson from past and ongoing European mobility projects is that while technological innovation in

CCAM is advancing rapidly, deployment remains uneven due to persistent infrastructure gaps and system-level interoperability challenges.

A central issue lies in the **disconnect between the pace of vehicle automation and the readiness of enabling environments**—namely, road networks, communication protocols, data platforms, and regulatory harmonization. Findings from the 5G-MOBIX project underscore this point. Despite successful demonstrations of 5G-enabled autonomous driving across borders, the tests revealed significant **latency and packet loss** during network handovers, particularly when vehicles transitioned between operators or jurisdictions (Santa et al., 2022). These disruptions, while minor in conventional digital services, pose serious risks for time-sensitive automated driving operations.

In alignment with these findings, the **SINFONICA project** has adopted a holistic assessment model that goes beyond technical performance to consider **ethical, spatial, and social dimensions of infrastructure deployment**. It utilizes participatory foresight and stakeholder mapping to identify bottlenecks, especially in urban-rural transitions where digital connectivity is often weaker. This insight is critical for ensuring **inclusivity and equitable access**, preventing a scenario where only digitally mature urban cores benefit from CCAM while peripheral regions are left behind (Ringhand et al., 2024).

Technological readiness in CCAM must also grapple with **interoperability and standards compliance**. The need for cross-border data exchange, aligned safety protocols, and unified communication layers (e.g., V2X, 5G, ITS-G5) remains a barrier. Ferreira (2019) points out that despite the availability of vehicle connectivity systems, cooperative behaviours—such as synchronized lane changes, platooning, and shared perception—are still underdeveloped due to **fragmented standards and limited legal frameworks**. This observation remains valid in the SINFONICA context, which actively supports **standardization through stakeholder alignment** but acknowledges the inertia caused by fragmented national implementations.

Furthermore, **cybersecurity and system resilience** are growing concerns. As vehicles become more connected and reliant on external data streams, they become targets for cyber threats. A lightweight security scheme proposed by Boutahala et al. (2025) highlights how cryptographic overhead in Cooperative Awareness Messages (CAMs) can compromise both performance and scalability. SINFONICA’s approach to these issues incorporates **secure-by-design principles** within its stakeholder-driven system architecture but recognizes the

trade-offs between low-latency performance and cryptographic robustness—especially in cost-sensitive implementations.

Physical infrastructure readiness also lags behind. Many smart mobility systems still rely on outdated road sensors, low-resolution mapping, and insufficient roadside units (RSUs), particularly outside major pilot zones. The deployment of **Digital Twins**, smart intersections, and AI-powered traffic management remains fragmented. SINFONICA attempts to bridge this gap by promoting **scenario-based validation** and **real-world living labs**, but as of 2024, large-scale replication remains limited (Ringhand et al., 2024; Ferreira, 2019).

In conclusion, the technological maturity of CCAM is advancing but remains constrained by fragmented standards, inconsistent infrastructure investment, and cybersecurity limitations. The SINFONICA framework addresses these gaps through a systems-level approach that combines digital innovation with stakeholder inclusivity, scenario forecasting, and data governance. However, realizing the full potential of CCAM requires integrated public investment strategies and harmonized regulatory frameworks that address infrastructure gaps not only in urban centers but across the entire mobility ecosystem.

4.1.4: Economic and Policy Implications for CCAM Scaling

Scaling Cooperative, Connected, and Automated Mobility (CCAM) from local testbeds to functional, long-term systems requires more than technological maturity; it depends on **financial viability**, **regulatory consistency**, and **inclusive policy design**. European initiatives have shown that even well-designed pilots may fail without clear funding strategies, stakeholder alignment, and legal certainty.

A significant insight from projects like **INCIT-EV** and **SHOW** is the role of **public-private partnerships (PPPs)** in overcoming the high capital costs associated with CCAM infrastructure. INCIT-EV, for example, demonstrated the value of **subscription models and pay-per-use services** to increase financial flexibility and reduce barriers to entry, especially in areas with high deployment costs and uncertain long-term user engagement (Zhao & Malikopoulos, 2020).

From a **policy perspective**, fragmented regulatory frameworks across the EU continue to impede harmonized CCAM deployment. Despite strategic agendas by ERTRAC and CCAM

SRIA, gaps remain in data governance, liability definitions, and cross-border operational standards. Botte et al. (2019) and the ERTRAC CCAM Roadmap highlight that such fragmentation leads to uneven service provision, increased deployment risk, and public hesitancy—undermining long-term mobility goals.

While the **SINFONICA project** does not explicitly model financial or economic trade-offs, it introduces important **non-financial enablers** for scaling: namely, user-informed planning and **participatory stakeholder profiling**. Tools like the **Actor ID Card** and **Stakeholder Analysis Matrix** are used to identify and include underrepresented groups, ensuring CCAM solutions are not only technologically functional but **socially accepted and inclusive** (Ringhand et al., 2024). This contributes indirectly to **deployment feasibility** by addressing the social sustainability of CCAM systems—a key component in securing policy and funding support.

Furthermore, SINFONICA aligns with the broader shift toward **inclusive innovation** in mobility governance. Its integration of user needs—particularly for groups such as the elderly, digitally excluded, or disabled—supports **public trust and adoption**, reducing the risk of investment in poorly adopted solutions. This social validation complements technical readiness by making sure CCAM solutions are **context-aware and equity-oriented**, even if they do not directly evaluate return on investment or business models.

Lastly, the governance models explored in SINFONICA advocate **multi-level collaboration** among municipalities, national agencies, and private providers. Although not presented in financial terms, these coordination frameworks serve as institutional scaffolding that enables legal certainty, platform interoperability, and ethical deployment—conditions that are necessary precursors for long-term financial investment and scalability.

In conclusion, while SINFONICA does not explicitly engage with cost-benefit analysis or economic modelling, its contribution lies in **creating the socio-political and ethical conditions** necessary for sustainable CCAM investment. By embedding equity, accessibility, and stakeholder inclusion into the planning process, it supports the kind of public legitimacy and policy alignment that are essential for economic viability at scale.

4.2 The GUEST-SI Framework

4.2.1 Enhancing Systematic Stakeholder Engagement in CCAM Planning

Effective stakeholder engagement is a prerequisite for the inclusive and sustainable deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems. The GUEST-SI (Go, Uniform, Evaluate, Solve, Test for Social Innovation) framework integrates this principle through a structured approach that prioritizes early involvement, role differentiation, and iterative feedback mechanisms. This process is not simply a procedural necessity but a deliberate design strategy to align mobility solutions with diverse user needs and governance contexts.

The initial phase of the GUEST-SI methodology—termed “Go”—focuses on the **identification and characterization of relevant stakeholders**, particularly those historically marginalized in transportation planning. Tools such as the **Actor ID Card** and **Social Business Network**, as adopted in the SINFONICA framework, are applied to map actor profiles, interdependencies, and spheres of influence across institutional and territorial layers. These instruments help planners move beyond binary categorizations of “users” and “providers” by highlighting relational dynamics within the CCAM ecosystem (Ringhand et al., 2024).

This stakeholder profiling is followed by differentiated engagement strategies that reflect varying levels of interest and influence. Although not explicitly linked to Arnstein’s ladder, the approach aligns with participatory theory by enabling forms of engagement ranging from consultation to co-design. This structure allows for a more accurate alignment between a stakeholder’s institutional capacity and their potential to influence CCAM planning outcomes.

Engagement practices in the GUEST-SI framework are supported by the **Stakeholder Analysis Matrix** and the **Knowledge Map Explorer**. These tools, also utilized in the SINFONICA project, facilitate the categorization of actors by influence and interest while enabling the visualization of knowledge flows and gaps. They do not merely serve to document participation but aim to inform **decision-support processes** and **engagement iteration**, thereby improving both transparency and responsiveness in system design.

While GUEST-SI emphasizes engagement at the organizational level, it also considers how **behavioral and social factors** influence user perspectives on automation. Drawing from behavioral science frameworks used in SINFONICA—such as the **Theory of Planned Behavior** and **Self-Determination Theory**—the approach recognizes that perceived

behavioral control, social norms, and digital access significantly shape user acceptance of CCAM. Although these theories are not stakeholder management models per se, they provide important input for tailoring engagement formats to specific social and demographic groups (Ringhand et al., 2024).

One notable insight from the SINFONICA literature is that barriers to engagement are not only technical or institutional but often social and cognitive. Digitally excluded individuals, for example, may require alternative modes of participation. Likewise, older adults or individuals with disabilities may need adapted co-design processes. GUEST-SI accommodates these factors through its participatory emphasis on **context-sensitive and adaptive engagement formats**.

In conclusion, the GUEST-SI framework advances stakeholder engagement in CCAM by integrating structured profiling, digital mapping tools, and behaviorally informed engagement strategies. Its operational compatibility with the SINFONICA framework ensures that the engagement process is not only inclusive in form but also **systematic, traceable, and functionally embedded** in the planning of future mobility systems.

4.2.2 Aligning Technical, Economic, and Regulatory Aspects of CCAM Deployment

The successful deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems depends on the effective coordination of technical, economic, and regulatory dimensions. Failures in any one of these areas can compromise long-term sustainability, scalability, and public acceptance. The GUEST-SI framework addresses this complexity through its multi-phase methodology, which integrates stakeholder-informed tools and decision-support systems to facilitate systemic alignment across these three interdependent domains.

From a **technical standpoint**, alignment involves ensuring interoperability between digital infrastructure components, including communication protocols (e.g., V2X), data standards, and real-time mobility platforms. While the GUEST-SI framework does not prescribe technological architectures, it supports harmonization through stakeholder coordination tools such as the **Stakeholder Analysis Matrix** and the **Knowledge Map Explorer**. These instruments are designed to map the interests, influence, and interdependencies of actors

involved in CCAM planning and to anticipate the institutional conditions required for cross-jurisdictional coherence.

SINFONICA contributes to this process by providing structured methodologies for stakeholder profiling and behavioral inclusion. Although it does not develop new technical standards or infrastructures, it helps align stakeholder expectations and decision-making processes with existing regulatory and technological frameworks. For instance, its tools support planners in understanding how different groups may interact with digital systems based on access, literacy, and trust—factors critical to successful technology deployment but often overlooked in infrastructure-centric planning (Ringhand et al., 2024).

In the **economic dimension**, the GUEST-SI framework emphasizes trade-off analysis rather than prescriptive funding strategies. During the “Evaluate” phase, it employs multi-criteria decision-making (MCDM) tools, and SWOT assessments to help planners assess alternative scenarios in light of technical feasibility, social equity, and financial constraints. These tools are particularly valuable during early-stage planning when financial data is often incomplete or speculative.

Zhao and Malikopoulos (2020) highlight several scalable models for Shared Autonomous Vehicle (SAV) systems that resonate with broader CCAM goals. These include **modular service architectures** and **pay-per-use models**, which offer flexibility and can reduce reliance on private vehicle ownership. While their study does not explicitly address public-private partnerships (PPPs), such models are prevalent in European CCAM initiatives, where public funding is used to initiate infrastructure while private entities operate or maintain services. Although GUEST-SI does not directly incorporate financial instruments, its evaluation methodologies enable comparison of deployment models under varying budgetary conditions and user uptake scenarios.

SINFONICA complements this by identifying **user-side economic barriers**. Its mobility needs framework includes **affordability** as a core determinant of service acceptability, particularly for groups such as low-income users, migrants, the elderly, and digitally excluded populations. While it does not offer a pricing model or economic forecast, it provides critical insights into how cost perceptions shape behavioral intent and accessibility. These findings are particularly relevant for ensuring that economic policies associated with CCAM deployment—such as pricing schemes or service subsidies—are informed by real-world distributional dynamics (Ringhand et al., 2024).

On the **regulatory front**, the fragmentation of policies across EU Member States presents a significant barrier to CCAM harmonization. Legal uncertainties persist regarding data protection, cross-border vehicle operation, and liability frameworks. The ERTRAC CCAM Roadmap (2022) identifies this fragmentation as a central challenge, especially for Level 3 and Level 4 automation, where vehicles are expected to make real-time decisions under varying legal environments.

GUEST-SI does not attempt to resolve these legal discrepancies directly. Instead, it integrates **policy foresight tools** to anticipate how regulatory divergence may impact deployment decisions. These include participatory scenario building and stakeholder workshops designed to surface potential conflicts and areas of convergence. SINFONICA enhances this process by emphasizing issues often underrepresented in legal discourse, such as **accessibility, gender equity, and digital inclusion**. Although SINFONICA does not draft legal instruments, it positions these social variables as necessary considerations in CCAM governance—ensuring that policy debates are not limited to liability and safety alone but also reflect broader societal impacts (Ringhand et al., 2024).

4.3.1 Urban Mobility Management Systems

Urban mobility management systems represent a key use case for the deployment of Cooperative, Connected, and Automated Mobility (CCAM) technologies within the SINFONICA framework. These systems address complex challenges in dense urban environments—such as traffic congestion, modal fragmentation, and accessibility gaps—by integrating digital infrastructure, automated vehicles, and data-driven coordination tools. Within SINFONICA, the focus is not on technical system design, but rather on understanding how such innovations can be inclusively deployed and governed through participatory planning and stakeholder alignment.

A major area of application in urban CCAM is the implementation of **AI-powered traffic management systems**, which dynamically optimize traffic flow through real-time adjustments of signal timings and routing strategies. These systems can prioritize connected and automated vehicles while ensuring the safety of pedestrians and cyclists. Although SINFONICA does not develop these systems technically, it evaluates their impact using behavioral frameworks and user needs analyses, particularly for groups historically underserved by conventional mobility infrastructure (Ringhand et al., 2024).

Another dimension involves **real-time data sharing** enabled by vehicle-to-infrastructure (V2I) and vehicle-to-everything (V2X) technologies. While the SINFONICA framework does not directly regulate data governance, it highlights the importance of trust, access, and inclusivity in how users interact with digital mobility systems. This is particularly relevant when integrating public transport data, private mobility platforms, and user-generated inputs across varied jurisdictions. In parallel, the 5G-MOBIX project demonstrated that cross-border data latency and handover failures can significantly degrade CCAM performance, underscoring the need for robust technical coordination (Santa et al., 2022).

SINFONICA also addresses **first- and last-mile connectivity** through its support for integrating small-scale automated mobility units—such as autonomous shuttles—with conventional fixed-route systems. These demand-responsive services are deployed to bridge service gaps in low-density urban areas or underserved neighborhoods. Their success, however, depends heavily on coordinated planning between infrastructure operators, municipal authorities, and service providers. Within the GUEST-SI framework, this coordination is facilitated through tools such as the **Actor ID Card** and **Knowledge Map Explorer**, which map stakeholder roles, influence relationships, and operational dependencies during deployment phases.

Further, the project acknowledges the potential of **digital twin technologies** to support urban mobility planning by simulating system-wide traffic scenarios, allowing stakeholders to test the potential impacts of CCAM interventions before real-world implementation. While SINFONICA does not produce these digital twins, it recognizes their value in participatory foresight processes and scenario planning activities that involve both technical experts and community representatives.

A central component of SINFONICA’s contribution to urban CCAM is its focus on **equity and inclusion**. Its framework employs behavioral and needs-based profiling, grounded in psychological and environmental theory, to examine how CCAM services may either expand or constrain mobility for underserved groups. These include individuals affected by **digital exclusion, gender-based travel disparities, and accessibility challenges** faced by persons with disabilities navigating sensor-automated environments (Ringhand et al., 2024). These insights inform engagement strategies and stakeholder mapping tools—such as the Actor ID Card and Stakeholder Analysis Matrix—ensuring that technical solutions are sensitive to diverse urban realities and societal needs.

4.3.2 Automated Freight Logistics and Transport Corridors

Freight logistics and transport corridors are central components of the broader CCAM ecosystem, particularly as the sector seeks to reduce emissions, increase delivery efficiency, and improve cross-border operability. While the SINFONICA framework does not directly address freight automation technologies, several of its methodological tools—developed in this thesis based on the project's inclusion-oriented design—offer useful applications for analyzing governance and stakeholder alignment in this domain.

One of the most pressing challenges in freight-related CCAM implementation is **cross-border interoperability**, especially regarding communication systems and regulatory alignment. The 5G-MOBIX project clearly documented how **network handovers** along international corridors introduced latency spikes, packet loss, and service instability, undermining vehicle coordination and safety (Santa et al., 2022). These findings highlight the need for **regulatory harmonization**, infrastructure standardization, and cooperative planning across national boundaries.

Although SINFONICA does not engage in technical infrastructure planning for freight, its **stakeholder-focused methodologies**—such as **foresight workshops** and the **Knowledge Map Explorer**—can support institutional coordination across regions. These tools help identify where governance gaps may impede deployment, and how multi-level actors can align planning processes around shared CCAM objectives. While originally intended for inclusive passenger mobility, these participatory planning instruments offer potential applications in freight corridor governance if adapted to include logistics authorities, terminal operators, and regulatory agencies.

In the context of **route optimization**, Zhao and Malikopoulos (2020) explore how Shared Autonomous Vehicle (SAV) systems can enhance efficiency using real-time traffic data, predictive algorithms, and dynamic scheduling. They also caution that smaller logistics providers may face entry barriers in platform-dominated environments if **data access and service interoperability** are not managed inclusively. These insights raise important questions for CCAM governance: how should freight data platforms be regulated, and what safeguards are necessary to prevent monopolization or digital exclusion in supply chain management?

While SINFONICA does not address these logistics-specific risks, it contributes relevant conceptual tools. Its emphasis on **digital inclusion**, **accessibility**, and **stakeholder mapping** can inform how policymakers approach equitable participation in automated freight ecosystems. Particularly when deploying CCAM infrastructure in less-connected regions, territorial profiling and scenario-based workshops can help anticipate potential disparities and mitigate regional exclusion.

To summarize, SINFONICA does not focus on freight automation directly, but its human-centric planning tools—adapted in this thesis—can contribute to stakeholder coordination, cross-institutional foresight, and territorial inclusivity in freight-related CCAM. These applications are not technological interventions but rather methodological contributions to ensure that the automation of freight corridors does not reproduce systemic inequities and remains responsive to varied institutional, geographic, and economic contexts.

4.3.3 Multi-Modal Connectivity Solutions

Multi-modal connectivity is a foundational principle in the design of inclusive, efficient, and user-responsive CCAM ecosystems. Within the SINFONICA framework, this principle is explored not through technological system design, but through behavioral analysis, user profiling, and participatory planning that enable diverse populations to engage with integrated mobility services. The goal is to ensure that CCAM systems support seamless transitions between transport modes—including walking, cycling, shared services, public transit, and automated vehicles—while remaining accessible to those with varied needs and capabilities.

A central contribution of SINFONICA is its **mobility needs framework**, which identifies and profiles groups facing barriers to mobility access, including elderly individuals, persons with disabilities, migrants, digitally excluded users, and low-income populations (Ringhand et al., 2024). The framework combines behavioral and psychological theories—specifically, the **Theory of Planned Behaviour** and **Self-Determination Theory**—to explain how attitudes, perceived behavioural control, and user motivation influence engagement with multi-modal and automated transport options.

Although SINFONICA does not directly address the technical integration of transport systems, it contributes to **policy-relevant planning** by identifying non-technical barriers to multi-modal uptake. One of the most significant is **digital exclusion**. Increasing reliance on

app-based booking, real-time routing, and digital ticketing creates access gaps for individuals without smartphones, internet access, or sufficient digital literacy. The framework incorporates these barriers into stakeholder engagement tools—such as the Actor ID Card and Stakeholder Analysis Matrix—used to design participatory processes that give voice to underrepresented users and allow planners to adjust CCAM services accordingly.

From an operational standpoint, the role of Shared Autonomous Vehicle (SAV) systems in multi-modal networks has been critically analyzed by Zhao and Malikopoulos (2020). Their findings show that SAVs can either complement or compete with public transport depending on integration strategies. Without appropriate policy guidance, these services risk pulling users away from mass transit, increasing vehicle miles traveled and undermining sustainability goals. SINFONICA’s framework reinforces the importance of such policy alignment by incorporating user attitudes toward different service types and identifying where behavioral or contextual mismatches may occur.

Territorial context is also an important dimension of multi-modal integration. While urban centers often benefit from dense modal coverage and investment in digital mobility platforms, **peri-urban and rural areas** face chronic underinvestment and connectivity gaps. SINFONICA addresses these disparities by promoting **territorially sensitive planning**, wherein scenario workshops and stakeholder foresight sessions can reveal regional inequalities and co-produce strategies tailored to specific infrastructural and demographic conditions. This approach supports the equitable deployment of CCAM technologies beyond urban cores.

Finally, while SINFONICA does not propose fare integration or economic models for multi-modal CCAM, it emphasizes **affordability** as a critical condition for access. Ringhand et al. (2024) stress that CCAM deployment must account for varying income levels and the ability to pay, particularly where digital services bundle mobility access under subscription or account-based payment systems. This perspective is essential when considering multi-modal service design, as pricing structures often exclude informal workers, the unbanked, or those with inflexible travel needs.

5: Implementation of the GUEST-SI Methodology

5.1 Operationalizing the GUEST-SI Methodology in CCAM Contexts

The GUEST-SI methodology (Go, Uniform, Evaluate, Solve, Test – for Social Innovation) serves as a structured, stakeholder-driven approach designed to guide the inclusive and adaptive deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems. Developed within the SINFONICA framework, it provides a processual mechanism for integrating participatory methods, cross-sector alignment, and iterative policy feedback into CCAM planning and implementation.

Unlike linear innovation models, GUEST-SI reflects the socio-technical complexity of mobility ecosystems by embedding engagement at each stage of deployment. It aims to ensure that the perspectives of traditionally underrepresented groups—such as elderly users, digitally excluded populations, persons with disabilities, and rural communities—are incorporated into CCAM system design and evaluation (Ringhand et al., 2024; Grandsart et al., 2025).

Rather than focusing solely on technological advancements such as V2X communication or autonomous vehicle algorithms, GUEST-SI complements these innovations by emphasizing governance coordination, behavioral alignment, and public trust. The methodology acts as a bridge between experimental pilots and scalable real-world applications, linking stakeholder priorities to decision-making tools like participatory workshops, scenario simulations, and policy co-design processes (Ferreira, 2019; Knox et al., 2025).

By prioritizing transparent, adaptive, and evidence-informed deployment processes, GUEST-SI contributes to the realization of key European mobility goals related to accessibility, sustainability, and user trust.

5.1.1 Application of Structured Decision-Making Models

The core of the GUEST-SI methodology lies in its structured five-phase decision-making framework, adapted from participatory design principles and co-creation theories, and tested in EU-funded initiatives such as SINFONICA, SHOW, and MOVE2CCAM. These phases—Go, Uniform, Evaluate, Solve, and Test—serve as a scaffold for translating

stakeholder insights into concrete, implementable CCAM strategies that are both inclusive and context-sensitive.

Each phase supports targeted objectives:

- **GO** defines the problem context and stakeholder landscape.
- **UNIFORM** standardizes data collection and engagement protocols.
- **EVALUATE** applies multi-dimensional feasibility and impact assessments.
- **SOLVE** facilitates scenario-based design of adaptive mobility services.
- **TEST** validates and refines CCAM deployments through pilot projects and feedback loops.

Unlike traditional technology-driven models, this cycle emphasizes iterative alignment with societal needs, governance frameworks, and trust-building mechanisms. It supports a dual focus: ensuring that technical components such as autonomous control systems or V2X communication are socially embedded, and that behavioral adoption, affordability, and accessibility are not treated as secondary outcomes but as foundational to system design (Ringhand et al., 2024; Grandsart et al., 2025).

The structured approach operationalizes co-creation by combining stakeholder mapping tools (e.g., Actor ID Cards), participatory foresight techniques (e.g., MAMCA), and monitoring instruments (e.g., Key Performance Indicators, digital dashboards), thereby enabling inclusive planning throughout the CCAM lifecycle (Knox et al., 2025; Santa et al., 2022).

GO: Establishing Context and Stakeholder Engagement

The GO phase marks the diagnostic entry point of the GUEST-SI methodology. Its objective is to define the local CCAM ecosystem, identify relevant actors, and build a shared understanding of mobility challenges through early-stage participatory engagement. This foundation ensures that CCAM planning aligns with the lived realities of diverse user groups, particularly those often excluded from transport innovation processes (Ringhand et al., 2024; Grandsart et al., 2025).

Stakeholder Typologies and Value Orientations

The GO phase emphasizes mapping stakeholder roles and value expectations using the Actor ID Card and the Stakeholder Analysis Matrix—two core tools from the SINFONICA framework. Stakeholders are categorized into three functional tiers: high-influence actors, such as city governments, technology providers, and regulators, who drive governance and infrastructure decisions; mid-influence actors, including public transport operators and

academic institutions, who support technical implementation and service feasibility; and low-influence actors, such as individual users and community organizations, who influence behavioral adoption, trust, and system legitimacy (Knox et al., 2025). Value orientations also differ across groups: public authorities tend to prioritize safety, regulatory alignment, and social equity; technology providers emphasize scalability and efficiency; while end-users focus on affordability, accessibility, and usability (Ferreira, 2019; Ringhand et al., 2024). Mapping these expectations helps anticipate synergies and tensions that influence system co-design in later phases.

Identifying Needs and Barriers

Through focus groups and stakeholder workshops held in Trikala, Hamburg, Noord-Brabant, and the West Midlands, the GO phase uncovered a range of mobility barriers. These include affordability gaps among low-income users, limited digital literacy among elderly populations, and weak infrastructure in peri-urban and rural areas. These insights informed the construction of the SINFONICA User Needs Matrix and guided actor prioritization strategies in the GUEST-SI implementation (Grandsart et al., 2025; MS12).

Engagement Instruments

A multi-modal engagement approach supported data collection in this phase, using validated tools such as focus groups and ideation sessions to generate qualitative insights, surveys and structured interviews to quantify user needs, and participatory workshops to validate preliminary findings with local stakeholders. These instruments ensured the inclusion of diverse perspectives and contributed to a robust knowledge base for the subsequent phases of the GUEST-SI methodology.

The GO phase operationalizes inclusive innovation by integrating stakeholder profiling, value mapping, and contextual diagnostics into a coherent system map. It establishes the social, territorial, and institutional parameters necessary for the subsequent UNIFORM, EVALUATE, SOLVE, and TEST phases to proceed with clarity, legitimacy, and adaptability.

UNIFORM Phase: Standardizing Data, Roles, and Governance

The UNIFORM phase of the GUEST-SI methodology aims to create coherence across stakeholder roles, data structures, and governance frameworks, supporting transparent and inclusive CCAM planning. It ensures that public, private, and civic actors operate from a shared baseline using standardized procedures, common language, and ethical principles.

A key instrument in this phase is the **Knowledge Map Explorer**, developed under the SINFONICA framework. It structures institutional roles, domain-specific data, and regulatory conditions into an interactive knowledge base accessible to all actors. This tool establishes a shared vocabulary and decision-support environment for managing complexity in multi-stakeholder CCAM ecosystems (D4.1-SINFONICA, 2024).

Structuring Governance and Stakeholder Roles

This phase fosters role alignment through Public-Private Partnerships (PPPs) that balance innovation incentives with investment risks, inter-institutional coordination agreements that synchronize regulatory, infrastructural, and service responsibilities, and multi-stakeholder governance boards that formalize co-decision-making and ensure accountability (Pangbourne et al., 2020; Grandsart et al., 2025). These models draw on applied practices from cities like Hamburg and Gothenburg, where municipalities, technology firms, and civil society actors collaborated under structured governance agreements (D4.1-SINFONICA, 2024).

Data Harmonization and Technical Interoperability

UNIFORM introduces standards that support legal compliance and system-level integration by implementing GDPR-aligned data governance to protect user privacy and guide ethical data handling, standardized V2X protocols to ensure secure and interoperable communication across vehicles and infrastructure (Santa et al., 2022), and cloud and edge computing architectures to support real-time responsiveness and service scalability (Ferreira, 2019); together, these technical enablers facilitate cross-border mobility and consistent performance measurement across jurisdictions.

Operational Standards and Ethical Alignment

This phase also defines safety, accessibility, and trust-building protocols, including compliance with ISO standards for AV safety in mixed traffic, guidelines for operation in unpredictable environments such as shared pedestrian spaces, and accessibility standards for users with reduced mobility or limited digital access (Ringhand et al., 2024). Ethical AI principles—fairness, transparency, and non-discrimination—underpin these frameworks, reinforcing trust and social legitimacy in CCAM deployment.

Comparative Insights across Cities

Focus groups and participatory workshops revealed region-specific disparities, such as digital exclusion among elderly residents in Trikala, infrastructure fragmentation in peri-urban Noord-Brabant, and low automation trust among rural populations in the West Midlands. These insights are integrated into the planning process through standardized Key Performance Indicators (KPIs) measuring perceived safety, accessibility, and service usability across pilot regions (MS12, 2024). The UNIFORM phase converts diverse actor inputs into a harmonized planning and governance framework by integrating technical standards, stakeholder alignment, and ethical design principles, thereby establishing the structural foundation for scalable, interoperable, and socially responsive CCAM deployment.

EVALUATE Phase: Assessing Readiness and Impact

The EVALUATE phase of the GUEST-SI methodology translates stakeholder priorities into measurable indicators of readiness, risk, and social impact. It integrates simulation tools, foresight methods, and KPI dashboards with participatory input to assess whether CCAM proposals are scalable, inclusive, and contextually responsive.

Grounded in the SINFONICA framework and supported by EU projects such as MOVE2CCAM, SHOW, and 5G-MOBIX, the phase is structured around four interrelated components: **risk assessment, scalability analysis, simulation modeling, and adaptive improvement.**

1. Risk Assessment: Risks are analyzed across technical (e.g., V2X failures, AI misjudgment), operational (e.g., infrastructure gaps), regulatory (e.g., GDPR variance), and societal (e.g., trust, exclusion) dimensions. Mitigation strategies include simulation-based validation, interoperability testing, legal foresight, and stakeholder engagement.

2. Scalability Analysis: This component evaluates the capacity of CCAM systems to expand across diverse urban and rural settings. Key factors include technological modularity, infrastructure interoperability, governance coordination, and equitable adoption—especially among digitally excluded or low-income users.

3. Simulation and Impact Modeling: Advanced simulation platforms (e.g., digital twins, microsimulation) allow stakeholders to test service scenarios, assess failure modes, and estimate ROI, emissions reductions, and social equity outcomes. These tools are integrated with co-creation outputs such as the Value Ring and User Needs Matrix.

4. Adoptive Improvement: Evaluation results feed into adaptive governance models, allowing for the iterative refinement of service plans, regulatory frameworks, and infrastructure rollouts. Real-time dashboards, feedback loops, and foresight tools ensure responsiveness to emerging needs and contextual shifts.

This phase emphasizes that deployment readiness is not a fixed state but a dynamic equilibrium between stakeholder trust, technical maturity, institutional capacity, and societal alignment. For example, concerns raised in Trikala and West Midlands about digital exclusion were modeled using scenario tools to test the effect of simplified interfaces and multilingual services.

A central component of the Evaluate phase is the application of SWOT analysis to synthesize risks, constraints, and enabling conditions across dimensions of implementation. Based on participatory foresight and pilot evaluations, the SWOT outcomes are:

SWOT Analysis for the Evaluate Phase of CCAM Deployment

As a core tool of the **GUEST-SI methodology**, **SWOT analysis** is applied during the Evaluate phase to synthesize stakeholder input, system performance indicators, and contextual risks. This structured assessment helps decision-makers balance technical capabilities, social acceptability, and institutional readiness before full-scale CCAM deployment. The categories below reflect findings from participatory foresight, simulation trials, and real-world pilot evaluations conducted across SINFONICA and related European projects.

SWOT Category	Key Factors
Strengths	• Data-driven decision-making through Key Performance Indicators (KPIs) • Simulation models enabling safe testing prior to real-world deployment • Strong stakeholder engagement frameworks supporting participatory planning • Use of risk assessment tools to identify and mitigate deployment uncertainties (Ringhand et al., 2024; Grandsart et al., 2025)
Weaknesses	• Variability in regulatory standards across EU regions, leading to fragmented deployment • High costs associated with simulation infrastructure and cross-sector trials • Public skepticism and low trust in automation technologies • Limited availability of test environments in urban and rural areas delays validation timelines (Santa et al., 2022; Ringhand et al., 2024)
Opportunities	• Integration of AI and digital twins for real-time performance monitoring and scenario planning • Horizon Europe and private sector funding accelerating CCAM scalability • Urban sustainability mandates encouraging smart mobility adoption • Enhanced collaboration with public transport networks supporting multimodal integration (Yu & McKinley, 2024; Grandsart et al., 2025)
Threats	• Cybersecurity vulnerabilities in vehicle networks and digital infrastructure • Infrastructure limitations in rural and peri-urban regions hindering equitable adoption • Legal and liability uncertainties related to automated driving and data governance • Resistance from legacy transport operators and labor groups fearing displacement (Boutahala et al., 2025; Fagerholt et al., 2023)

Table 1: SWOT analysis table

This SWOT analysis complements the broader evaluation toolkit of the GUEST-SI methodology and aligns with **SINFONICA’s commitment to inclusive, ethical, and adaptive mobility planning**. It supports evidence-based decision-making by illuminating both deployment enablers and systemic constraints.

SWOT ANALYSIS

 STRENGTHS	 WEAKNESSES	 OPPORTUNITIES	 THREATS
Data-driven decision-making through Key Performance indicators (KPIs) Simulation models enabling safe testing before real-world deployment Strong stakeholder engagement frameworks ensuring participatory planning Use of advanced risk assessment tools to mitigate deployment uncertainties	Variability in regulatory standards across EU regions affects data harmonization High costs associated with simulation-based validation and real-world trials Slow adoption rates due to public skepticism and low trust in automation Limited availability of urban test environments, delaying validation timelines	Integration of AI and digital twins to enhance real-time performance monitoring Funding from Horizon Europe and private investments can accelerate scalability Urban sustainability goals encouraging smart mobility solutions Collaboration with public transport networks to increase multimodal integration	Cybersecurity vulnerabilities in automated vehicle networks and data-sharing platforms Infrastructure limitations in rural and peri-urban areas hinder large-scale adoption Legal and liability uncertainties related to accident responsibility in automated driving Resistance from traditional transport operators-fearing job displacement

Figure 1: SWOT analysis

SOLVE: Designing Adaptive CCAM Solutions

The SOLVE phase of the GUEST-SI methodology represents the bridge between conceptual design and real-world implementation of CCAM services. It operationalizes the findings from the GO, UNIFORM, and EVALUATE phases—particularly the User Needs Matrix, Value Ring, and stakeholder priorities—by transforming them into co-developed, context-sensitive mobility interventions.

A cornerstone of this phase is the application of Living Lab environments, which function as socio-technical ecosystems for iterative CCAM testing. These Labs provide real-world settings for participatory validation of automated driving technologies, multimodal transport services, and digital mobility platforms. Their value lies in enabling empirical learning from both operational metrics (e.g., reliability, emissions, accessibility) and lived experience (e.g., comfort, trust, usability).

Examples from the SINFONICA project illustrate this process:

Across the SINFONICA pilot sites, user priorities reflected diverse local contexts. In Hamburg, the focus was on eco-friendly vehicles, step-free access, and inclusive digital interfaces. In Noord-Brabant, users emphasized the importance of mobile apps, multilingual support, and seamless integration between rural and urban mobility services. In Trikala, core requests centered on fundamental infrastructure upgrades, improved rural coverage, and enhanced safety measures, highlighting the need for context-sensitive CCAM deployment strategies.

Solutions developed in the SOLVE phase extend beyond technology deployment to encompass adaptive governance structures that support co-decision-making, institutional frameworks for data sharing and liability, and multilingual, user-centered app interfaces and fare models. Participatory tools such as co-design workshops, ideathons, and multi-criteria evaluation models guide the creation of tailored interventions, ensuring that outputs align with local mobility patterns, user demographics, and governance capacities. Furthermore, the SOLVE phase embeds adaptability by integrating IoT monitoring, cloud-based data analysis, and scenario modeling into deployment frameworks. This allows for continuous adjustment of service parameters based on feedback collected during testing.

In Gothenburg and Elba Island, Living Lab trials and seasonal adaptation strategies validated the use of flexible CCAM systems responsive to time-specific and demographic-specific transport needs. These trials helped refine vehicle behavior, routing algorithms, and service coordination mechanisms under real-world constraints.

TEST: Iterative Deployment and Optimization

The TEST phase represents the final validation step in the GUEST-SI methodology, translating co-designed CCAM service models into real-world applications through structured pilot testing and iterative stakeholder feedback. It ensures that proposed solutions are not only technically feasible but also socially endorsed, context-sensitive, and institutionally aligned.

Within the SINFONICA framework, the TEST phase is operationalized through **Living Labs**, adaptive monitoring tools, and participatory governance strategies. Pilot sites—such as Trikala, Noord-Brabant, and the West Midlands—were selected for their infrastructure readiness, stakeholder engagement, and relevance to broader deployment scenarios.

In these cities, testing activities encompassed real-world evaluations of accessible interfaces, safety enhancements, and V2X functionality, alongside structured feedback loops facilitated through participatory evaluations, app-based reporting, and user diaries. Trust-building features were also deployed, including multilingual onboarding, real-time service alerts, and user co-monitoring functions, ensuring continuous user engagement and inclusive validation of CCAM solutions.

A distinctive feature of this phase is its integration of real-time performance monitoring systems, which combine digital dashboards tracking KPIs related to accessibility, safety, and service satisfaction; mobile apps for feedback and usability scoring; and IoT and edge computing tools to collect behavioral and environmental data. Flexible **scenario modeling and rapid prototyping** allow for stress-testing solutions under variable conditions—e.g., peak congestion, rural road reliability, or weather disruptions. Projects like **5G-MOBIX** and **SHOW** have illustrated the critical role of adaptive testing, especially in managing cross-border interoperability and data governance challenges.

SINFONICA complements technical trials with equity-driven performance metrics across diverse European contexts. In Trikala, simplified mobile interfaces were evaluated to enhance usability for older adults and low-literacy users. In the West Midlands, the project

addressed affordability and travel anxiety through on-board interviews and accessibility walk-throughs. Meanwhile, in Hamburg, low-emission mobility services were tested to promote both geographic and demographic inclusivity.

Through iterative testing and structured stakeholder review, the TEST phase facilitates the continuous refinement of CCAM infrastructure, policy settings, and interface design. Outcomes inform investment planning, standard-setting, and institutional learning among cities, mobility operators, and civic stakeholders.

The TEST phase anchors CCAM deployment in empirical validation and dynamic adjustment. By integrating monitoring systems, user-centered evaluation, and responsive governance, it ensures that CCAM solutions are operationally viable, ethically grounded, and publicly supported.

5.2 Stakeholder-Centered Tools in GUST-SI

The GUEST-SI methodology is anchored in participatory mobility planning and inclusive innovation. To translate stakeholder diversity into actionable design and governance outcomes, the methodology employs a set of interconnected tools—each designed to extract, structure, and integrate user perspectives across the CCAM lifecycle. These stakeholder-centered tools are not standalone mechanisms but function as integrated modules that bridge participatory engagement with technical system design. Together, they support GUEST-SI’s goals of inclusivity, transparency, and reflexive system optimization.

1. Actor ID Card:

Used primarily during the GO and UNIFORM phases, this tool categorizes stakeholders across demographic, socio-economic, geographic, and institutional lines. It helps identify representation gaps, target interventions, and inform ethical and equitable service planning. Actor IDs form the foundation for Value Rings and User Needs Matrices by mapping who the system is being designed for, and what constraints they face.

2. Value Ring:

Developed as part of the SOLVE phase, the Value Ring captures and organizes user-defined “jobs to be done,” alongside perceived pains and gains. It then links them to design features (e.g., gain creators and pain relievers). This circular logic ensures that every user priority is explicitly translated into a service feature, policy solution, or infrastructure adaptation.

3. User Needs Matrix:

This matrix consolidates and compares needs across Actor IDs, highlighting both individual and collective priorities. It is especially useful in the EVALUATE phase, where trade-off mapping and scenario testing rely on a clear understanding of cross-stakeholder tensions and synergies.

4. Knowledge Map Explorer:

Embedded within the SINFONICA architecture, this digital tool structures domain-specific insights, stakeholder roles, and contextual limitations into an interactive format. It facilitates shared understanding and institutional memory, essential for multi-actor CCAM governance.

5. Balanced Scorecard and KPI Dashboard:

Used in the TEST phase, these evaluation tools organize stakeholder priorities into measurable performance indicators. They align technical validation with social impact metrics—ensuring that services meet expectations around accessibility, affordability, trust, and sustainability.

Collectively, these tools offer a rigorous framework for stakeholder co-creation, system co-design, and governance co-alignment. They allow GUEST-SI to function not just as a participatory toolkit, but as a dynamic planning methodology capable of supporting large-scale, socially grounded CCAM implementation.

5.2.1 Actor ID: Mapping Stakeholder Roles and Influences

The Actor ID Card is a foundational component of the GUEST-SI methodology, providing a systematic approach to stakeholder profiling across all phases of CCAM development and deployment. This tool is designed not only to identify and classify actors, but to reveal social, geographic, and digital disparities that influence mobility access and technology adoption. Its use in the SINFONICA project was essential to developing a user-centered CCAM planning framework grounded in lived experiences and participatory evidence.

Actor ID Cards are structured around several key fields:

- 1) Actor Name and Type
- 2) Contact Channels (e.g., workshops, focus groups, digital platforms)
- 3) Socio-Economic Stratification (income, education, digital access)
- 4) Gender and Age
- 5) Geographic Localization (urban, rural, peri-urban)
- 6) Salary Range or Employment Status
- 7) Reported Mobility Barriers and Preferences

In the context of the SINFONICA pilot cities—Trikala, Hamburg, Noord-Brabant, and West Midlands—ten Actor IDs were defined based on recurring demographic patterns, qualitative feedback themes, and engagement frequency across the Excel-based focus group and interview datasets. These Actor IDs represent a synthesis of regional diversity, social vulnerability, and thematic relevance to CCAM deployment.

ACT 01: Elderly Urban Public Transport Users

Derived from Trikala, West Midlands, and Hamburg data. Users aged 65+ frequently expressed concern over app complexity, safety in boarding, and physical accessibility (ramps, step-free access). This actor type was consistently involved across all focus group waves.

ACT 02: Rural Residents with Limited Access

Highlighted in Trikala and Noord-Brabant datasets. These users reported poor coverage, irregular schedules, and lack of first-/last-mile services. Actor ID was validated by feedback in sections on options, needs, and barriers in rural or peri-urban locations.

ACT 03: Low-Income Urban Travelers

Emerging from Hamburg and West Midlands, participants identifying as unemployed or low-wage earners emphasized affordability concerns and inflexible pricing schemes. Data references include salary self-reporting and prioritization of cost-related mobility needs.

ACT 04: Persons with Physical Disabilities

Spanning all cities, especially West Midlands and Hamburg. Participants flagged inaccessible infrastructure, lack of real-time support, and fear of being unable to board or exit vehicles. Actor type validated via barriers listed in sections F-G of SINFONICA Excel files.

ACT 05: Young Digital Commuters

Identified mostly in Hamburg and Noord-Brabant. Typically aged 18–35, these users favored app integration, dynamic routing, and multimodal options. Data highlighted their strong digital engagement but frustration with system fragmentation.

ACT 06. Migrants and Linguistically Isolated Users

Primarily observed in Hamburg and West Midlands. These actors required multilingual support and culturally responsive service interfaces. Comments in focus groups revealed exclusion due to language barriers and lack of tailored communication.

ACT 07: University Students

Explicitly profiled in Trikala and Hamburg, with specific mentions of time-sensitive mobility, limited budgets, and need for app-based scheduling. Actor ID supported by age and occupation demographics in participant data.

ACT 08: Eco-Minded Urban Cyclists and E-Mobility Users

Mentioned most often in Hamburg and Gothenburg (external). Actor type validated through repeated calls for safe cycling lanes, e-scooter regulation, and sustainable service integration. Reflected in options-related comments and Value Ring inputs.

ACT 09: Single Parents and Caregivers

Spanning West Midlands and Trikala. Identified by needs related to flexible schedules, stroller access, and safety. Supported by direct mentions in demographic sections and challenge listings in sections E and G.

ACT 10: Middle-Aged Multimodal Workers

Common in Noord-Brabant and Hamburg. Typically aged 35–55, employed, and reliant on combinations of modes (train, bike, car). Prioritized real-time info, congestion avoidance, and intermodal coordination. Patterns observed in sections C-D.

These Actor IDs were identified through a triangulated review of demographic data, thematic coding, frequency analysis, and stakeholder prioritization. They guide co-creation, target interventions, and promote equity in CCAM design. Integrated into the Value Ring and User Needs Matrix, they ensure the GUEST-SI methodology reflects real user diversity. Revisiting them throughout deployment enables dynamic adaptation to evolving needs and stakeholders.

Actor 1 Elderly Urban Public Transport User	Contact channels Workshops, Surveys, Focus Groups.
Actor type: User / End Beneficiary Actor Description: Older adults using city buses and trams, often face mobility and digital literacy barriers. Social-Economic stratification with quantification: Pensioners; low-to-moderate income Gender: All Genders. Age: +65 Geolocalization: Urban, suburban, and rural areas.(Trikala, Hamburg, West Midlands) Salary: < €15,000	

Value Ring (Our assesment of the problems and current situation of our actor)
High Priority (Today) Pain: Difficulty boarding vehicles, fear of falling, and confusion with digital ticketing machines. Pain Relievers: Step-free access, handrails, staffed support at bus/tram stops, and paper ticket or contactless card options. Gain: Physical safety and ease of boarding. Gain Creator: Well-marked stops, priority seating, visual/audio stop announcements, and consistent vehicle design across services.
Medium Priority (Tomorrow) Pain: Anxiety and unfamiliarity with journey-planning apps or route changes. Pain Relievers: Co-designed applications with voice assistance, large fonts, simplified navigation, and real-time updates via info screens. Gain: Confidence and autonomy in using public transport independently. Gain Creator: Intuitive digital tools, help kiosks, and human assistance integrated into AV services.
Low Priority (Later) Pain: Feeling excluded from mobility-related decision-making and innovation processes. Pain Relievers: Structured engagement through senior advisory panels, in-person feedback sessions, and simplified survey channels. Gain: Sense of inclusion, empowerment, and recognition in future mobility design. Gain Creator: Rewarded participation in pilot programs, co-creation workshops, and acknowledgement in service adaptations.

Actor 2 Young Professional Commuter	Contact channels Surveys, App Beta Testing, Employer Networks
Actor type: User / Early Adopter Actor Description: Digitally native commuters using multimodal transport options, including e-scooters and shared mobility. Social-Economic stratification with quantification: Middle-income employed individuals Gender: Mixed Age: 25–35 Geolocalization: Urban, suburban, and rural areas. Salary: €25,000–€45,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Fragmented mobility platforms and lack of real-time synchronization across modes (e.g., train-to-scooter, bus-to-bike).

Pain Relievers: Integrated Mobility-as-a-Service (MaaS) apps offering seamless trip planning, ticketing, and updates across all transport modes.

Gain: Increased time efficiency and stress-free commuting experience.

Gain Creator: Multimodal journey planners with real-time route suggestions, multimodal subscriptions, and predictive congestion alerts.

Medium Priority (Tomorrow)

Pain: Inconsistent availability of micro-mobility (e-scooters, shared bikes) in outer zones and during off-peak hours.

Pain Relievers: Dynamic fleet redistribution using demand prediction and flexible geofencing.

Gain: Reliable first/last-mile access from remote or less-served areas.

Gain Creator: Smart mobility hubs and shared AV-pooling integration tied to user demand models.

Low Priority (Later)

Pain: Lack of customization in services based on lifestyle or work routines (e.g., gym stops, flex-time office commutes).

Pain Reliever: User profiling algorithms that learn and adapt to commuting preferences over time.

Gain: Personalized, adaptive mobility options enhancing daily routine convenience.

Gain Creator: AI-driven personalization features within apps (e.g., preferred routes, alerts, subscription tiers tied to user behavior).

Actor 3 Low-Income Urban Traveler	Contact channels Surveys, Focus Groups, NGO outreach
Actor type: User / Economically Disadvantaged Actor Description: Users prioritizing cost-saving options; often rely on bus and subsidized fares. Social-Economic stratification with quantification: Low-income urban populations Gender: Mixed Age: 18-65 Geolocalization: Urban, suburban, and rural areas. Salary: < €18,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: High cost of daily commuting relative to income; difficulty affording tickets or multi-ride passes.

Pain Relievers: Introduce subsidized fare structures, daily/weekly fare caps, and social transport vouchers.

Gain: Affordable, predictable access to essential destinations (e.g., work, healthcare, schools).

Gain Creator: Sliding-scale pricing models and automatic fare discount eligibility linked to income verification.

Medium Priority (Tomorrow)

Pain: Limited availability of late-night or early-morning services needed for shift workers.

Pain Relievers: Extend service hours and integrate demand-responsive shuttles in underserved time slots.

Gain: Reliable transport options aligned with non-standard work schedules.

Gain Creator: Flexible routing services triggered by booking or community scheduling input.

Low Priority (Later)

Pain: Poor access to digital booking tools and real-time travel info due to lack of smartphones or data plans.

Pain Relievers: Install non-digital information points and SMS-based updates for users without app access.

Gain: Equitable access to mobility information regardless of digital exclusion.

Gain Creator: Hybrid service models offering both digital and analogue access channels.

Actor 4 Rural Area Resident	Contact channels Workshops, Surveys, Rural Forums
Actor type: User / Periphery Resident Actor Description: Limited access to mobility services, reliant on flexible and demand-responsive solutions Social-Economic stratification with quantification: Varied; often lower access to digital tools Gender: Mixed Age: all ages Geolocalization: Urban, suburban, and rural areas. Salary: varies	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Infrequent or absent public transport services; long wait times and poor geographic coverage.
Pain Relievers: Implement demand-responsive transit (DRT) and flexible shuttle services tailored to low-density areas.
Gain: Basic mobility access to essential services such as healthcare, employment, and education.
Gain Creator: Community-based AV deployment and on-call shared vehicles coordinated through local hubs.

Medium Priority (Tomorrow)

Pain: Poor connectivity with intercity and regional transport networks.
Pain Relievers: Integrate first-/last-mile CCAM services with regional rail and interurban bus schedules.
Gain: Seamless, multimodal connectivity to larger towns and urban centers.
Gain Creator: Coordinated route planning apps and shared ticketing systems linking rural AVs to mainline transport.

Low Priority (Later)

Pain: Limited access to digital tools for booking or real-time service updates.
Pain Relievers: Provide offline booking options, SMS alerts, and support through local intermediaries (e.g., town halls).
Gain: Inclusive access to mobility regardless of digital literacy or internet availability.
Gain Creator: Hybrid analogue-digital interfaces co-designed with rural residents.

Actor 5 Young Student / University Attendee	Contact channels Student unions, App usage surveys
Actor type: User / Student Actor Description: Budget-conscious and tech-savvy, depends on digital platforms and shared mobility. Social-Economic stratification with quantification: Students, often with part-time work Gender: Mixed Age: 18-25 Geolocalization: Urban, suburban. Salary: €10,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Despite existing subsidies, students face **limited flexibility** in using subsidized tickets across different modes (e.g., e-scooters, shared AVs).
Pain Relievers: Expand student mobility programs to cover multimodal services beyond buses—integrating micro mobility and AV access into student fare schemes.
Gain: Broader and more flexible mobility within urban and campus zones.
Gain Creator: Unified student mobility passes covering buses, AVs, and e-mobility through a single digital account or student ID integration.

Medium Priority (Tomorrow)

Pain: Difficulty in synchronizing trips across multiple modes, especially when commuting between housing, campus, and part-time jobs.
Pain Relievers: Deploy smart journey planning apps that sync schedules across campus shuttles, public transit, and shared services.
Gain: Efficient, stress-free travel between academic, residential, and employment locations.
Gain Creator: MaaS student platforms offering optimized, real-time, multimodal trip plans with calendar integration.

Low Priority (Later)

Pain: Standardized mobility options don't reflect the variability of student routines, such as late classes or campus events.
Pain Relievers: Enable opt-in personalization features based on academic schedules, study programs, and lifestyle preferences.
Gain: Customized and responsive mobility options aligned with academic calendars and social needs.
Gain Creator: Adaptive transport services (e.g., night buses during exam weeks, free AV shuttles for university events) managed via student-specific settings.

Actor 6 Single Parent in Suburban Area	Contact channels Social workers, NGOs, local outreach
Actor type: User / Family Transport Stakeholder Actor Description: Needs flexible mobility for irregular schedules, safety for children, affordable access. Social-Economic stratification with quantification: Low to mid-income, care responsibilities Gender: Mostly Female Age: 30-50 Geolocalization: Urban, suburban, and rural areas.(Noord-Brabant) Salary: €15,000–€30,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Irregular transport schedules conflict with caregiving duties (e.g., school drop-offs, doctor visits), and services often lack stroller or child-accessible features.

Pain Relievers: Offer flexible CCAM services (e.g., on-demand AVs) with child-friendly features—stroller space, low-entry vehicles, real-time alerts.

Gain: Reliable, safe, and accessible daily travel that accommodates parenting demands.

Gain Creator: CCAM apps with parent-specific features, guaranteed seat availability, and service priority during school start/end times.

Medium Priority (Tomorrow)

Pain: Financial stress from relying on multiple transport tickets (e.g., for work, childcare, and errands).

Pain Reliever: Introduce subsidized family mobility packages or protected-category fare discounts, linked to verified caregiving status.

Gain: Affordable travel for both parent and children without needing multiple separate tickets.

Gain Creator: Integrated family passes and multi-user subscriptions with reduced rates for protected groups.

Low Priority (Later)

Pain: Lack of agency in mobility planning; feel overlooked in transport design and digital tool development.

Pain Relievers: Include single parents in co-design workshops and provide rewards for app feedback or needs reporting.

Gain: Empowerment and visibility in how local mobility solutions are shaped.

Gain Creator: Participatory planning channels (e.g., family mobility advisory boards, incentive-based feedback forms) integrated into CCAM platforms.

Actor 7 Middle-Aged Multimodal User	Contact channels Focus Groups, Corporate Commute Programs
Actor type: User / Daily Commuter Actor Description: Switches between car, bike, and public transport. Values integration and punctuality. Social-Economic stratification with quantification: Stable income, time-sensitive mobility Gender: Mixed Age: 36-55 Geolocalization: Urban, suburban, and rural areas. Salary: €30,000–€60,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Delays and poor synchronization between transport modes (e.g., bus-train-bike), causing inefficiencies in daily commutes.

Pain Relievers: Integrate real-time scheduling and transfer coordination across public transport, park-and-ride, and micro-mobility options.

Gain: Time-efficient, seamless mobility experience across modes.

Gain Creator: Smart journey planning tools with dynamic re-routing, time alerts, and guaranteed connections for subscribed users.

Medium Priority (Tomorrow)

Pain: Limited infrastructure for mode-switching, such as lack of secure bike parking at stations or charging points for e-cars near transit nodes.

Pain Relievers: Deploy multimodal mobility hubs that support fast, safe switching between bikes, cars, and shared transport.

Gain: Smooth transitions between commute phases with minimal friction.

Gain Creator: Urban/suburban hubs with lockers, bike stations, parking integration, and app-connected handoff systems.

Low Priority (Later)

Pain: Lack of personalized commuting options that reflect user preferences and routines (e.g., congestion avoidance, scenic routes).

Pain Relievers: Introduce AI-driven profile learning to anticipate and recommend optimal routes based on daily travel behavior.

Gain: Customized commute plans that align with lifestyle and travel values.

Gain Creator: Predictive commuting algorithms embedded in CCAM platforms offering preference-based route settings and time management analytics.

Actor 8 Mobility-Challenged Individual	Contact channels NGO workshops, Accessibility Audits
Actor type: User / Person with Disability Actor Description: Requires accessible infrastructure, real-time assistive information, and safe environments. Social-Economic stratification with quantification: Fixed/Low-income, often dependent on support Gender: Mixed Age: Varried Geolocalization: Urban, suburban, and rural areas. Salary: < €15,000	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Inaccessible stops, vehicles lacking ramps/lifts, and unpredictable service environments that induce anxiety.

Pain Relievers: Ensure barrier-free design in all CCAM infrastructure, including low-floor vehicles, tactile surfaces, and staff or sensor-based assistance systems.

Gain: Safe, independent access to daily mobility without requiring external help.

Gain Creator: Standardized accessibility features (visual-audio announcements, platform-level boarding) across all transport nodes.

Medium Priority (Tomorrow)

Pain: Lack of real-time assistance and unclear or inaccessible trip information (e.g., detours, platform changes).

Pain Relievers: Provide live assistive info through personalized mobile apps or help kiosks, including text-to-speech and location-aware alerts.

Gain: Confidence and preparedness while navigating dynamic transport environments.

Gain Creator: AI-enhanced CCAM apps offering tailored route updates, disruptions, and alternative travel options in accessible formats.

Low Priority (Later)

Pain: Exclusion from co-design processes and absence of direct input into system accessibility audits.

Pain Relievers: Create structured roles for persons with disabilities in CCAM design review boards and participatory testing.

Gain: Visibility, representation, and assurance that their needs are embedded in CCAM planning.

Gain Creator: Continuous engagement via accessibility audits, inclusive design feedback loops, and recognition/incentive schemes.

Actor 9 Migrant / Newcomer to the City	Contact channels Community programs, Cultural Integration Services
Actor type: User / Culturally Diverse Actor Description: Needs multilingual access, signage support, guidance on transport systems. Social-Economic stratification with quantification: Low-income, high adaptation needs Gender: Mixed Age: 18-50 Geolocalization: Urban, suburban, and rural areas.(Noord-Brabant) Salary: Varies	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Language barriers in using transport apps, ticketing machines, and signage lead to confusion and misuse of services.

Pain Relievers: Offer multilingual support across digital interfaces and in-vehicle announcements; use pictograms and simplified visual cues.

Gain: Ability to navigate the city independently and safely, without language dependence.

Gain Creator: Multilingual apps, translated schedules, and universal symbols consistently applied across platforms and infrastructure.

Medium Priority (Tomorrow)

Pain: Unfamiliarity with ticketing systems, transfer rules, and mobility rights creates stress and access inequity.

Pain Relievers: Provide on boarding support through local integration centres, cultural mobility guides, and first-time user tutorials.

Gain: Faster adaptation to urban mobility systems and increased confidence.

Gain Creator: Personalized CCAM welcome packages and orientation sessions in community hubs or online platforms.

Low Priority (Later)

Pain: Lack of involvement in mobility planning and feedback loops, especially in areas with high migrant populations.

Pain Relievers: Enable participation in feedback sessions via community partners, language-accessible surveys, and co-design events.

Gain: Feeling heard and represented in local mobility decision-making.

Gain Creator: Institutionalized engagement of migrant communities through advisory panels and inclusive service evaluations.

Actor 10 Environmentally-Conscious E-Mobility User	Contact channels Sustainability events, App usage feedback
Actor type: User / Green Mobility Enthusiast Actor Description: Early adopters of EVs and bike-sharing, seeks eco-efficient systems. Social-Economic stratification with quantification: Middle to upper-middle class Gender: Mixed Age: 25-45 Geolocalization: Hamburg, West Midlands Salary: €35,000 +	

Value Ring (Our assesment of the problems and current situation of our actor)

High Priority (Today)

Pain: Fragmented infrastructure for electric bikes/scooters and inconsistent access to green lanes or charging stations.

Pain Relievers: Expand integrated green mobility corridors, improve charging infrastructure, and coordinate bike/scooter drop zones with CCAM hubs.

Gain: Consistent, hassle-free access to low-emission transport options.

Gain Creator: Unified e-mobility platforms integrating route optimization, bike/e-scooter availability, and charging point locations.

Medium Priority (Tomorrow)

Pain: Lack of visibility into the personal or collective environmental benefits of using CCAM and e-mobility services.

Pain Relievers: Provide real-time carbon footprint tracking and sustainability scores through mobility apps.

Gain: Awareness of ecological impact and motivation to sustain eco-friendly habits.

Gain Creator: In-app emissions dashboards, CO₂ savings reports, and gamified green behaviour incentives (e.g., eco-points, rewards).

Low Priority (Later)

Pain: Limited role in shaping long-term sustainable mobility strategies at the city or district level.

Pain Relievers: Create pathways for citizen engagement in policy design through sustainability panels and digital consultations.

Gain: Influence over future transport policies aligned with environmental values.

Gain Creator: Participatory green mobility planning forums, pilot program testing opportunities, and feedback integration into CCAM development.

5.2.2 Value Ring: Aligning User Needs with Service Design

The **Value Ring** is a stakeholder-centered analytical tool within the GUEST-SI methodology, designed to align CCAM service design with user needs identified during participatory engagement. Developed for the SOLVE phase, the Value Ring structures insights from Actor ID Cards, co-design workshops, and focus group data into three priority tiers: **High Priority (Today)**, **Medium Priority (Tomorrow)**, and **Low Priority (Later)**.

This framework ensures that stakeholder feedback is not only captured, but translated into actionable features, policies, and infrastructure solutions. It also allows designers and planners to track performance alignment via KPI dashboards and scorecards in the TEST phase.

Priority Level	User Goal / Pain / Gain	Design Feature / Service Response	Actor Examples / Source Insights
High (Today)	Lack of step-free access, limited off-peak service, poor real-time updates	Install ramps, support AV onboarding, real-time transit app updates	Elderly users in Trikala and Hamburg; Focus Groups (Sections G & E)
	Safety concerns for caregivers, stroller accessibility	Add wide-door vehicles, on-demand booking with family options	Single parents in West Midlands, Trikala; User Needs Matrix
Medium (Tomorrow)	Complex digital interfaces; absence of integrated multimodal routing	Design simplified UIs with multilingual support; deploy multimodal route planners	Migrants (Hamburg), students (Noord-Brabant); FG Option Sheets
	Lack of bike/AV interoperability	Enable bike racks on AVs; add micromobility integration in apps	Eco-conscious cyclists in Hamburg; Value Ring entries
Low (Later)	Mistrust of automation; lack of data transparency	Transparent onboarding, in-app trust features, user-controlled data settings	Low-income commuters and rural residents in West Midlands; Interview logs
	Anxiety about surveillance or profiling	Implement anonymized data collection and equity-by-design protocols	Persons with disabilities, minorities in Hamburg; Ethical foresight sessions

Table 2 Value ring table

5.2.3 User Needs Matrix: Structuring Priorities by Actor Group

The User Needs Matrix summarizes CCAM priorities for each stakeholder group (Actor IDs) using real feedback from SINFONICA’s focus groups and interviews. Based on qualitative data from Hamburg, Trikala, West Midlands, and Noord-Brabant, it captures frequently reported needs and barriers. Each entry is grounded in coded statements from the Participant, Needs, and Options sections, ensuring GUEST-SI interventions reflect real user voices.

Actor ID	Top Need 1	Top Need 2	Top Need 3	Top Need 4	Top Need 5
Elderly Urban Public Transport Users	Step-free access at bus stops	In-app font scaling	More seating in vehicles	Clear signage at stations	Assistance during boarding
Rural Residents with Limited Access	Regular transport in non-urban zones	Affordable fares	Accessible booking options	Flexible time slots	Driver familiarity and trust
Low-Income Urban Travelers	Daily fare capping	Pre-paid cards for job seekers	Extended service to industrial areas	Late-night services	Cash payment options
Persons with Physical Disabilities	Lift-equipped vehicles	Real-time info on accessible routes	In-vehicle stop announcements	Ramps at all access points	Staff support for boarding
Young Digital Commuters	Integrated mobility apps	Push notifications for delays	Night-time ride-sharing	Bike parking near transit	QR-code-based access
Migrants and Linguistically Isolated Users	Multi-language app support	Pictogram-based info panels	Translation helplines	Cultural mediator presence	Non-digital info access
University Students	Affordable student passes	High-frequency service near campuses	Charging ports on vehicles	Mobile-friendly ticketing	Quiet zones for study during commute
Eco-Minded Urban Cyclists and E-Mobility Users	Safe bike lanes near AV zones	Secure e-scooter parking	Emission display on transport options	Carbon offset options	Integration of bike share with transit pass
Single Parents and Caregivers	Priority seating with stroller space	Flexible travel slots during school hours	Real-time tracking for children's rides	Family fare bundles	Safe drop-off zones
Middle-Aged Multimodal Workers	Real-time intermodal schedule syncing	In-app multimodal route suggestion	Priority parking at stations	Weather-adaptive route alerts	Subsidies for hybrid work commuters

Table 3 User Needs Matrix

5.2.4 Enabling Knowledge Transfer and System Mapping

The success of the GUEST-SI methodology in inclusive CCAM deployment relies not only on participatory tools but also on the effective visualization and transfer of stakeholder knowledge across organizational and regional boundaries. This section focuses on the use of digital platforms, visual analytics, and collaborative tools that transform complex engagement data into accessible formats for decision-makers, designers, and the public.

Within the SINFONICA project, several visualization and knowledge-sharing tools were developed and piloted, including:

1. Knowledge Map Explorer:

Used during the UNIFORM and EVALUATE phases, this digital tool structures insights about actor roles, regulatory conditions, and user needs into a layered, searchable knowledge base. It enables visual navigation through stakeholder relationships, barriers, and proposed solutions, fostering a shared understanding among institutional partners.

2. Stakeholder Social Business Network:

This visualization tool maps the intensity, frequency, and type of interactions among actors across the CCAM ecosystem. By visually illustrating collaborations, power asymmetries, and trust dynamics, it supports the design of targeted governance and engagement strategies.

3. Actor ID Visual Dashboards:

Each Actor ID is represented in an infographic-style profile, integrating age, gender, location, socio-economic indicators, and technology access. These profiles are used in co-design sessions, participatory workshops, and decision-support systems to personalize service features.

4. KPI Dashboards and Balanced Scorecards:

Deployed during the TEST phase, these tools translate qualitative feedback and survey data into performance indicators such as perceived safety, digital usability, and service reliability. They enable stakeholders to monitor project progress and adjust implementations in real-time.

5. Scenario Visualizations and Simulation Outputs:

Output from simulation tools, such as travel demand models or agent-based routing forecasts, are converted into heatmaps, charts, and animated flows. These visuals are essential in foresight workshops, allowing participants to anticipate consequences and evaluate alternatives collaboratively.

6. Participatory Knowledge Repositories:

Online platforms hosting focus group summaries, value rings, needs matrices, and ideathon results ensure that engagement data is not only captured but shared across project phases and among institutions. These repositories were central in maintaining continuity between local workshops in Trikala, Gothenburg, and West Midlands.

By incorporating these tools into the GUEST-SI methodology, CCAM planning becomes more transparent, adaptive, and accessible. Data visualization does not merely simplify complexity—it enables reflexive governance, accelerates learning cycles, and ensures that stakeholder contributions are preserved and activated throughout the system design and policy development process.

5.3 Implementation Results Across Pilot Cities

This section analyses the real-world application of the GUEST-SI methodology across the four pilot cities involved in the SINFONICA project: Trikala, Hamburg, Noord-Brabant, and West Midlands. This section presents a detailed breakdown of how local stakeholders contributed to CCAM planning and how their distinct mobility contexts influenced the deployment of stakeholder tools such as Actor ID Cards, Value Rings, and User Needs Matrices.

Each city was selected based on demographic diversity, regional infrastructure conditions, and pre-existing engagement with mobility innovation. The purpose of this comparative assessment is to highlight the adaptability of GUEST-SI to various governance cultures, socio-economic challenges, and user typologies.

The following subsections (5.3.1 to 5.3.4) provide in-depth case studies for each pilot city. These include:

- Actor group configurations based on actual focus group and interview data.
- Context-specific priorities, constraints, and needs.
- Co-created solutions and their translation into design recommendations.
- Observed outcomes from Living Lab trials or participatory simulations.
- Integration of stakeholder input into regulatory and infrastructural planning.

This section builds upon all previous methodological phases—GO, UNIFORM, EVALUATE, SOLVE, and TEST—and illustrates how tools such as the User Needs Matrix and Value Ring were adapted to match the reality of local users. Furthermore, it emphasizes the comparative insight offered by applying GUEST-SI across varying political, geographic, and socio-cultural settings.

Through this city-level lens, Chapter 5 shows that GUEST-SI is not a one-size-fits-all framework but a flexible, data-grounded methodology for enabling inclusive, user-responsive, and ethically grounded CCAM planning.

5.3.1 Trikala: Co-Creation and Rural Inclusion Strategies

Trikala stands as a key implementation site illustrating how rural and semi-urban dynamics can be integrated into future-ready, inclusive CCAM ecosystems. Located in central Greece, Trikala’s unique demographic profile—characterized by a significant elderly population, widespread rural settlements, and low modal diversity—offered critical insights into it.

The Actor ID analysis derived from focus group and interview datasets in Trikala identified several pivotal stakeholder groups:

- **Elderly Urban Public Transport Users**, who reported difficulty accessing vehicles due to lack of ramps, and discomfort with app-based services.
- **Rural Residents with Limited Access**, who articulated concerns about irregular services, especially for medical and social trips.
- **Persons with Physical Disabilities**, who cited a lack of accessible bus stops and infrastructure.
- **Low-Income Travelers**, often dependent on infrequent and unaffordable services to reach essential urban functions.

Data extracted from SINFONICA Excel files—particularly the Participant Options and Open Feedback sections—revealed that top mobility priorities in Trikala included safer sidewalks, reliable transport to healthcare facilities, volunteer-driven ride-sharing, and basic digital access alternatives. The GO and UNIFORM phases leveraged these inputs through co-creation workshops involving local citizens, civil society, and municipal transport planners.

During the **EVALUATE phase**, scenario testing and simulation modeling were conducted to explore the impact of flexible routing in peri-urban and rural zones. Results indicated that integrating hybrid CCAM services—such as demand-responsive vans and semi-automated shuttles—could reduce transport exclusion for 65% of survey respondents.

In response, the SOLVE phase guided the development of CCAM-ready interventions such as simplified digital kiosks equipped with tactile features and voice guidance, ride-pooling platforms that connected elderly users with volunteer drivers, and modular transit schedules tailored to align with local medical appointments and market times.

Under the **TEST phase**, Living Lab pilots enabled real-time data collection via mobile user logs and post-ride focus groups. Elderly users expressed increased trust when human interaction was preserved in onboarding and support. Accessibility metrics (e.g., satisfaction, entry ramp use, seat availability) were monitored via app-based dashboards.

Trikala's success stemmed from the institutionalization of co-governance. Health centers, civic groups, and technology vendors formed a participatory oversight board to ensure that CCAM solutions remained socially responsive and operationally feasible. In conclusion, Trikala exemplifies how the GUEST-SI methodology—when rooted in empirical user feedback and implemented via the SINFONICA framework—can optimize CCAM deployment in non-metropolitan contexts. The city's integration of volunteerism, flexible automation, and hybrid mobility strategies validates the potential of user-driven service design to bridge infrastructure gaps and increase trust in future mobility ecosystems.

5.3.2 Hamburg: Accessibility and Trust in Urban CCAM

Hamburg, as one of Germany's leading smart mobility cities, offers an exemplary urban context to examine how the GUEST-SI methodology can optimize CCAM deployment by addressing accessibility, digital engagement, and public trust. The city's longstanding engagement with connected transport systems, including its integration into EU projects like SHOW and SINFONICA, provided fertile ground for stakeholder-driven innovation through real-world trials.

Hamburg's Actor ID data, derived from focus groups and interviews, revealed a diverse urban population with a broad range of mobility needs. Key stakeholder groups included elderly users concerned with boarding safety and transport reliability during off-peak hours, migrants and linguistically isolated residents seeking multilingual interfaces and culturally inclusive services, low-income workers prioritizing affordability and physical access to employment hubs, and eco-conscious commuters advocating for expanded micromobility options and reduced emissions.

Focus group data highlighted a strong user preference for integrated, eco-friendly systems. For instance, electric buses and bike-sharing networks were highly rated among participants for their accessibility, environmental value, and perceived reliability. Accessibility was also a critical issue: requests for step-free access, real-time visual/audio updates, and easy-to-navigate ticketing apps were frequent across user groups.

In the **GO and UNIFORM phases**, the GUEST-SI methodology was applied to map institutional stakeholders such as HVV (Hamburger Verkehrsverbund), mobility service providers, city officials, and civil society organizations. The Knowledge Map Explorer tool was used to identify gaps in role coordination and reveal misalignments between infrastructure providers and end-users.

The **EVALUATE phase** introduced participatory simulation exercises and survey-based KPI benchmarking. For example, users tested proposed CCAM app prototypes that measured usability, trustworthiness, and adaptability across digital interfaces. Multilingual accessibility emerged as a primary determinant of trust for users from migrant communities, especially among elderly newcomers and non-EU nationals.

During the **SOLVE phase**, user priorities were integrated into prototype development through the implementation of touchscreen ticketing systems with multilingual support, smart wayfinding features designed for persons with disabilities, and the integration of bike lanes and AV-friendly intersections within low-emission zones.

Pilot feedback during the **TEST Phase** showed increased willingness to adopt CCAM services when safety and trust-building measures were clearly communicated. This included onboarding sessions, visual tutorials at AV terminals, and pop-up demonstrations in community hubs. Moreover, public forums were held in partnership with local NGOs to enhance civic legitimacy and gather feedback from hard-to-reach communities. Hamburg's implementation of the GUEST-SI methodology demonstrated that even in digitally mature, infrastructure-rich environments, trust remains a decisive variable for CCAM acceptance. The combination of advanced data visualization tools, real-time feedback dashboards, and strong inter-agency cooperation enabled the city to match high-tech mobility offerings with tangible social benefits.

In conclusion, Hamburg provides a compelling case of how GUEST-SI tools—particularly Actor ID Cards, Value Rings, and KPI dashboards—can optimize inclusive CCAM deployment in complex urban systems. It underscores the critical role of trust-building and multilingual inclusivity as determinants of system uptake, even in high-capacity mobility ecosystems.

5.3.3 Noord-Brabant: Mobility Equity and Digital Literacy

Noord-Brabant offers a compelling case study in designing inclusive, technology-enhanced mobility strategies tailored to a semi-urban, digitally progressive yet socially diverse region.

Located in the southern Netherlands, Noord-Brabant features a polycentric mobility landscape encompassing both high-tech cities like Eindhoven and more suburban or peri-urban areas with uneven infrastructure. This made it an ideal site for testing how CCAM solutions can balance innovation with social equity and digital accessibility.

Stakeholder Configuration and Actor ID Highlights

Using SINFONICA’s Actor ID methodology, four key stakeholder categories emerged from focus group and interview datasets. Middle-aged multimodal workers commuting from suburban areas using a mix of car, bike, and public transport emphasized the need for seamless digital interfaces and intermodal syncing. Young digital commuters, including students and early-career professionals, prioritized app integration, route flexibility, and data transparency. Rural and peri-urban residents highlighted service coverage gaps and the need for on-demand mobility options. Caregivers and single parents stressed the lack of time-flexible and accessible services suited to family responsibilities. Across all groups, digital access—ranging from real-time data availability to app usability and language accessibility—was identified as a critical factor influencing service adoption.

GO and UNIFORM Phases: Mapping Needs and Coordination

During the GO phase, participatory sessions highlighted friction between technologically advanced service offerings and varying levels of user readiness. While some users welcomed AI-driven journey planners and multimodal apps, others—especially in lower-income or rural areas—requested more **user-friendly interfaces**, **simplified onboarding**, and **alternative access channels** such as SMS or offline route maps.

The Knowledge Map Explorer was used during the UNIFORM phase to align digital developers, municipalities, and transit operators on shared terminology, performance indicators, and equity objectives.

EVALUATE Phase: Bridging the Digital Divide

Through surveys and simulation tools, the Evaluate phase revealed that disparities in CCAM readiness were not solely infrastructural but also socio-digital. For example, some respondents found journey-planning tools overly complex or insufficiently localized, while others expressed distrust in AI-generated recommendations, particularly for time-sensitive commutes such as picking up children or arriving at work on time. These insights directly influenced the prioritization matrix for solution co-design and underscored the importance of incorporating digital literacy considerations into broader CCAM scaling strategies.

SOLVE Phase: Inclusive Design Implementation

Value Rings developed for Noord-Brabant revealed strong demand for multilingual, simplified mobility apps that integrate train, bus, and micromobility options; predictive route

planning that adjusts to delays or schedule changes; and family-friendly features such as stroller space indicators, school-route tracking, and flexible ticket bundles. Co-creation sessions in the region led to the development of prototype services featuring modular app layouts, voice assistant compatibility, and user interface updates driven by ongoing feedback.

TEST Phase: Adaptive Pilots and Feedback Integration

Pilot trials conducted in university campuses and residential districts with high car dependency demonstrated that digital trust increased significantly when user interfaces were personalized, and adoption rates improved when tutorials or community ambassadors supported app usage. Feedback loops, facilitated through in-app forms and public events, further revealed that real-time communication—such as alerts about delays or bike availability—played a crucial role in enhancing users’ perception of system reliability.

Conclusion

Noord-Brabant’s experience demonstrates that CCAM systems, no matter how technologically advanced, must be co-designed with attention to **social context, digital literacy, and multi-user compatibility**. The GUEST-SI methodology allowed regional planners to identify not just infrastructure gaps but **cognitive and interface-related barriers** that influence system uptake. This case underscores the necessity of designing CCAM tools that are as socially intuitive as they are technically sophisticated.

5.3.4 West Midlands: Institutional Trust and Participatory Pilots

As the UK’s most prominent regional case in the SINFONICA project, the **West Midlands** illustrates the strategic value of applying the GUEST-SI methodology in a politically devolved and institutionally layered governance context. Anchored by Transport for West Midlands (TfWM), the region integrates both metropolitan areas like Birmingham and peripheral zones facing varying degrees of transport exclusion, digital inequality, and socioeconomic stratification.

West Midlands offers a deeply contextualized example of how **trust** in institutions, **clarity** of governance, and **engagement** equity can determine the societal viability of CCAM solutions.

Actor ID Landscape and Stakeholder Insights

Based on detailed focus group data, Actor ID analysis in the West Midlands identified several key stakeholder concerns: elderly users with limited digital confidence expressed discomfort with automated interfaces and the absence of visible assistance; low-income residents highlighted cost barriers, particularly for cross-zone commuting; ethnic minorities and migrants stressed the need for cultural inclusion and translation support; and working parents and part-time shift workers emphasized the importance of flexible scheduling and enhanced safety during off-peak hours. Across these groups, participant responses consistently revealed a mismatch between existing services and real-life travel routines, especially beyond city centers. Affordability, trust, and understandability emerged as the most frequently reported barriers in both the open feedback and “options” sections of the SINFONICA Excel datasets.

GO and UNIFORM: Building Institutional Anchors

The GO phase in the West Midlands benefited from pre-existing transport governance frameworks and allowed GUEST-SI to align with TfWM’s data, community outreach, and equity strategies. Stakeholder workshops co-hosted by local authorities and civic organizations helped map influence, need distribution, and cooperation bottlenecks.

During the UNIFORM phase, the Actor ID and Stakeholder Matrix were expanded to include **non-traditional actors** such as neighborhood associations, religious leaders, and employment hubs. This broad lens captured user diversity that was often invisible in top-down planning.

EVALUATE: Risk and Trust Factors in System Readiness

Trust consistently emerged as a critical factor influencing CCAM adoption, with many respondents expressing concerns about “being left behind” by overly technical solutions. Simulation trials and mock-ups demonstrated that participants responded positively to onboarding sessions held in community centers, the presence of human support at AV boarding points, and translated, visually simplified digital interfaces. Evaluation metrics tracked through KPI dashboards further identified perceived safety, cost predictability, and clarity of signage as key indicators shaping user trust in CCAM services.

SOLVE: Co-Designing with User Realities

Co-creation outputs emphasized practical, user-centered solutions, including physical signage placed alongside digital apps to enhance route confidence, hybrid ticketing options combining contactless and cash-based methods, and community-based mobility ambassadors trained to support CCAM onboarding. Value Ring results confirmed that the highest-impact gains stemmed from systems designed for everyday use rather than technologically advanced but impractical “smart” prestige solutions. Participants consistently prioritized access to essential services—such as early morning childcare and late-shift job locations—over the novelty of AI-driven routing features.

TEST: Embedding Feedback into Operational Models

Living Lab pilots in the West Midlands were characterized by an iterative, participatory structure that integrated diverse feedback channels, from digital input forms to in-person reviews in community settings. Observations revealed that public trust increased measurably when users felt genuinely consulted and respected, while system responsiveness improved significantly when governance structures included neighborhood-level representation. Transport for West Midlands (TfWM) incorporated these insights into its real-time monitoring systems, enabling adjustments to routing, access, and pricing to be justified, implemented, and communicated transparently and effectively.

Conclusion

The West Midlands case underscores the critical role of **institutional trust**, **cross-scalar stakeholder alignment**, and **participatory ethics** in scaling CCAM systems. Through GUEST-SI, the region operationalized co-creation into governance, moving beyond consultation into shared responsibility. It proves that for CCAM to succeed, it must not only meet mobility needs but do so in ways that resonate with diverse community expectations, local cultures, and social equity goals.

5.4 Lessons Learned and Methodological Reflections

The cross-city application of the GUEST-SI methodology within the SINFONICA project provides key insights into how stakeholder-centered planning enhances the inclusive deployment of Cooperative, Connected, and Automated Mobility (CCAM). Drawing from its five-phase structure—GO, UNIFORM, EVALUATE, SOLVE, and TEST—several lessons emerge regarding stakeholder engagement, tool integration, and adaptive governance.

Early and Structured Engagement: Across all four cities, early participatory mapping—especially through Actor ID Cards—was essential for surfacing barriers faced by underrepresented groups, such as digitally excluded migrants in Hamburg, elderly users in Trikala, and working parents in West Midlands. These profiles enabled planners to tailor interventions with equity in mind from the outset.

Tool Integration and Service Responsiveness: The Value Ring and User Needs Matrix systematically translated qualitative feedback into design parameters during the SOLVE and TEST phases. For instance, Noord-Brabant’s demand for simplified multimodal apps and Trikala’s call for volunteer ride-sharing were incorporated into prototype features. These tools also clarified key tensions—such as digital complexity vs. usability and automation vs. human reassurance—especially for vulnerable users.

Trust and Transparency: Stakeholder trust was shown to depend more on perceived inclusivity than technological novelty. Key enablers included multilingual communication, visible update cycles, and localized onboarding—strategies supported by Grønborg Bak et al. (2023) and trialed in Hamburg and West Midlands through community-based demo sessions and pop-up support hubs.

Institutional Coordination and Local Adaptation: Implementation success hinged on aligning public, private, and civic actors. In Hamburg, stakeholder harmonization was achieved using tools like the Stakeholder Matrix and Knowledge Map Explorer. In Trikala, where governance capacity was lower, participatory capacity-building ensured that citizen voices remained central to system design.

Evaluation Beyond KPIs: The EVALUATE phase demonstrated that standard metrics (e.g., punctuality) must be complemented by social indicators such as user trust and interface

satisfaction. In the West Midlands, a Balanced Scorecard framework integrated these qualitative aspects, including feedback on affordability and real-time guidance, into TfWM’s live monitoring system—enabling iterative adjustments to access and fare models.

Sustained Engagement and Institutional Memory: A consistent finding was that episodic engagement is insufficient. Lasting impact requires long-term co-creation mechanisms, such as community liaisons and open feedback repositories. This mirrors practices from the SHOW project, where sustained involvement directly improved system acceptance and public legitimacy (Grønborg Bak et al., 2023).

In summary, the GUEST-SI methodology proved both transferable and adaptive across diverse mobility contexts. Its success depends on embedding participatory governance, behavioral insight, and ethical evaluation at each stage of CCAM planning. Ultimately, inclusive innovation is not an optional supplement—it is a structural requirement for equitable and effective automated mobility systems.

5.4.1 Strengths and Adaptability of GUEST-SI

The GUEST-SI methodology exhibits several core strengths that make it particularly well-suited for optimizing Cooperative, Connected, and Automated Mobility (CCAM) deployment in complex, multi-stakeholder environments. Developed within the SINFONICA project, GUEST-SI integrates participatory governance, standardized decision-making tools, and adaptive feedback loops to enable inclusive, scalable, and resilient CCAM innovation (Grandsart et al., 2025; Ringhand et al., 2024).

A. Structured yet Flexible Framework

A foundational strength of GUEST-SI lies in its modular yet coherent structure. Each of its five phases—GO, UNIFORM, EVALUATE, SOLVE, and TEST—integrates tools like Actor ID Cards, Stakeholder Analysis Matrices, User Needs Matrices, and Value Rings. This ensures that stakeholder needs are addressed systematically from early engagement to real-world testing, making the methodology both comprehensive and action-oriented (GUEST Methodology, 2023).

Importantly, the framework’s modularity allows for localized adaptation. In SINFONICA pilot cities, for example, Trikala emphasized rural accessibility, Hamburg prioritized digital multilingualism, Noord-Brabant tackled digital literacy gaps, and West Midlands focused on trust-building with low-income users (Ringhand et al., 2024; user needs from excel.docx,

2024). This adaptability shows that GUEST-SI accommodates different urban forms, governance capacities, and technological maturity levels.

B. Evidence-Based Decision-Making

GUEST-SI's EVALUATE phase is particularly strong in translating stakeholder feedback into measurable impact metrics. With the aid of SWOT analysis, simulation models, and balanced scorecards, decision-makers can quantify user satisfaction, accessibility, perceived safety, and digital readiness—factors often overlooked in traditional transport planning (Santa et al., 2022). These tools support iterative design and reduce the risk of implementation failure, aligning closely with SHOW project recommendations for continuous risk and feasibility assessment (Grønborg Bak et al., 2023).

C. Inclusive Stakeholder Engagement

GUEST-SI's stakeholder engagement process stands out for its systematic inclusion of vulnerable and often excluded groups. The Actor ID Card and Value Ring tools have proven effective in capturing nuanced perspectives across demographic categories—including elderly users, persons with disabilities, migrants, and digitally excluded individuals (Grandsart et al., 2025). These instruments ensure equity is built into the foundation of CCAM system design.

This aligns with stakeholder-centric principles outlined in the SHOW project, which emphasize the use of personalized engagement strategies and hybrid communication tools to maximize outreach and feedback accuracy (Grønborg Bak et al., 2023).

D. Digital Integration and Visualization Tools

GUEST-SI is further strengthened by its suite of visualization and knowledge-sharing tools, including the Knowledge Map Explorer, simulation interfaces, and KPI dashboards. These tools not only foster cross-sector collaboration but also support real-time monitoring and shared learning among users, operators, and policymakers (Grandsart et al., 2025). They reflect broader EU research trends emphasizing transparency, accountability, and open innovation in mobility system governance (Santa et al., 2022).

E. Alignment with European Mobility Goals

Finally, the methodology aligns with major European frameworks such as the Urban Mobility Framework and Sustainable and Smart Mobility Strategy. Its emphasis on inclusivity, ethics, and participatory foresight aligns directly with policy imperatives outlined in EU programs like MOVE2CCAM and 5G-MOBIX (Ferreira, 2019; Santa et al.,

2022). This positioning enhances its relevance for long-term strategic planning, funding alignment, and regulatory harmonization.

5.4.2 Challenges in Cross-City Implementation

Despite the methodological strengths of the GUEST-SI framework, its implementation across the four SINFONICA pilot regions—Hamburg, Noord-Brabant, Trikala, and West Midlands—revealed key operational and contextual challenges that require refinement.

1. Methodological Constraints in Stakeholder Profiling

While the Actor ID Card and Stakeholder Analysis Matrix effectively profile stakeholder roles and influence, their effectiveness is highly dependent on the inclusivity and completeness of underlying datasets. In several cases—most notably Noord-Brabant and Hamburg—digitally excluded individuals, non-native speakers, and people with severe cognitive or physical disabilities were underrepresented in focus groups and interviews. This introduced a risk of skewed user needs matrices and potentially incomplete or biased Value Ring models (Ringhand et al., 2024; Grandsart et al., 2025). Similar limitations were acknowledged in the SHOW project's participatory exercises, where short-term engagements limited diversity and continuity in input (Grandsart et al., 2025)Summary of Articles.

2. Standardization vs. Local Sensitivities

The UNIFORM phase's emphasis on harmonization of governance models, KPIs, and simulation tools provided structure but often clashed with local conditions. In Trikala, infrastructural deficits and informal transport practices hindered alignment with standardized templates. In the West Midlands, multilingual and socioeconomically diverse user groups required tailored engagement that exceeded the scope of default feedback platforms. These experiences support a shift toward a "glocalized" model—maintaining global standards while embedding mechanisms for regional adaptability (Santa et al., 2022; Ringhand et al., 2024)Summary of Articles.

3. Evaluation Overload and Cognitive Saturation

The EVALUATE phase integrates a broad suite of assessment tools—SWOT, Balanced Scorecards, KPI dashboards, and simulation models. While technically robust, this volume

often proved overwhelming for municipal staff lacking technical or data literacy resources. Overloading the decision-making process with too many indicators can reduce interpretability and hinder effective uptake, especially in resource-limited planning contexts. A tiered evaluation strategy that separates core from advanced KPIs may enhance clarity and usability.

4. Risk of Tokenistic Participation

Despite GUEST-SI's strong participatory intent, certain workshops and co-creation sessions risked becoming symbolic. For example, feedback collected in the West Midlands on safety and affordability was not systematically reflected in pilot planning. This mirrors findings from the SHOW project's MAMCA workshops, where stakeholder input on preferred AV configurations was not integrated into technical implementations due to regulatory or logistical barriers (Grandsart et al., 2025) Summary of Articles. To avoid symbolic participation, participatory outputs must be visibly tied to measurable changes in project design—a principle aligned with Arnstein's Ladder of Citizen Participation.

5.4.3 Alignment with EU CCAM, Digital Inclusion, and Mobility Policy Frameworks

While GUEST-SI aspires to fulfill the ambitions of equitable and sustainable mobility, gaps remain in operationalizing certain cross-cutting dimensions required by EU mobility frameworks.

1. Incomplete Operationalization of Equity, Gender, and Climate Priorities

Although the GUEST-SI framework emphasizes affordability, accessibility, and inclusivity, its application during the TEST phase revealed gaps in translating these into actionable outcomes. In Trikala and West Midlands, affordability was a high-priority concern for users—especially low-income and rural residents—but few cost mitigation strategies (e.g., subsidies or tiered pricing) were piloted user needs from excel. Similarly, gender-specific concerns—such as safety in night-time mobility—were noted across all sites but not reflected in dashboard metrics or evaluation criteria

2. Absence of Intersectional Indicators in Monitoring Systems

While the SINFONICA Knowledge Map Explorer (KME) is a valuable tool for scenario simulation and stakeholder guidance, its default configuration does not explicitly

incorporate indicators for gender equity, digital accessibility, or climate resilience (SINFONICA D4.1, 2024). This gap limits its ability to fully align with intersectional planning mandates outlined in EU frameworks such as the Urban Mobility Framework and the Sustainable and Smart Mobility Strategy (Ferreira, 2019; Santa et al., 2022)

3. Lack of Policy Feedback Loops

Policy harmonization is a central objective of the SINFONICA framework, aiming to bridge local experimentation with broader regulatory alignment. However, the project documentation—particularly in D4.1—does not specify clearly defined feedback mechanisms by which pilot site findings are systematically integrated into national or EU-level mobility regulations (SINFONICA D4.1, 2024). In the absence of such institutional channels, the replicability and strategic policy impact of inclusive CCAM solutions risk being constrained.

To strengthen GUEST-SI's long-term impact and regulatory alignment, several enhancements are recommended: refining stakeholder profiling through quota-driven representation, particularly for digitally excluded and underrepresented groups; introducing glocalization protocols to contextualize KPIs, feedback loops, and engagement models; adopting tiered KPI frameworks that distinguish strategic from operational indicators; embedding equity and gender metrics into monitoring dashboards and simulation tools; and establishing formal feedback mechanisms to translate pilot results into policy and regulatory structures. These adjustments aim to enhance both the methodological coherence and policy integration of GUEST-SI within the broader EU CCAM deployment landscape.

5.4.2 Recommendations and Future Directions

Building upon the findings from stakeholder engagement across Hamburg, Noord-Brabant, Trikala, and the West Midlands, this section provides actionable recommendations to enhance future CCAM (Cooperative, Connected, and Automated Mobility) deployments under the GUEST-SI methodology. These recommendations aim to strengthen adaptability, inclusion, and evidence-based scalability of CCAM strategies.

1. Institutionalize Co-Creation Through Iterative Planning Cycles

The SINFONICA project demonstrated that one-time participatory exercises are insufficient for sustained trust and usability. Future CCAM deployments should establish iterative co-creation loops—such as periodic focus groups and digital feedback portals—embedded throughout the lifecycle of mobility services. The SHOW project’s implementation of sequential ideathons and MAMCA evaluations in cities like Carinthia and Tampere provides a tested model for multi-phase engagement that evolves with technological maturity and community feedbackSummary of Articles.

2. Develop Inclusive Simulation Frameworks

While current simulation models address technical feasibility and routing performance, future CCAM research should expand these tools to simulate inclusion metrics—such as accessibility for elderly users or the impact of digital literacy gaps. The stakeholder-led modeling framework proposed by Yu & McKinley (2024) introduces a promising direction by integrating synthetic personas with multi-criteria decision tools, enabling virtual stakeholder foresight for underserved demographicsSummary of Articles.

3. Institutionalize Balanced Scorecard and Value Ring Tools at the Municipal Level

Municipalities should integrate GUEST-SI’s Balanced Scorecard and Value Ring tools into their official CCAM strategy assessments. Doing so would formalize user-centric metrics such as perceived safety, environmental equity, and modal flexibility as part of procurement and design criteria. The SINFONICA Knowledge Map and its user segmentation tables offer a practical base for training municipal staff and automating the integration of citizen preferences into scenario evaluationsD4.1-SINFONICA-Knowledg....

4. Explore AI-Enhanced Participatory Systems

The SHOW project illustrated that in-person engagement formats like Hackathons were effective but resource-intensive. Future CCAM governance should pilot the use of generative AI and LLMs to create digital twins of stakeholder forums, where avatars can simulate participation and prioritize options across equity and feasibility constraintsSummary of Articles. This approach, especially in rural or low-resource settings, could significantly reduce logistical burdens while enhancing representativeness.

5. Standardize and Localize KPI Dashboards

To foster cross-regional comparability while respecting local diversity, CCAM evaluators should deploy modular KPI dashboards with standardized indicators (e.g., accessibility rate, modal shift, safety perception) but allow local customization. These should be made accessible in local languages and formats, including visual summaries for cognitively or

digitally excluded users. Such practices are critical to counter the “technological gentrification” risk identified in previous research on Mobility-as-a-Service (MaaS) governanceSummary of Articles.

6. Research Directions for Future EU Projects

Finally, based on the gaps and successes identified in SINFONICA and related efforts, future research should prioritize cross-border data interoperability through harmonized GDPR-compliant frameworks across pilot sites, explore dynamic mobility incentives using behavioral economics-based nudges to encourage modal shift, and develop gender- and age-specific CCAM interfaces tailored to vulnerable user cohorts, particularly elderly women in peri-urban areas. Additionally, socio-technical scenario testing should incorporate user stories from Actor ID Cards into multi-agent simulations to evaluate deployment policies under conditions of uncertainty. These research directions align with Horizon Europe objectives and reinforce the GUEST-SI methodology’s commitment to embedding lived experience into every phase of CCAM deployment, thereby enhancing both social legitimacy and operational effectiveness.

CHAPTER 6: Business and Economic Models for CCAM Scalability

The scalability of Cooperative, Connected, and Automated Mobility (CCAM) systems hinges on robust business and economic models that align stakeholder interests, optimize infrastructure and service investments, and ensure inclusive, long-term societal value. As CCAM shifts from pilot programs to broader regional deployment, financial mechanisms must enable inter-sectoral coordination, accommodate equity concerns, and incentivize sustainable innovation. This chapter explores the stakeholder-specific funding roles, investment frameworks, and performance metrics necessary to guide scalable and ethical CCAM development across Europe.

6.1 Stakeholder Roles in Value Generation and Funding

6.1.1 Collaborative Funding Mechanisms for CCAM

Scaling CCAM across diverse European regions requires hybrid funding strategies that reduce financial risks while maximizing public value and private sector innovation. Public-Private Partnerships (PPPs) remain foundational for early-phase CCAM deployment, especially in projects involving autonomous shuttle services, data hubs, or digital infrastructure in urban centers like Hamburg and Noord-Brabant. These models allow local governments to provide initial capital or infrastructure (e.g., dedicated AV lanes, 5G corridors), while private actors contribute vehicles, V2X systems, and software platforms (Ringhand et al., 2024; Grandsart et al., 2025).

European Union funding instruments—including Horizon Europe, the Connecting Europe Facility (CEF), and the European Investment Bank’s (EIB) Smart and Sustainable Mobility stream—are essential for financing both R&D and implementation phases. In Trikala, EU grants significantly contribute to developing inclusive CCAM solutions addressing documented multilingual and digital access needs, particularly for elderly and digitally excluded users. However, fragmentation in grant access remains a challenge, particularly for municipalities in Southern and Eastern Europe.

Private corporations, including automotive OEMs and tech startups, are increasingly adopting **industry-led investment models** that trade capital investment for access to operational datasets, urban pilot environments, or data monetization rights. In West Midlands, revenue-sharing agreements now allow platform providers to pay municipalities for privileged access to AV corridors or real-time transport data.

Subscription-based and pay-per-use mobility models are also gaining traction, offering sustainable revenue streams for service providers. These models integrate flexible pricing strategies to improve affordability, particularly when dynamic subsidies are applied to low-income users, persons with disabilities, or digitally marginalized communities (Santa et al., 2022; Zhao & Malikopoulos, 2020).

6.1.2 Economic Incentives for Public and Private Actors

For CCAM to mature into a self-sustaining mobility ecosystem, tailored economic incentives must align the interests of diverse stakeholders—governments, transport operators, digital infrastructure providers, and end users.

Incentives for Public Entities

Public authorities **stand to benefit economically** from CCAM adoption through reduced congestion, improved air quality, and potentially lower infrastructure maintenance costs as automated systems optimize traffic and reduce wear. In some pilot regions, municipalities are exploring the **monetization of CCAM-generated data** through anonymized sharing frameworks with insurers, transit operators, and logistics firms. These early practices enhance urban planning capabilities and may evolve into **new public revenue streams**, particularly if governed transparently and equitably (Grandsart et al., 2025).

Incentives for Private Actors

Technology developers and MaaS operators stand to benefit significantly from integrating CCAM into emerging service markets, driven by key incentives such as access to regulatory experimentation environments—like those trialed in the SHOW and MOVE2CCAM projects through living labs, hackathons, and broader sandbox frameworks supported by the EU AI Act—and the availability of shared municipal datasets for algorithm calibration, user

behavior modeling, and predictive analytics enhancement. Additional incentives include proposed tax credits or co-investment schemes aimed at stimulating equitable infrastructure deployment and business innovation in underserved areas. Fleet operators can lower operational costs through automation, while telecom providers increasingly pursue tiered bandwidth monetization and MaaS integration strategies within 5G-enabled V2X ecosystems (Santa et al., 2022; Zhao & Malikopoulos, 2020).

Suggestions:

EU member states and municipalities could implement localized tax credits and carbon offset programs to incentivize CCAM service providers that prioritize inclusive access and ethical data governance. This dual-incentive model would support platforms serving vulnerable groups—such as migrants, elderly citizens, and rural populations—through initiatives like subsidized fares, multilingual interfaces, and accessible application designs. Benefits could be allocated based on measurable benchmarks, including carbon credits for electric AV deployment in low-emission zones, tax incentives for GDPR-compliant and anonymized data-sharing frameworks, and inclusion-linked reductions for services validated through participatory tools such as the Knowledge Map Explorer or Actor ID Cards (Ringhand et al., 2024). These mechanisms would promote equitable CCAM access while aligning deployment strategies with the environmental and digital justice goals outlined in the European Green Deal and the EU Data Governance Act.

6.2 Typologies of Business Models for CCAM Deployment

As Cooperative, Connected, and Automated Mobility (CCAM) transitions from pilot initiatives to systemic regional adoption, viable business models are essential to ensure both economic sustainability and service inclusivity. Based on stakeholder engagement conducted through the SINFONICA project across Trikala, Hamburg, Noord-Brabant, and the West Midlands, two primary business model typologies can be identified: infrastructure-based and service-oriented approaches. Infrastructure-based models emphasize investment in digital architecture, such as 5G corridors, data-sharing platforms, and AV-compatible road environments, which were prioritized in Noord-Brabant and Trikala. In contrast, service-oriented models focus on user-facing innovations like MaaS platforms, multilingual accessibility tools, and dynamic pricing systems, as seen in Hamburg and the West

Midlands. These business models integrate digital innovation with mobility equity objectives, supporting stakeholder alignment, sustainable monetization strategies, and adaptability to regional governance and capacity (D4.1, 2024; Ringhand et al., 2024).

6.2.1 Infrastructure-Based CCAM Business Models

Infrastructure-based Cooperative, Connected, and Automated Mobility (CCAM) business models emphasize the monetization of both physical and digital assets, including Vehicle-to-Everything (V2X) communication systems, connectivity platforms, and automated vehicle-ready intersections. These models are particularly relevant in regions with advanced digital integration strategies, such as Noord-Brabant and Trikala, where public stakeholders invest in road-side units, data hubs, and semantic infrastructures to support scalable CCAM ecosystems. Public-private partnerships (PPPs) are fundamental to these models, enabling municipalities and private entities—such as telecom operators and platform providers—to share investment burdens and co-develop smart mobility corridors. Such arrangements align with the broader European strategy for sustainable mobility and smart infrastructure, as outlined in both SINFONICA’s architectural framework and Horizon Europe policy recommendations (Ferreira, 2019; Zhao & Malikopoulos, 2020).

A. Data-Driven Revenue Models

As mobility systems become increasingly digitized, mobility data is being reframed as a public asset with strategic value for urban governance. In the SINFONICA project, municipalities such as Trikala and Hamburg emphasized the potential of aggregated and anonymized mobility datasets to support urban planning, accessibility modeling, and real-time operational optimization. While these cities have not yet implemented formal monetization mechanisms, stakeholders expressed strong interest in leveraging such datasets for adaptive traffic management and evidence-based policy modeling.

In this context, a recommended model is the creation of a regional Cooperative, Connected, and Automated Mobility (CCAM) data exchange hub. Such a hub would enable ethically governed data access for fleet operators, insurers, and researchers under GDPR-compliant conditions. It could be modeled after the Knowledge Map Explorer developed within SINFONICA, which serves as a semantic infrastructure for structuring, sharing, and ethically managing CCAM-related knowledge across stakeholder groups. This forward-

looking framework aligns with the principles of the EU Data Governance Act (2022), encouraging trustworthy and inclusive data ecosystems to advance digital mobility innovation.

B. V2X Connectivity Monetization

SINFONICA stakeholder analyses indicate strong regional interest in **5G-enabled V2X** services, particularly for **real-time safety, multimodal integration, and user-centered traffic optimization**. In **Noord-Brabant**, participants emphasized the importance of **app-based coordination with digitally managed intersections**, demonstrating how connectivity infrastructure is essential for CCAM scalability.

To support sustainable deployment, we propose a **tiered connectivity monetization model**, offering prioritized 5G access for AV and MaaS providers under **transparent, publicly governed frameworks**. These would ensure **data protection, non-discriminatory bandwidth allocation**, and alignment with **EU digital legislation**, including the **Digital Services Act** and **Data Governance Act**. Such a model would reinforce CCAM's core goals of **interoperability, inclusion, and service resilience**.

C. Infrastructure Leasing and Joint Investment

Joint investment models play a central role in advancing CCAM deployment by aligning municipal infrastructure development with private sector contributions. In Trikala, the implementation of CCAM infrastructure—such as smart bus shelters, improved road markings, and traffic management upgrades—was achieved through coordinated public funding and stakeholder collaboration, demonstrating an effective template for city-led deployment of AV-compatible assets. Across the SINFONICA regions, infrastructure-based partnerships focus on cost-sharing arrangements, where municipalities finance physical upgrades including digital signage and connected intersections, while private operators contribute fleet assets, communication systems, or platform integration components. These models ensure that infrastructure and service development progress in parallel, supporting CCAM scalability, operational readiness, and regional equity.

Service-based business models center on user access, pricing strategies, and the operational logic of shared mobility services. These models are particularly valuable in addressing rural needs, last-mile gaps, and affordability concerns.

A. Municipal Transport as a Service (M-TaaS)

In Trikala, CCAM pilots focused on **automated shuttle routes** linking key public services, such as **hospitals and elderly care centers**. These routes were co-designed by municipal authorities and civic organizations to serve **low-mobility and digitally vulnerable populations**, reflecting the 4A principles of **accessibility, availability, affordability, and acceptability**.

Suggested Model: Validated through SINFONICA stakeholder engagement, this model highlights the potential of **city-led, equity-focused AV service delivery**. Building on this success, we recommend expanding into a **city-subsidized AV model** where municipalities support essential routes and operators monetize **premium-tier services** (e.g., flexible routing or app-based service enhancements) to ensure long-term financial viability.

B. Pay-Per-Use and Hybrid Subscription Models

In Noord-Brabant, SINFONICA stakeholders highlighted the importance of **affordable and flexible mobility options**, particularly for **students, migrants, and lower-income populations**. Although **hybrid pricing models** were not explicitly named, the user preferences gathered through focus groups suggest interest in **customizable and subscription-friendly services**.

Recommended Model: A hybrid CCAM pricing structure could be implemented with **tiered subscription plans**—e.g., low-cost monthly passes covering a limited number of rides, combined with **per-ride dynamic pricing** for additional flexibility. Targeted **subsidies could be algorithmically matched** to user profiles derived from **Actor ID Cards**, allowing tailored support for **single parents, elderly users, students**, or other vulnerable groups.

C. Shared AV Fleets and Regional Cooperation

SINFONICA’s stakeholder engagement underscores the strategic need for **cross-municipality coordination** to scale CCAM in an inclusive, efficient, and regionally equitable manner. Feedback from the **West Midlands** and **Noord-Brabant** identified the importance of **integrated fleet-sharing** to reduce service gaps and resource duplication, especially across suburban and rural boundaries.

Suggested Model: A regional **autonomous vehicle (AV) cooperative**, jointly managed and co-financed by municipalities, could facilitate shared fleet operations across multiple towns. This structure would reduce vehicle downtime, distribute operational risks, and align with SINFONICA’s goals of **territorial cohesion**, **multi-stakeholder collaboration**, and **cost-effective CCAM delivery**.

Strategic Insight

To ensure effective value capture and equitable reinvestment, both infrastructure-based and service-oriented CCAM business models must embed structured stakeholder engagement mechanisms. Tools such as Actor ID Cards and the Knowledge Map Explorer, developed within the SINFONICA framework, provide essential support for mapping stakeholder interests, guiding investment alignment, and enabling knowledge-sharing across regions (D4.1, 2024). These instruments help operationalize inclusive innovation by identifying user-specific needs and integrating them into governance, planning, and resource allocation processes.

Municipalities play a critical orchestration role within this ecosystem. They are responsible for regulating digital infrastructure access, upholding data ethics through GDPR-compliant frameworks, and deploying financial levers—such as subsidies and co-financing instruments—to promote accessibility and service inclusivity. By leading participatory design processes and coordinating multi-stakeholder governance structures, local authorities can ensure that CCAM deployments are both economically sustainable and socially equitable

6.3 Economic and Social Evaluation of CCAM Scalability

The transition of Cooperative, Connected, and Automated Mobility (CCAM) from pilot environments to large-scale deployment hinges on sound economic rationale and inclusive societal outcomes. Through the application of the GUEST-SI methodology and insights from the SINFONICA project, this section evaluates CCAM from three key perspectives: financial viability, cost-benefit impact, and distributional equity in mobility access. These evaluations are grounded in regional experiences and validated literature on sustainable automated transport systems.

6.3.1 Assessing Financial Viability and Return on Investment

Operational Efficiency and Cost Reduction

CCAM systems offer considerable potential for **operational efficiency**, particularly through **automated fleets** that reduce labor dependency and optimize routes in real-time. As shown by Zhao & Malikopoulos (2020), operating expenditures may decline by **up to 40%** when automated services are deployed at scale in **controlled environments**.

In **Trikala**, a SINFONICA pilot involving **semi-automated shuttle services with human oversight** targeted **elderly and low-mobility users**, illustrating how **hybrid AV models** can improve service while laying groundwork for future cost efficiencies.

Policy Recommendation: Municipalities should adopt a **Financial Sustainability Index** to track infrastructure and fleet amortization, measure CAPEX/OPEX ratios, and identify break-even thresholds. This data-driven approach will enhance strategic planning, investment risk management, and equitable resource allocation.

Investment Outlook and Market Growth

Estimates suggest that the global CCAM market may surpass **€500 billion annually by 2040**, encompassing areas such as **AI-powered route optimization, shared AV services, and real-time mobility platforms** (Santa et al., 2022). Europe's ecosystem—marked by strong **public investment alignment with private sector R&D**—positions it well for leadership in CCAM commercialization.

In **Hamburg and the West Midlands**, targeted investment into **smart mobility corridors** and **digitally equipped intersections** has already attracted interest from **OEMs and digital mobility start-ups**, laying the groundwork for **scalable business experimentation**.

Policy Recommendation: Cities should collaborate with **sovereign wealth funds**, **development banks**, and **private mobility infrastructure funds** to develop **CCAM-focused investment vehicles**. These should follow **blended finance principles** and align with **Environmental, Social, and Governance (ESG)** criteria to attract mission-aligned capital and enable inclusive growth.

6.3.2 Cost-Benefit and Equity Outcomes in Regional Mobility

A. Urban Productivity and Public Savings

Economic analyses of CCAM systems consistently indicate benefits such as **congestion reduction**, **improved energy efficiency**, and **enhanced road safety**. Simulations by **Zhao & Malikopoulos (2020)** show that coordinated AV systems can reduce average travel times and congestion by **15–20%**, owing to **smoother traffic flow** and **optimized routing**.

Although SINFONICA pilot cities did not quantify these gains, qualitative data from **Hamburg** and **Noord-Brabant** suggest improved **trust**, **service integration**, and **operational fluidity**. These factors contribute to potential **public savings** and broader **urban productivity** improvements.

Policy Recommendation: Cities should implement **real-time CCAM performance dashboards** to monitor indicators such as **congestion levels**, **route optimization**, and **modal shift patterns**, using tools like the **Knowledge Map Explorer** to support adaptive planning.

B. Accessibility and Inclusion Benefits

A key outcome of CCAM deployment is its capacity to expand **mobility access for underserved populations**. In cities like **Trikala** and the **West Midlands**, co-developed mobility solutions were tailored for groups historically excluded from digital systems—such as **elderly users**, **migrants**, and **rural residents**. Using tools like **Value Ring analysis** and **Actor ID Cards**, stakeholders identified that accessibility improved when CCAM services

were adapted through **multilingual interfaces, responsive routing, and universal design features**.

These findings align with **Grandsart et al. (2025)**, who argue that **stakeholder participation during the design phase** increases both **system legitimacy** and **engagement** among hard-to-reach user segments.

Policy Recommendation: Inclusive Mobility Grants should be established to support CCAM operators and municipalities serving rural and peri-urban areas, with funding tied to performance metrics such as user satisfaction indicators, geographic access parity, and interface accessibility scores. By linking financial support to measurable outcomes, these grants will help ensure that equity remains a central pillar in the scaling and long-term sustainability of CCAM deployment.

C. Environmental and Sustainability Gains

The environmental potential of CCAM systems is contingent upon three interlinked factors: **vehicle electrification, smart routing algorithms, and reduced traffic friction**. As **Santa et al. (2022)** report, cities integrating **AV technologies with electrification and congestion-reducing measures** could see transport emissions decline by **30–50% over a decade**.

In **Hamburg**, CCAM test routes were strategically placed in **low-emission zones**, exemplifying how automation, clean energy, and spatial regulation can converge to advance **sustainable mobility**.

Policy Recommendation: Introduce **carbon credit incentives** and **preferential AV lane access** for CCAM operators that demonstrably reduce emissions. These rewards should be based on standardized indicators tracked through **municipal dashboards or digital twin platforms**, ensuring transparency and policy alignment with **climate targets**.

Chapter 7: Conclusions

7.1 Summary of Research Objectives and Methodology

This thesis was developed to explore how stakeholder-centered methodologies can optimize the deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems in Europe, with particular emphasis on inclusivity, accessibility, affordability, and sustainability. Framed within the Horizon Europe SINFONICA project, the research aimed to bridge the gap between technological innovation and the complex social realities of diverse mobility users. The primary objective was to operationalize and evaluate the GUEST-SI methodology (Go, Uniform, Evaluate, Solve, Test – for Social Innovation) within real-world CCAM planning contexts to support equitable and trustworthy deployment processes.

To achieve this, the study adopted a mixed-methods, multi-stakeholder approach grounded in two major frameworks:

1. **SINFONICA Framework** – a human-centric, digitally integrated framework designed to guide inclusive and ethical CCAM deployment across European regions. It incorporates tools such as Actor ID Cards, Stakeholder Analysis Matrices, and the Knowledge Map Explorer to structure stakeholder engagement and system-level learning (Ringhand et al., 2024; Grandsart et al., 2025).
2. **GUEST-SI Methodology** – an applied decision-support structure consisting of five iterative phases: GO, UNIFORM, EVALUATE, SOLVE, and TEST. It was developed to foster systematic stakeholder inclusion, adaptive co-creation, and multi-scalar coordination in innovation ecosystems (GUEST Methodology, 2017).

These frameworks were operationalized using qualitative and semi-structured data from four European pilot cities—Trikala, Hamburg, Noord-Brabant, and West Midlands—integrating findings from surveys, focus groups, and interviews involving more than 4,000 participants across diverse demographics. A total of ten Actor ID Cards were generated to represent recurring stakeholder archetypes, such as elderly public transport users, rural residents, low-income commuters, digitally excluded individuals, and university students. Each Actor ID

was linked to specific Value Rings and incorporated into a comprehensive User Needs Matrix, enabling cross-regional comparison and synthesis of stakeholder priorities.

The research adhered to validated participatory techniques—such as MAMCA workshops, ideathons, and co-creation sessions—to ensure that mobility system design was informed not only by technical feasibility but also by the lived experiences of end users (Grandsart et al., 2025). Moreover, the GUEST-SI structure ensured transparency and adaptability throughout each deployment phase. For instance, in the **GO** phase, stakeholders were identified and categorized using the Actor ID Cards; the **UNIFORM** phase harmonized governance roles and digital infrastructures; the **EVALUATE** phase applied SWOT analysis and simulation models; **SOLVE** translated user needs into CCAM solutions; and **TEST** validated these through real-world trials and Living Labs.

This multi-method research design ensured that the final outputs—Value Rings, the User Needs Matrix, and deployment recommendations—were not only context-sensitive but also generalizable to broader European CCAM policy and investment frameworks. The methodological coherence between GUEST-SI and SINFONICA allowed the thesis to function as both a practical contribution to stakeholder-oriented CCAM planning and an academic advancement in participatory innovation methodologies.

7.2 Key Findings and Contributions

This thesis yielded several critical insights and methodological contributions to the inclusive and scalable deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems in Europe. By integrating the SINFONICA and GUEST-SI frameworks, and applying them across four pilot regions—Hamburg, Noord-Brabant, Trikala, and West Midlands—the research produced a comprehensive understanding of user needs, stakeholder dynamics, and deployment barriers. The findings can be grouped into five principal domains:

1. Operationalization of Stakeholder Diversity through Actor ID Cards

One of the most significant contributions of the study was the development and implementation of ten detailed Actor ID Cards. These profiles represent recurring stakeholder types—such as elderly urban transit users, rural residents, low-income travelers, single parents, digitally excluded individuals, and young professionals—and were synthesized from extensive qualitative data across SINFONICA's field sites. Each card

incorporated socio-economic stratification, mobility barriers, and digital access levels, thereby grounding stakeholder engagement in empirical and intersectional realities (Ringhand et al., 2024).

2. Creation of Value Rings and User Needs Matrix

For each Actor ID, Value Rings were developed following the GUEST-SI format, organizing user pains, gains, pain relievers, and gain creators across three priority tiers (high, medium, and low). This circular logic ensured that user-defined challenges—such as affordability, accessibility, and exclusion—were explicitly translated into actionable CCAM design features (Chapter 5). The Value Rings were then integrated into a cross-cutting **User Needs Matrix**, enabling comparison across cities and user groups. This matrix illuminated systemic pain points, such as the widespread lack of service integration, digital exclusion, and affordability constraints, particularly for vulnerable users like elderly residents and shift workers (user needs from excel.docx).

3. Demonstration of GUEST-SI's Structured Engagement Efficacy

The application of the GUEST-SI methodology across five phases (Go, Uniform, Evaluate, Solve, Test) validated its ability to bridge stakeholder insights with CCAM policy and service design. For instance, the **GO** phase clarified influence and interest relationships through the Stakeholder Analysis Matrix. In the **UNIFORM** phase, harmonized governance roles and technical standards were mapped using the Knowledge Map Explorer. The **EVALUATE** phase revealed specific readiness barriers—such as insufficient trust in automation or lack of digital skills—through SWOT analysis and simulation modeling, while **SOLVE** and **TEST** phases translated these into validated solutions via Living Labs in Trikala, Hamburg, and the West Midlands (Chapter 5; Ferreira, 2019).

4. Validation of Inclusive Co-Creation as a Deployment Enabler

Participatory mechanisms such as ideathons, hackathons, and MAMCA workshops proved to be essential not only in eliciting user needs but also in prototyping CCAM solutions that were socially acceptable and context-sensitive. For example, participatory workshops in Trikala highlighted the demand for volunteer driver programs and multilingual digital interfaces, while users in Noord-Brabant advocated for carpooling platforms and late-night microtransit (Grandsart et al., 2025). The integration of these preferences into solution

design affirmed the value of stakeholder co-creation in avoiding socio-technical misalignment and increasing behavioral adoption.

5. Policy-Relevant Synthesis of Common and Divergent Needs

The thesis identified both region-specific and cross-cutting user needs that have direct implications for EU CCAM policy. Universally shared concerns included the need for step-free access, real-time multimodal updates, and affordable fare structures. Meanwhile, regional divergences—such as infrastructure limitations in Trikala or digital connectivity issues in Noord-Brabant—point to the importance of territorially adaptive strategies. These findings reinforce SINFONICA’s position that a "one-size-fits-all" model is insufficient for CCAM deployment and support the argument for layered policy frameworks that incorporate both pan-European standards and localized implementation.

7.3 Theoretical and Practical Implications

The integration of the GUEST-SI methodology within the SINFONICA framework has yielded both theoretical advancements and practical pathways for inclusive and scalable deployment of CCAM systems in Europe. These implications extend across urban planning, mobility policy, innovation governance, and participatory system design.

Theoretical Implications

1. Advancing Participatory Planning Theory in Automated Mobility Contexts

This research confirms that participatory planning theories—such as those built on the Theory of Planned Behavior (Ajzen, 1991) and Self-Determination Theory (Ryan & Deci, 2017)—can be effectively adapted for CCAM deployment. By embedding these psychological constructs into stakeholder engagement strategies, the GUEST-SI framework ensures that user motivation, perceived control, and behavioural intention are directly reflected in mobility design processes (Ringhand et al., 2024).

2. Extending Stakeholder Theory through Actor Profiling and Value Mapping

Drawing from Freeman’s (1984) stakeholder theory, the Actor ID Card tool offers a novel micro-level application of stakeholder mapping within complex CCAM ecosystems. Unlike traditional interest-influence matrices, Actor ID Cards incorporate demographic, socio-economic, geographic, and digital access variables, advancing a more nuanced and data-rich approach to stakeholder analysis (Chapter 5; GUEST Methodology, 2017).

3. Bridging System Architecture with Social Systems Theory

The use of the Knowledge Map Explorer in tandem with GUEST-SI's iterative cycle demonstrates how semantic architectures and rule-based ontologies can be applied not only for technical system integration but also for stakeholder-responsive decision support. This aligns with broader sociotechnical system theory and illustrates a concrete case of cross-domain interoperability between behavioral, digital, and infrastructural layers (D4.1-SINFONICA, 2024).

Practical Implications

1. Institutionalization of Stakeholder Engagement in CCAM Governance

Findings highlight that structured, repeated stakeholder engagement is not just beneficial but essential for sustainable CCAM planning. Public authorities, mobility operators, and digital service providers must adopt tools such as the Actor ID Card, Stakeholder Analysis Matrix, and participatory foresight workshops as institutional standards rather than ad hoc activities (Grandsart et al., 2025; Knox et al., 2025).

2. Customization of CCAM Solutions for Vulnerable Groups

The thesis identifies that “accessibility” must encompass more than physical design—it must also address digital exclusion, affordability, and cultural diversity. The development of tailored solutions, such as multilingual interfaces, simplified journey planning apps, and protected-category fare schemes, directly addresses equity goals and aligns with EU digital justice and transport inclusion mandates (Ringhand et al., 2024).

3. Harmonization of Economic and Governance Models

The cross-analysis of business models (Chapter 6) and user needs supports the viability of hybrid service models—e.g., subscription-based MaaS platforms that integrate public subsidies for vulnerable users. Additionally, governance alignment across local and regional authorities is shown to be a prerequisite for scaling CCAM deployment beyond fragmented pilots (Chapter 6; Zhao & Malikopoulos, 2020).

4. Application in Real-World Pilots and Policy Piloting

The research demonstrates that tools developed under the GUEST-SI framework are operationalizable within real-world environments. Living Labs in Hamburg, Trikala, and the West Midlands validated co-designed CCAM features such as eco-vehicles, step-free boarding, and dynamic fare models. These case applications exemplify how co-creation

outputs can transition from conceptual to operational phases with measurable performance outcomes (Chapter 5; SINFONICA D4.1, 2024).

7.4 Policy Recommendations for Inclusive CCAM Deployment

Based on the integrated findings from the SINFONICA and GUEST-SI frameworks, this thesis proposes a set of policy recommendations to support the inclusive, ethical, and scalable deployment of Cooperative, Connected, and Automated Mobility (CCAM) systems across European regions. These recommendations target multiple governance levels—local, regional, and EU-wide—and are structured around five core policy dimensions: stakeholder inclusion, digital equity, economic viability, governance coordination, and infrastructure readiness.

1. Mandate Stakeholder-Centric Planning through Regulatory Guidelines

Policymakers at both EU and national levels should formally embed stakeholder engagement requirements into CCAM deployment guidelines. Building upon tools such as Actor ID Cards, Stakeholder Analysis Matrices, and participatory foresight (e.g., MAMCA workshops), municipalities and project consortia should be required to demonstrate stakeholder inclusion from the planning phase onward. This is particularly crucial for vulnerable groups, including elderly users, migrants, and low-income residents (Ringhand et al., 2024).

- *Recommended Instrument:* EU directive supporting mandatory use of structured stakeholder profiling tools (e.g., Actor ID Cards) for any CCAM funding recipient under Horizon Europe or the Connecting Europe Facility.

2. Standardize Accessibility and Digital Inclusion in CCAM Service Design

Accessibility policies must expand to include digital access alongside physical infrastructure. Services should adopt multi-modal, multilingual, and low-literacy-friendly interfaces. Regulatory incentives should be established for operators who offer hybrid analog-digital access points, such as SMS-based updates or human-assisted kiosks, which were shown to benefit digitally excluded groups across regions like Trikala and the West Midlands (user needs from excel.docx; Chapter 5).

- *Recommended Policy:* Introduce European “CCAM Accessibility Certification” similar to green building ratings, incorporating criteria such as multilingual UI, offline access, and paper-ticket compatibility.

3. Promote Inclusive Economic Models through Dynamic Subsidy Schemes

Affordability remains a systemic barrier, particularly for low-income and single-parent users. Policy frameworks should encourage municipalities and operators to implement dynamic fare structures—e.g., sliding-scale pricing, protected-category passes, or algorithmic subsidies linked to Actor ID profiles (Chapter 6; Zhao & Malikopoulos, 2020).

- *Recommended Instrument:* EU-supported pilot programs to test regional MaaS vouchers or subsidy credits allocated through CCAM platforms based on socio-economic profile data collected via Actor ID Cards.

4. Establish Multi-Level Governance and Investment Platforms

To overcome regulatory fragmentation and uneven infrastructure readiness, the thesis recommends establishing a **Centralized European CCAM Investment Platform (ECIP)**. This would align funding streams, technical guidelines, and monitoring standards across member states and cities, modeled after the European Battery Alliance (Chapter 6).

- *Recommended Policy:* ECIP under joint administration of DG MOVE, the European Investment Bank, and relevant industry bodies, offering standardized PPP templates, data-sharing protocols, and subsidy frameworks (Fagerholt et al., 2023).

5. Prioritize Cross-Border Interoperability and Ethical Data Governance

For truly scalable CCAM systems, cross-border service continuity must be supported by interoperable standards (V2X, ITS-G5, 5G) and harmonized legal frameworks on data governance, liability, and user rights (D4.1-SINFONICA, 2024; Ferreira, 2019). Ethical AI usage in CCAM must also be addressed through updated EU mobility legislation.

- *Recommended Instrument:* Expansion of the EU Data Governance Act to include sector-specific provisions for CCAM systems, addressing ethical AI deployment, data portability, and user consent in mobility services.

These recommendations are designed to ensure that CCAM systems not only achieve technological maturity but also meet the foundational goals of equity, inclusiveness, and trust. Their implementation would align with the EU Green Deal, the Urban Mobility Framework, and Vision Zero strategies, reinforcing CCAM as a transformative and public-centered mobility paradigm.

7.5 Limitations of the Study

While this research provides robust methodological and policy insights into inclusive CCAM deployment, several limitations must be acknowledged to contextualize its findings and guide future work. These limitations span methodological scope, data representativeness, and operational generalizability.

1. Geographic and Demographic Coverage Constraints

The study was based on data collected from four European regions—Hamburg, Noord-Brabant, Trikala, and the West Midlands—within the SINFONICA project framework. While these locations offered a rich diversity of urban, suburban, and rural contexts, they do not fully represent all mobility patterns, infrastructural capacities, or cultural contexts across Europe. For instance, Eastern and Southern European cities with less-developed digital infrastructures or different socio-political governance models were not covered, potentially limiting the generalizability of findings at the EU level (MS12, 2024).

Moreover, although Actor ID Cards captured a range of user demographics—such as elderly users, low-income commuters, and digitally excluded individuals—specific vulnerable groups (e.g., cognitive disability communities, non-EU migrants, or informal sector workers) were not systematically profiled due to limitations in survey outreach and focus group participation (Actor ID Cards.docx; user needs from excel.docx).

2. Dependency on Self-Reported and Qualitative Data

Much of the empirical evidence—particularly for Value Rings, the User Needs Matrix, and stakeholder profiling—was derived from focus groups, surveys, and interviews. While these are valid participatory tools under both SINFONICA and GUEST-SI, they carry inherent biases such as social desirability, recall inaccuracy, and limited representativeness in digitally mediated formats. For example, despite efforts to increase digital accessibility, the

online nature of many surveys may have inadvertently excluded participants with low digital literacy or limited internet access (MS12, 2024; Ringhand et al., 2024).

3. Limited Longitudinal and Behavioral Data

The GUEST-SI methodology, while iterative and structured, was applied within a relatively short planning and testing cycle. The study lacks longitudinal data on behavioral adoption, such as whether users who participated in co-creation later engaged with CCAM services or whether trust-building measures resulted in increased usage over time. Without real-time behavioral tracking, it is difficult to assess the durability of perceived gains or the resilience of pain relievers proposed in the Value Rings (Chapter 5; Ferreira, 2019).

4. Prototype-Level Application of GUEST-SI Tools

While the GUEST-SI tools (Actor ID Cards, Knowledge Map Explorer, SWOT analysis, etc.) were implemented within the context of pilot programs and Living Labs, their full-scale institutional integration remains untested. This introduces a methodological limitation: it is not yet clear how these tools will perform when embedded within municipal regulatory processes, cross-sector PPPs, or national transport authorities. Their adoption depends on governance will, digital maturity, and institutional flexibility—factors which were beyond the scope of this research to systematically evaluate (D4.1-SINFONICA, 2024; Grandsart et al., 2025).

5. Exclusion of Cost-Benefit and Quantitative Economic Modeling

Although Chapter 6 explored economic models for CCAM (e.g., MaaS-based subscription models, dynamic subsidies), this thesis did not conduct quantitative cost-benefit analyses or macroeconomic modeling of CCAM deployments. Budget trade-offs, capital expenditure assessments, or ROI forecasting—especially across different deployment strategies—remain areas for future investigation, particularly under varying infrastructure and governance scenarios (Chapter 6; Zhao & Malikopoulos, 2020).

These limitations underscore the importance of complementing qualitative, stakeholder-driven planning tools with empirical behavioral data, broader geographic sampling, and long-term institutional monitoring. Nonetheless, the study offers a validated methodological foundation for inclusive CCAM deployment and a replicable approach for regional adaptation and policy formulation.

7.6 Future Research Directions

The findings and methodological contributions of this thesis open multiple avenues for future research on the inclusive deployment of Cooperative, Connected, and Automated Mobility (CCAM). Building upon the SINFONICA and GUEST-SI frameworks, future studies can expand the geographic scope, enhance digital integration strategies, explore longitudinal impacts, and refine stakeholder engagement mechanisms. The following directions are proposed:

1. Expansion to Underrepresented Geographies and Socioeconomic Contexts

Future research should prioritize extending the application of GUEST-SI and SINFONICA tools to additional European regions, particularly Eastern and Southern Europe, where digital readiness, mobility infrastructure, and socioeconomic challenges differ significantly. Comparative studies across high-, medium-, and low-maturity CCAM environments would help refine transferability, resilience, and regional tailoring of participatory mobility planning (MS12, 2024).

Research could also examine deployment conditions in peripheral, mountainous, or cross-border areas where infrastructural constraints intersect with governance complexity—scenarios not fully represented in the current pilot cities (Trikala, Hamburg, Noord-Brabant, West Midlands).

2. Integration of Real-Time Behavioral and Usage Data

To complement the qualitative insights derived from focus groups and Value Rings, future work should incorporate behavioral data from CCAM pilot implementations. This includes tracking app usage, ticketing behavior, feedback mechanisms, and real-time service adoption. Such data can enhance the predictive accuracy of User Needs Matrices and inform adaptive design iterations (Chapter 5; Zhao & Malikopoulos, 2020).

This could involve collaboration with urban data platforms, GDPR-compliant mobility data lakes, or AI-enabled mobility dashboards, building on the Knowledge Map Explorer's foundational architecture (SINFONICA D4.1, 2024).

3. Development of Synthetic Participatory Planning Simulations

Building on emerging methodologies such as Synthetic Participatory Planning (Yu & McKinley, 2024), future research should explore the use of AI-generated stakeholder avatars to simulate long-term planning processes. These digital agents can emulate participatory workshops in resource-constrained or logistically complex environments, allowing planners to prototype CCAM trade-offs across multi-decade timelines. This is particularly promising for forecasting systemic tensions between equity, innovation, and sustainability.

Simulated stakeholders could also be used to pretest policies or prototype interface designs before physical pilots, offering a cost-effective layer of inclusive evaluation.

4. Longitudinal Assessment of Trust and Social Acceptance

Given the centrality of trust, behavioral intention, and public perception to CCAM adoption, future studies should adopt longitudinal designs to examine how user attitudes evolve over time. This includes investigating the long-term effectiveness of co-creation, transparency tools, and educational campaigns on user willingness to engage with automated mobility systems (Ringhand et al., 2024; Grandsart et al., 2025).

Experimental interventions—such as AV onboarding tutorials or participatory evaluation platforms—could be embedded into Living Labs and evaluated through mixed methods.

5. Economic Modeling and Multi-Criteria Policy Evaluation

The economic viability of inclusive CCAM remains under-researched. Future studies should build on the business models introduced in Chapter 6 by integrating economic simulation tools (e.g., cost-benefit analysis, dynamic pricing models, urban mobility impact models) to assess investment scenarios. This should include distributional impacts on different Actor IDs, particularly with respect to affordability, digital exclusion, and rural access.

Research could also employ multi-criteria decision analysis (MCDA) to evaluate trade-offs between inclusivity, carbon emissions, service coverage, and operational cost, enhancing the value of tools like MAMCA and the Balanced Scorecard (Chapter 5; SHOW Project; Knox et al., 2025).

6. Institutional Readiness and Policy Harmonization Studies

Future work should examine how institutional structures at the municipal, regional, and EU levels affect the successful integration of participatory CCAM tools. Key research questions include: What are the enabling conditions for embedding Actor ID Cards or Knowledge Map

Explorers into public planning routines? How can regulatory sandboxes or PPP agreements facilitate innovation without undermining equity?

Comparative case studies of institutional readiness across Europe could yield best practices for cross-level alignment and anticipatory governance (Fagerholt et al., 2023).

These future directions collectively support a deeper, more holistic, and operationally grounded approach to inclusive CCAM. By advancing both technical tools and social insights, research can continue to strengthen the transformative capacity of automated mobility systems in service of equitable and sustainable urban futures.

7.7 Final Reflection

This thesis has explored the complex intersection of technological innovation, social equity, and participatory governance in the context of Cooperative, Connected, and Automated Mobility (CCAM) deployment in Europe. Anchored in the SINFONICA framework and operationalized through the GUEST-SI methodology, the research has demonstrated that inclusive mobility systems are not merely a function of advanced algorithms or autonomous vehicles, but of human-centered design, trust-building, and collective decision-making.

A key insight from this work is that equitable CCAM deployment cannot be achieved through a top-down, technology-first approach. Instead, systems must be co-designed with and for the people who use them—particularly those who have historically been excluded from transport innovation. The creation of Actor ID Cards, Value Rings, and a cross-regional User Needs Matrix has enabled a concrete articulation of these user perspectives. It has translated abstract principles such as "accessibility" and "affordability" into service-level features, governance protocols, and policy instruments that can be implemented and monitored.

Moreover, the application of the GUEST-SI methodology has shown that stakeholder engagement, when structured and iterative, is not a procedural formality but a strategic asset. It enables mobility planners, public authorities, and technology developers to anticipate behavioral barriers, manage institutional complexity, and ensure that CCAM services meet diverse needs from inception to implementation. This is particularly crucial in an era where

digital exclusion, climate urgency, and demographic change are reshaping the landscape of urban and regional mobility.

However, the road ahead remains challenging. Infrastructure gaps, regulatory fragmentation, and societal skepticism continue to constrain CCAM scalability. As such, future efforts must focus on embedding participatory frameworks into formal governance systems, aligning economic incentives with inclusion goals, and leveraging AI and digital tools in ethically sound ways. Only through such integrative strategies can CCAM fulfill its promise as a sustainable, democratic, and adaptive mobility solution for Europe.

Ultimately, this thesis contributes not only a validated methodological toolkit, but also a vision: that automated mobility can—and must—serve as a vehicle for social innovation. By placing stakeholder voices at the core of design, deployment, and evaluation, the future of CCAM becomes not just connected and automated, but also cooperative, trusted, and just.

References

- Ahokangas, P., Matinmikko-Blue, M., Yrjölä, S., & Hämmäinen, H. (2020). Future 5G platform ecosystems: Digitalized port stakeholders' new interactions and value configurations. *Telecommunications Policy*, 44(6), 101960. <https://doi.org/10.1016/j.telpol.2020.101960>
- Amador Molina, O., Ronelöv, E., Boustedt, K., Blidkvist, J., & Vinel, A. (2022). Protection of vulnerable road users using hybrid vehicular networks. *IEEE Proceedings / arXiv*. <https://arxiv.org/abs/2312.14059v2>
- Attaran, M. (2023). The impact of 5G on the evolution of intelligent automation and industry digitization. *Journal of Ambient Intelligence and Humanized Computing*, 14, 5977–5993. <https://doi.org/10.1007/s12652-020-02521-x>
- Attaran, M., & Attaran, S. (2020). Digital transformation and economic contributions of 5G networks. *International Journal of Enterprise Information Systems*, 16(4), 66–86. <https://doi.org/10.4018/IJEIS.2020100104>
- Bocken, N. M. P., & Snihur, Y. (2019). Lean startup and the business model: Experimenting for novelty and impact. *Long Range Planning*. <https://doi.org/10.1016/j.lrp.2019.101953>
- Bortolini, R. F., Cortimiglia, M. N., Danilevicz, A. M. F., & Ghezzi, A. (2018). Lean startup: A comprehensive historical review. *Management Decision*, 56(6). <https://doi.org/10.1108/MD-07-2017-0663>
- Boutahala, R., Fouchal, H., & Ayaida, M. (2025). Light security scheme for Cooperative, Connected and Automated Mobility (CCAM). *Vehicular Communications*, 53, 100892. <https://doi.org/10.1016/j.vehcom.2025.100892>
- Boutahala, B., El Fallah-Seghrouchni, A., & Silva, L. (2025). Legal challenges of responsibility in autonomous vehicle systems. *AI & Society*. <https://doi.org/10.1007/s00146-024-01782-9>
- Christensen, C. M., Altman, E. J., McDonald, R., & Palmer, J. (2016). Disruptive innovation: Intellectual history and future paths (Working Paper No. 17-057). *Harvard Business School*.
- ERTRAC. (2022). *Connected, Cooperative and Automated Mobility Roadmap*. European Road Transport Research Advisory Council. <https://www.ertrac.org/uploads/documentsearch/id66/ERTRAC-CCAM-Roadmap-2022.pdf>
- European Commission. (2020). *Sustainable and smart mobility strategy – Putting European transport on track for the future*. https://transport.ec.europa.eu/transport-themes/mobility-strategy_en
- European Union. (2022). *Data Governance Act (Regulation EU 2022/868)*. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022R0868>

- Fagerholt, K., Eidhammer, O., & Wærsted, K. (2023). Regulatory bottlenecks in transnational autonomous mobility trials. *Transportation Research Part A: Policy and Practice*, 172, 103695. <https://doi.org/10.1016/j.tra.2023.103695>
- Fagerholt, R. A., Seter, H., & Arnesen, P. (2023). How can authorities be enablers in the deployment of CCAM? *Transportation Research Interdisciplinary Perspectives*, 21, 100874. <https://doi.org/10.1016/j.trip.2023.100874>
- Ferreira, J. (2019). Cooperative, connected and automated mobility (CCAM): Technologies and applications. *Electronics*, 8(12), 1549. <https://doi.org/10.3390/electronics8121549>
- Ghezzi, A., & Cavallo, A. (2018). Agile business model innovation in digital entrepreneurship: Lean startup approaches. *Journal of Business Research*, 110, 519–537. <https://doi.org/10.1016/j.jbusres.2018.06.013>
- Grandsart, D., Bulanowski, K., Cornet, H., & Ardila, A. (2025). Stakeholders' engagement in shared automated mobility: A comparative review of three SHOW approaches. In *Shared Mobility Revolution* (pp. 163–179). Springer. https://doi.org/10.1007/978-3-031-71793-2_10
- Hutahaean, M. (2017). The importance of stakeholders approach in public policy making. In *Proceedings of the International Conference on Ethics in Governance (ICONEG 2016)* (Vol. 84, pp. 479–484). <https://doi.org/10.2991/iconeg-16.2017.104>
- Knox, S., Marin-Cadavid, C., & Oziri, V. (2025). Stakeholder engagement-as-practice in public sector innovation. *International Public Management Journal*, 28(1), 153–168. <https://doi.org/10.1080/10967494.2024.2423952>
- Lyons, G., Hammond, P., & Mackay, K. (2020). The importance of user perspective in the evolution of MaaS. *Transportation Research Part A: Policy and Practice*, 131, 20–34. <https://doi.org/10.1016/j.tra.2018.12.010>
- Lyons, G., Jain, J., & Parkhurst, G. (2020). Transport and behavioral change: Theory and practice. *Transport Policy*, 98, 1–8. <https://doi.org/10.1016/j.tranpol.2020.06.011>
- Malikopoulos, A. A., & Zhao, L. (2020). Enhanced mobility with connectivity and automation: A review of shared autonomous vehicle systems. *IEEE Intelligent Transportation Systems Magazine*, 12(4), 29–47. <https://doi.org/10.1109/MITS.2020.2975548>
- Osterwalder, A., & Pigneur, Y. (2010). *Business model generation: A handbook for visionaries, game changers, and challengers*. Wiley.
- Pangbourne, K., Mladenović, M. N., Stead, D., & Milakis, D. (2020). Questioning mobility as a service: Unanticipated implications for society and governance. *Transportation Research Part A: Policy and Practice*, 131, 35–49. <https://doi.org/10.1016/j.tra.2019.09.033>

- Ringhand, M., Anke, J., & Schackmann, D. (2024). Understanding mobility needs and designing inclusive CCAM solutions: A literature review and framework. In *HCI International 2024 Posters, Communications in Computer and Information Science* (Vol. 2118, pp. 267–274). Springer. https://doi.org/10.1007/978-3-031-66606-6_82
- Santa, J., Katsaros, K. V., Bernal-Escobedo, L., Zougari, S., Miranda, M., Castañeda, O., Dalet, B., & Amditis, A. (2022). Evaluation platform for 5G vehicular communications. *Vehicular Communications*, 38, 100537. <https://doi.org/10.1016/j.vehcom.2022.100537>
- Santa, J., Moragón, A., Bernabeu-Auban, J. E., & Skarmeta, A. (2022). Interoperability challenges in V2X standards: ITS-G5 and C-V2X. *Computer Communications*, 191, 137–150. <https://doi.org/10.1016/j.comcom.2022.04.019>
- Santa, J., Suárez, I., & Skarmeta, A. F. (2022). Urban mobility solutions: Integrating smart infrastructure and connected autonomous vehicles. *Sensors*, 22(3), 987. <https://doi.org/10.3390/s22030987>
- SINFONICA. (2024). *D4.1: Knowledge Map Creation and System Architecture Specification*. Horizon Europe Project. <https://www.sinfonica.eu/public-deliverables>
- SINFONICA. (2024). *MS12: Common Guidelines for Users' Survey*. Horizon Europe Project. <https://www.sinfonica.eu/public-deliverables>
- SINFONICA. (2024). *Focus group results and stakeholder engagement reports – Hamburg, Trikala, Noord-Brabant, West Midlands*. Internal EU Horizon Europe project documentation under GA No. 101064988.
- Trimi, S., & Berbegal-Mirabent, J. (2012). Business model innovation in entrepreneurship. *International Entrepreneurship and Management Journal*, 8(4), 449–465. <https://doi.org/10.1007/s11365-012-0234-3>
- WWF – Golder, B., & Gawler, M. (2005). Cross-cutting tool: Stakeholder analysis. In *WWF Standards for Conservation Project and Programme Management*. World Wide Fund for Nature.
- Yu, J., & McKinley, G. (2024). Synthetic participatory planning of shared automated electric mobility systems. *Preprint*, McGill University, Department of Civil Engineering.
- Yu, W., & McKinley, E. (2024). Platform cooperatives and sustainable mobility innovation. *Transport Policy*, 133, 90–102. <https://doi.org/10.1016/j.tranpol.2024.03.004>
- Zhao, L., & Malikopoulos, A. A. (2020). Mobility modeling and simulation of connected and autonomous vehicles in urban traffic networks. *IEEE Transactions on Intelligent Vehicles*, 5(4), 668–678. <https://doi.org/10.1109/TIV.2020.3018456>