



UNIVERSITÀ DEGLI STUDI DI PALERMO

PHD IN INFORMATION AND COMMUNICATION TECHNOLOGIES

IINF / 03-TELECOMUNICAZIONI

DIPARTIMENTO DI INGEGNERIA

ICT-DRIVEN STRATEGIES FOR SUSTAINABLE URBAN MOBILITY

BEHAVIOURAL CHANGE THROUGH GAME DESIGN, DATA INTEGRATION, AND ARTIFICIAL
INTELLIGENCE: THE CASE OF MUV

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XXXVII CYCLE

ACADEMIC YEAR 2024 - 2025

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Methodological Note

This thesis is grounded in the author's direct involvement in all phases of MUV's development, from initial conception to commercial implementation.

As founder and director of *PUSH Design Laboratory*, the author coordinated the MUV2020 Research and Innovation Action under Horizon 2020 (2017-2020), overseeing all technical aspects from proposal writing through final project evaluation.

Subsequently, as co-founder and Chief Technology Officer of *MUV Srl SB* (2020-present), the author has been responsible for all aspects of service design and development, including behavioural frameworks, technological architecture, and business model evolution.

The theoretical contributions, empirical analyses, and technological implementations presented represent original work developed through this comprehensive involvement, while acknowledging collaborative elements where appropriate (Schillaci, Tinnirello, et al. 2025; Schillaci, Di Dio, et al. 2024; Schillaci, Di Dio, et al. 2022; Schillaci 2022; Di Dio, Lissandrello, et al. 2019; Vesco et al. 2020; Di Dio, Massa, et al. 2020; Cirrincione et al. 2022; Barroca et al. 2023).

Glossary of Technical Terms

ACES	<i>Autonomous, Connected, Electric, and Shared mobility.</i> The four major trends transforming urban transport systems.
ADAS	<i>Advanced Driver-Assistance Systems.</i> Technologies designed to improve vehicle safety and assist drivers, including lane keeping, collision warning, etc.
AI	<i>Artificial Intelligence.</i> A field of computer science that focuses on creating systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, and problem-solving. In MUV, AI is used for personalised game design, behavioural profiling, and mobility planning automation.
API	<i>Application Programming Interface.</i> A set of tools and protocols that enable software components to communicate. In MUV, APIs are used to facilitate data exchange between the backend services and the frontend mobile application.
BCW	<i>Behaviour Change Wheel.</i> A theoretical model used to design and evaluate behavioural interventions, mixing capability, opportunity, and motivation factors.
BLE	<i>Bluetooth Low Energy.</i> A wireless communication protocol optimised for short-range, low-power data exchange, used in proximity-based mobility systems.
CMO	<i>Context-Mechanism-Outcome.</i> A framework used in evaluation to explain how specific contexts and mechanisms lead to particular outcomes.
CO₂eq	<i>Carbon Dioxide Equivalent.</i> A standard unit used to compare the emissions of various greenhouse gases based on their global warming potential, expressed in terms of the amount of CO ₂ that would have the same impact.
CSRD	<i>Corporate Sustainability Reporting Directive.</i> An EU regulation requiring companies to disclose environmental and social impacts.
DAU	<i>Daily Active Users.</i> A key engagement metric indicating the number of unique users who use the service each day.
EVs	<i>Electric Vehicles.</i> Vehicles powered by electric motors and batteries, seen as a key component of sustainable urban mobility.

FBM	<i>Fogg Behavior Model</i> . A behaviour model that explains how motivation, ability, and prompts interact to produce behaviour change.
GANs	<i>Generative Adversarial Networks</i> . AI systems used to create synthetic data.
GHG	<i>Greenhouse Gases</i> . Gases that trap heat in the atmosphere and contribute to global warming, including CO ₂ , CH ₄ , and N ₂ O.
GWP	<i>Global Warming Potential</i> . A measure of how much heat a greenhouse gas traps in the atmosphere over a specific time period, relative to carbon dioxide.
H2020	<i>Horizon 2020</i> . The EU's research and innovation funding programme (2014–2020), under which MUV was originally developed.
ICT	<i>Information and Communication Technologies</i> . Technologies used to collect, store, process, and exchange data, essential in enabling digital mobility systems.
IEA	<i>International Energy Agency</i> . An autonomous intergovernmental organisation that provides data and recommendations on energy.
INAIL	<i>Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro</i> . The Italian agency responsible for occupational injury insurance.
IoT	<i>Internet of Things</i> . A network of devices that can collect and exchange data, widely used in smart city infrastructure.
IoV	<i>Internet of Vehicles</i> . A subset of IoT focused on vehicles communicating with each other and with infrastructure.
IPCC	<i>Intergovernmental Panel on Climate Change</i> . The UN body for assessing climate change science.
ISO	<i>International Organization for Standardization</i> . A global standard-setting body, responsible for standards like ISO 14064-2 used in MUV.
KDE	<i>Kernel Density Estimation</i> . A statistical method used to estimate data distributions in mobility analysis.
KPI	<i>Key Performance Indicator</i> . A measurable value used to assess the success of an objective.
LEZ	<i>Low Emission Zone</i> . Urban areas where access is restricted to vehicles that meet low-emission criteria.
LLM	<i>Large Language Model</i> . A type of AI model trained on large text datasets for language understanding and generation.

LIST	<i>Luxembourg Institute of Science and Technology.</i> A research organisation involved in MUV international pilots.
LTZ	<i>Limited Traffic Zone.</i> City areas where vehicle access is limited, typically to reduce congestion.
MaaS	<i>Mobility as a Service.</i> A digital mobility model that integrates various transport services into a single platform, enabling users to plan, book, and pay for multimodal trips in a seamless, user-centred experience.
MAU	<i>Monthly Active Users.</i> A metric representing the number of unique users in a 30-day period.
MIT	<i>Ministero delle Infrastrutture e dei Trasporti.</i> The Italian Ministry of Infrastructure and Transport.
MOB	<i>Mobility on Board.</i> An educational pilot project in MUV involving students in sustainable mobility actions.
MUV	<i>Mobility Urban Values.</i> A digital platform that uses gamification and behavioural data to promote sustainable urban mobility.
PM	<i>Particulate Matter.</i> Airborne particles produced by vehicles and industry, harmful to human health.
RESTful	<i>Representational State Transfer.</i> An architecture style for designing scalable web services, used in MUV APIs.
SaaS	<i>Software as a Service.</i> A software delivery model in which software is accessed online via subscription. MUV's platform is transitioning into this form to enhance scalability and modularity.
SDK	<i>Software Development Kit.</i> Tools that allow developers to integrate third-party services into their own apps.
SDT	<i>Self-Determination Theory.</i> A theory of motivation that underpins engagement strategies in MUV.
SME	<i>Small and Medium-sized Enterprise.</i> Businesses targeted by MUV for workplace mobility initiatives.
SUMP	<i>Sustainable Urban Mobility Plan.</i> A long-term planning strategy to improve accessibility and reduce emissions.
UITP	<i>Union Internationale des Transports Publics.</i> The International Association of Public Transport.

UN	<i>United Nations</i> . Referenced for sustainable development goals and climate governance.
UNEP	<i>United Nations Environment Programme</i> . Provides environmental assessments used for sustainability benchmarking.
V2I	<i>Vehicle-to-Infrastructure communication</i> . Enables vehicles to exchange information with traffic lights, signs, etc.
V2V	<i>Vehicle-to-Vehicle communication</i> . Allows direct information sharing between vehicles.
V2X	<i>Vehicle-to-Everything</i> . Covers all vehicle communication systems, including V2V, V2I, and beyond.
WHO	<i>World Health Organization</i> . Cited for the health impacts of air pollution and active mobility.

Chapter 1

The Role of Green and Digital Transitions in Addressing the Climate Crisis

This chapter explores how the dual green and digital transitions, often referred to as the "twin transition", can serve as interdependent pillars in tackling the climate crisis. It investigates Europe's leadership in achieving net zero emissions through the European Green Deal, emphasising the synergy between environmental sustainability and digital innovation. Technologies such as the Internet of Things and Artificial Intelligence are identified as key enablers of the transformation across sectors, including energy and mobility. The chapter additionally analyses the environmental challenges posed by the ICT sector and how "green ICT" can contribute to mitigating its impacts while supporting broader climate goals.

1.1 A human-driven climate crisis

Climate change, the defining crisis of our era, is already manifesting its destructive power globally, making it not just a future concern but an urgent, immediate threat. Its consequences are already visible, from devastating wildfires and record-breaking heatwaves to increasingly severe hurricanes and floods, affecting millions of people and ecosystems worldwide. Climate change refers to long-term shifts in temperature and weather patterns, often resulting in profound and lasting consequences such as environmental degradation, ecosystem disruption, more frequent extreme weather events, climate-induced displacement, and the exacerbation of social tensions. Rising global temperatures are unequivocally the result of human activities (Steffen et al. 2015), which have pushed several Earth systems beyond safe thresholds.

Over the past two centuries, the relentless consumption of fossil fuels, such as coal, oil, and gas, has released significant quantities of greenhouse gases into the atmosphere. This has led to an increase in the global average temperature of approximately 1.2°C compared to preindustrial levels, edging dangerously close to what climate scientists have identified as a tipping point—a threshold beyond which the impacts of climate change could become

exponentially more severe and irreversible (Intergovernmental Panel on Climate Change 2023; Rockström et al. 2009).

The 2015 Paris Agreement marked a pivotal moment in the global response to climate change, setting a target to keep the global temperature rise "well below" 2 °C, with a concerted effort to limit it to 1.5 °C above preindustrial levels. Limiting warming to these thresholds would substantially reduce the risks and impacts of climate change. However, if emissions continue at current rates, global temperatures could increase by more than 3 °C by the end of the century, far exceeding the levels needed to avoid the worst impacts (United Nations Environment Programme 2023), with long-lasting and systemic disruptions to ecosystems, economies, and societies.

While the climate crisis is undeniable, there is still time to mitigate its worst effects. Achieving this requires profound transformations in how societies function, particularly in how we produce and consume energy, move people and goods, and structure daily life. Crucially, this must be underpinned by widespread behavioural changes across a significant portion of the global population. Addressing this crisis requires a systemic transformation that combines bold innovation, inclusive policy frameworks, and widespread civic engagement.

1.2 The European strategy towards net zero

Although climate change represents a global challenge, it is predominantly driven by developed nations. Europe, in particular, holds a historical responsibility and currently positions itself as a global leader in climate action. The European Union, presently the world's fourth largest emitter of greenhouse gases, released over 3.9 billion tonnes of carbon dioxide equivalent (CO₂eq) into the atmosphere in 2022 (European Environment Agency 2022; Crippa et al. 2023), accounting for 6.67 % of global emissions. The term CO₂eq is used to standardise the measurement of greenhouse gases by expressing their impact in terms of the equivalent amount of CO₂ that would produce the same global warming potential (GWP) over a specific time horizon.¹ This allows for a consistent comparison of the climate impact of various gases such as methane (CH₄) or nitrous oxide (N₂O), which differ significantly in potency and atmospheric lifespan. Acknowledging its responsibility, the EU has implemented an ambitious strategic framework to spearhead the green transition, demonstrating a resolute commitment to the objectives of the Paris Agreement and striving to become the first climate-neutral continent.

The European Green Deal, launched in late 2019, outlines the EU's commitment to reducing greenhouse gas emissions by at least 55 % below 1990 levels by 2030 and becoming climate-neutral by 2050 (European Commission 2019b). In addition to decarbonisation,

¹The global warming potential (GWP) is a metric developed by the IPCC to compare the relative climate impact of different greenhouse gases. It is typically calculated over a 100-year time frame (GWP100), and reflects both the radiative efficiency of a gas and its atmospheric lifetime. For example, methane (CH₄) has a GWP100 of 27–30, meaning that over 100 years, it has 27 to 30 times more warming potential than CO₂.

the Green Deal seeks to transform the EU into an equitable, prosperous society with a modern, resource-efficient, and competitive economy. The strategy is multifaceted and comprises a package of initiatives encompassing interconnected areas such as climate, energy, industry, environment, agriculture, mobility, and sustainable finance. Measures also extend to adapting to climate change, restoring biodiversity, ensuring food security, and adopting circular economy models.

The principal initiatives of the Green Deal focus on expanding renewable energy, enhancing energy efficiency, and decarbonising critical sectors like transport and heavy industry. These embrace ambitious objectives, including scaling up wind and solar power, retrofitting buildings to improve energy performance, and promoting cleaner, sustainable mobility modes, such as electric vehicles, cycling, and public transit. Moreover, the *European Climate Law*, which aligns EU legislation with its climate goals, has transformed political ambitions into legally binding commitments (European Commission 2021b). The law ensures that the carbon neutrality objective by 2050 is now a legal obligation for all EU member states.

Significant financial resources have been allocated to drive this change. At least 30 % of the EUR 800 billion *NextGenerationEU* Recovery Plan, Europe's blueprint for a greener, more resilient, and digital future, is earmarked for climate action and green projects. In addition, the *Just Transition Fund*, together with the European Investment Bank, provides essential financial support to regions and industries most affected by the green transition.

Despite these efforts, Europe faces significant challenges in achieving its goals. The continent's current reliance on fossil fuels, coupled with political resistance in some member states and economic disparities across regions, poses obstacles that require concerted action and continuous innovation.

In addition to establishing emission targets, these policy instruments are intended to transform the European socio-economic landscape by influencing sectors such as building renovations, transportation systems, and industrial production. The transformative potential of these policies lies in their ability to align economic incentives with climate objectives, thereby ensuring that sustainability is integrated not only into productive systems but also into the everyday decisions of individuals, communities, and institutions, turning climate ambition into a collective, lived experience.

This approach builds on substantial evidence demonstrating that "soft" mobility management measures—combining marketing, information, incentives and tailored services—can significantly reduce traffic. Research indicates potential for an 11 % reduction in national traffic levels and up to a 21 % reduction in peak urban periods, with excellent cost-effectiveness ratios exceeding 10:1 (Sally Cairns et al. 2008). Such evidence base supports the development of digital behavioural infrastructures that complement traditional policy instruments through voluntary participation, positive reinforcement, and community engagement mechanisms.

1.3 The green and digital twin transition: a synergistic approach

The twin transition, combining green and digital innovation, has become a cornerstone of the EU's strategic vision for building a sustainable, resilient, and competitive society. This concept refers to the simultaneous and interconnected transformation of Europe's economy and society through ecological sustainability and digital innovation. Far from being separate or parallel processes, these transitions are increasingly recognised as mutually reinforcing (OECD 2022). The twin transition should not be perceived as merely a concurrent development of two policy domains. Instead, digital technologies act as enablers and accelerators of climate goals, while the quest for sustainability influences digital innovation's trajectory and ethical considerations. When these elements are effectively integrated, they can facilitate significant structural transformations in key sectors, such as energy, industry, transport, and agriculture.

For instance, in the domain of urban mobility, data analysis platforms and smart traffic management systems have the potential to optimise traffic flow, reduce energy consumption, and encourage more sustainable travel behaviours, illustrating the tangible impact of integrated digital-green solutions. This synergy extends beyond technological advancements to encompass cultural shifts, influencing how citizens interact with services, make daily decisions, and contribute to shaping more liveable urban environments.

At the European level, the importance of the relationship between digitalisation and the environmental transition is reflected in major policy frameworks, such as the European Green Deal, the *New Industrial Strategy for Europe* and the *Digital Decade* (European Commission 2020a), which explicitly call for aligning digital development with environmental and social goals. In its December 2020 conclusions on "Digitisation for the benefit of the environment", the Council of the EU referred for the first time to a twin transition (2020). This concept emphasises the potential of digitalisation to generate new green and digital employment opportunities and facilitate European economic recovery. It denotes the interdependence between green and digital transformations, with each amplifying the other's impact.

On the one hand, digitalisation can accelerate the green transition by implementing efficient new technologies. These include smart grids for energy distribution, advanced weather forecasting systems for improved disaster preparedness, and precision agriculture for enhanced food production. Additionally, emerging technologies such as *Internet of Things* (IoT) and *Artificial Intelligence* (AI) play a fundamental role in improving energy savings, reducing emissions, and optimising resource use in sectors like mobility and urban infrastructure (Global Enabling Sustainability Initiative 2019). These technologies are critical to achieving climate neutrality targets. However, the environmental costs of digitalisation must also be addressed. The rapid expansion of digital technologies has led to increased energy consumption, particularly in data centres, and the rising production of electronic waste.

Therefore, measures to mitigate the negative environmental impacts of digitalisation, such as energy requirements or product disposal, must be implemented alongside efforts to maximise the benefits of digital transformation, ensuring that it serves as a genuinely sustainable enabler.

The two transformations upon which Europe will significantly rely in the coming decades appear inextricably linked and mutually dependent. While digitalisation can expedite the green pathway, it is also essential that digital technologies themselves become more sustainable. By embracing the twin transition and leveraging digital innovation to drive sustainable development across all sectors, the EU can position itself as a global leader in the green economy and ensure that both transitions move forward in harmony, creating a more resilient and equitable future.

1.4 The role of ICT in this pathway

1.4.1 Smart Cities and the evolution of ICTs

In this context, the Information and Communication Technology (ICT) sector plays a significant role in providing innovative tools to support the green transition. In 2009, through the Recommendation "Mobilising Information and Communication Technologies to facilitate the shift to an energy-efficient, low-carbon economy", the European Commission emphasised the untapped potential of ICTs to enhance energy efficiency, optimise production and distribution, and raise awareness among consumers regarding the benefits of low-energy technologies (European Commission 2009; European Parliament 2010). These principles align with the emergence of *Smart Cities*, which leverage ICTs to improve urban services' delivery, performance, and interactivity while minimising costs and environmental impact (European Commission 2012).

Smart Cities aim to enhance urban quality of life by deploying technologies like IoT, Big Data, and sensor-based infrastructures. These systems enable real-time monitoring and optimisation of energy grids, transport systems, and public services, significantly reducing resource consumption and emissions. For instance, *Intelligent Transport Systems* (ITS) that integrate roadside vehicle monitoring can optimise traffic flow, reduce congestion, and improve public transport efficiency, contributing to more sustainable urban mobility.

Since their conceptualisation in the early 2000s, Smart Cities have evolved through continuous technological innovation and widespread connectivity, giving rise to the broader "smartification" trend (IEEE Future Directions 2023). By increasing the *smartness* of urban environments, ICT supports the ecological transition across key economic sectors, boosting operational effectiveness while advancing environmental performance. The advancement towards intelligent behavioural systems, enhanced by artificial intelligence and machine learning, represents the next frontier in ICT-enabled sustainability interventions, enabling adaptive, personalised approaches that continuously optimise based on individual usage patterns and contextual factors.

1.4.2 **Green ICT: making the digital sector sustainable**

In recent years, information and communication technologies have been deployed rapidly and extensively worldwide, broadening their application scope and systemic relevance. However, the increasing demand for digital services has also brought attention to the environmental costs associated with ICTs, such as the rising energy use in data centres and increasing volumes of electronic waste. In 2020, the ICT sector was responsible for approximately 4 % of global electricity consumption and 1.4 % of greenhouse gas emissions (International Energy Agency 2023).

Although ICT is widely recognised as a critical catalyst for monitoring, adapting to, and mitigating climate change impacts (GeSI 2021), the sector is facing mounting pressure to reduce its environmental footprint. A progression towards sustainable ICT involves multiple strategies: reducing energy and material consumption in production, developing more resource-efficient software, and encouraging circular economy practices such as product repair, reuse, and recycling. For example, software optimisation can lower processing demands and reduce energy usage in devices, while circular initiatives in electronics manufacturing can mitigate the impact of e-waste (European Commission 2020b).

This transformation is already underway across Europe. According to Eurostat (Eurostat 2023b), in 2022, 58.5 % of EU enterprises reported considering environmental impact when selecting ICT services or equipment, indicating a growing awareness of the importance of sustainable digital practices (Eurostat 2023a). Industry initiatives, such as the *European Green Digital Coalition*, exemplify the dedication of leading ICT companies to support the dual transition by integrating digital innovation with climate objectives (European Green Digital Coalition 2021).

ICTs can serve both as drivers for sustainability and as subjects of transformation themselves. While they contribute to emissions reductions across multiple sectors, such as energy and mobility, they must also advance to achieve greater environmental efficiency in their design, deployment, and use. A sustainable digital future requires technologies that not only empower the ecological transition but also embody its principles, thereby becoming green by both function and nature.

The following chapters will shift the lens from macro-level systemic strategies to micro-level implementations, examining how digital services can empower individuals to actively take part in the green transition. The *MUV* platform, introduced as a case study, exemplifies how a citizen-centred approach combining ICT, behavioural insights, and data analytics can foster sustainable urban mobility.

However, realising this potential requires addressing fundamental gaps in how digital platforms systematically influence individual behaviour while contributing to broader urban transformation.

1.5 Research framework: from twin transition to behavioural infrastructure

1.5.1 Research gaps identified

The twin transition analysis reveals three critical gaps limiting sustainable urban mobility through digital innovation:

Gap 1: ICT-behaviour integration mechanisms. While Section 1.4 established ICT's sustainability potential, the specific mechanisms through which digital services influence individual mobility choices remain underexplored. Current approaches lack systematic integration of behavioural science principles with digital platform design, missing opportunities to enhance effectiveness beyond traditional informational or economic incentives (Bamberg et al. 2011; Steg and Vlek 2009).

Gap 2: Context-dependent effectiveness. Smart city vision promotes universal applicability of digital mobility solutions (European Commission 2012; Batty et al. 2012), yet empirical evidence on how demographic, institutional, and cultural factors moderate intervention effectiveness remains limited. This constrains evidence-based deployment guidelines and contextual adaptation strategies.

Gap 3: Systemic integration challenge. Despite comprehensive policy frameworks (European Commission 2019b), individual behaviour change tools operate as isolated applications rather than integrated transformation components. This reflects technological limitations in platform interoperability (Thakuriah et al. 2017) and theoretical gaps in understanding how individual changes aggregate to system-level transformation.

1.5.2 Research questions and theoretical contributions

These gaps motivate three interconnected research questions advancing both theoretical understanding and practical implementation:

RQ1: How can Information and Communication Technologies effectively support the transition towards sustainable urban mobility by influencing individual travel behaviours?

Expected contribution: A *sport-as-metaphor framework* that systematically applies athletic paradigms to mobility transformation, advancing beyond traditional gamification through metaphorical reframing, social reinforcement, and progressive achievement structures that activate intrinsic motivation.

RQ2: What factors determine the effectiveness of technology-mediated behavioural interventions across different demographic groups and institutional contexts?

Expected contribution: A *Context-Mechanism-Outcome (CMO) framework* identifying systematic patterns in how institutional embedding, temporal architecture, and motivational structures interact to determine effectiveness. This framework challenges universal design approaches while identifying transcendent core principles.

RQ3: How can digital mobility solutions be designed to scale effectively while integrating with broader urban transformation strategies and policy frameworks?

Expected contribution: Building on the contextual insights from RQ2, a *behavioural infrastructure model* conceptualising digital interventions as foundational systems supporting evidence-based urban planning through individual-level data collection, privacy-preserving analytics, and modular architectures enabling multi-stakeholder collaboration.

1.5.3 Thesis architecture and methodological approach

This thesis advances understanding through four interconnected investigations that systematically address each research question:

Chapter 2 establishes the mobility sustainability challenge and reviews ICT solutions, identifying behavioural intervention gaps that support RQ1's theoretical foundation.

Chapter 3 develops and implements the sport-as-metaphor framework through the MUV platform, directly addressing RQ1 by operationalising theoretical principles through concrete technological architectures and validated methodologies.

Chapter 4 validates effectiveness across four diverse contexts (4 872 participants), addressing RQ2 by revealing contextual moderation patterns and developing the CMO framework while demonstrating average 34 % emission reductions.

Chapter 5 explores AI-enhanced personalisation and modular architecture, addressing RQ3 by establishing scalability pathways from standalone applications to integrated policy support systems.

This integrated approach enables systematic theory-building while maintaining policy relevance and commercial viability, supporting EU twin transition objectives through evidence-based citizen engagement.

1.5.4 Expected contributions and implications

This research contributes to multiple academic fields while addressing practical challenges in sustainable urban mobility transformation.

Theoretical advances: Sport-as-metaphor framework extending gamification theory beyond engagement metrics toward sustained behaviour change; CMO framework establishing contextual adaptation principles for digital interventions; behavioural infrastructure model connecting individual change mechanisms to systemic transformation.

Practical innovations: Evidence-based implementation guidelines for gamified mobility interventions in organisational contexts; demonstrated emission reduction effectiveness through voluntary participation; scalable technological architectures enabling policy integration.

Policy support: European Green Deal implementation through citizen engagement; Corporate Sustainability Reporting Directive compliance frameworks; evidence-based Sustainable Urban Mobility Plan development through data-driven participation.

The approach establishes foundations for *digital behavioural infrastructures*, an emerging paradigm where individual engagement tools evolve into comprehensive systems supporting multi-stakeholder decision-making while preserving citizen autonomy and democratic participation in urban transformation processes.

Chapter 2

ICT for Sustainable Mobility: State of the Art and Challenges

This chapter examines the environmental consequences of urban mobility and the transformative potential of ICT in promoting sustainable solutions. It analyses the transport sector's critical contribution to global greenhouse gas emissions—accounting for 21 % of CO₂ emissions worldwide with the fastest growth rate among all major sectors—and establishes a systematic framework for understanding private vehicle dependency challenges. Through cross-analysis of four ICT innovations, Mobility as a Service platforms, Intelligent Transport Systems, data analytics, and electric mobility, the chapter identifies three convergent opportunities: effectiveness-adoption gaps, individual-system integration challenges, and evidence-policy gaps that limit transformation potential. These findings establish the empirical foundation for integrated behavioural-technical interventions, motivating the systematic infrastructure approach developed in subsequent chapters.

2.1 Urban mobility and its environmental impact

2.1.1 The transport sector's contribution to climate change

The transport sector represents one of the most carbon-intensive domains in the global economy, encompassing the movement of people and goods across all geographic scales via road, rail, sea, and air. At the same time, economic growth has driven the industry to a value of € 6.7 B in 2022, with projections exceeding € 10 B by 2030. This expansion trajectory conflicts directly with climate neutrality requirements.

At the global level, transport poses significant environmental threats through air pollution and greenhouse gas emissions. In 2023, the sector accounted for approximately 21 % of global CO₂ emissions, with road vehicles contributing 72 % of transport-related CO₂ (International Energy Agency 2024). When considering all greenhouse gases—expressed in carbon dioxide equivalents (CO₂eq) as introduced in Chapter 1—transport's share remains consistent at 15–21 % (Intergovernmental Panel on Climate Change 2023), with total anthropogenic emissions estimated at 54–59 Gt CO₂eq (Joint Research Centre, European Commission et al. 2021; Intergovernmental Panel on Climate Change 2023).

Figure 2.1 illustrates this global distribution of greenhouse gas emissions by sector, highlighting transport's critical position as the third-largest contributor and establishing the quantitative foundation for understanding mobility transformation requirements within broader climate action frameworks.

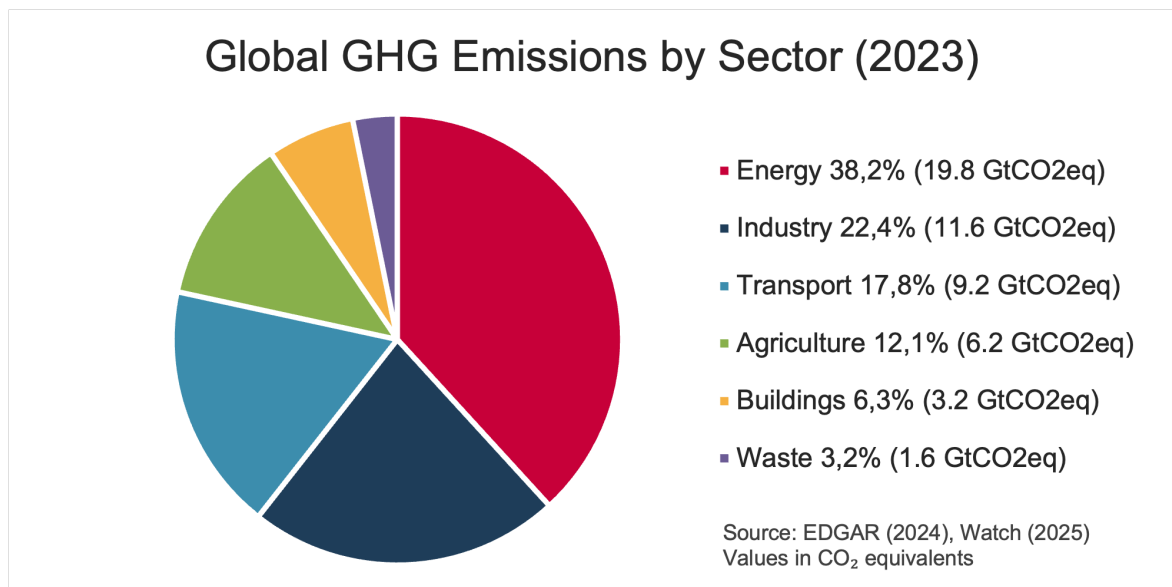


Figure 2.1: Breakdown of global greenhouse gas emissions by sector in 2023, revealing transport's 17.8 % contribution as the third-largest source. Source: adapted from *EDGAR - Emissions Database for Global Atmospheric Research* (2024) and *Climate Watch* (2025).

The sector's global emission trajectory reveals both the magnitude of the challenge and its accelerating nature. International transport emissions have surged by nearly 80 % since 1990, growing at 1.7 % annually—the fastest rate among all major sectors (United Nations Environment Programme 2023). Even the COVID-19 pandemic provided only temporary relief: after emissions dropped 14 % in 2020 from 8.1 to 7 Gt CO₂eq due to containment measures (Friedlingstein et al. 2023), they rebounded to exceed pre-pandemic levels by 2023, surpassing 8 Gt CO₂eq again (International Energy Agency 2024). The breakdown of global transport-related emissions by mode over recent decades is depicted in Figure 2.2.

European patterns mirror these global trends while exhibiting distinct characteristics. EU transport emissions reached 800 Mt of CO₂ in 2022, accounting for 29 % of total emissions (European Environment Agency 2023a; European Environment Agency 2023c)—a higher proportion than the global average shown in Figure 2.1. Emissions have increased by 26 % since 1990 despite policy efforts. The European Green Deal responds with ambitious targets: 55 % emission reductions by 2030 and 90 % by 2050 (compared to 1990 levels) (European Commission 2019b). These targets require implementation strategies encompassing cleaner fuels, renewable energy integration, Mobility as a Service solutions, and transport system digitalisation (European Commission 2020d).

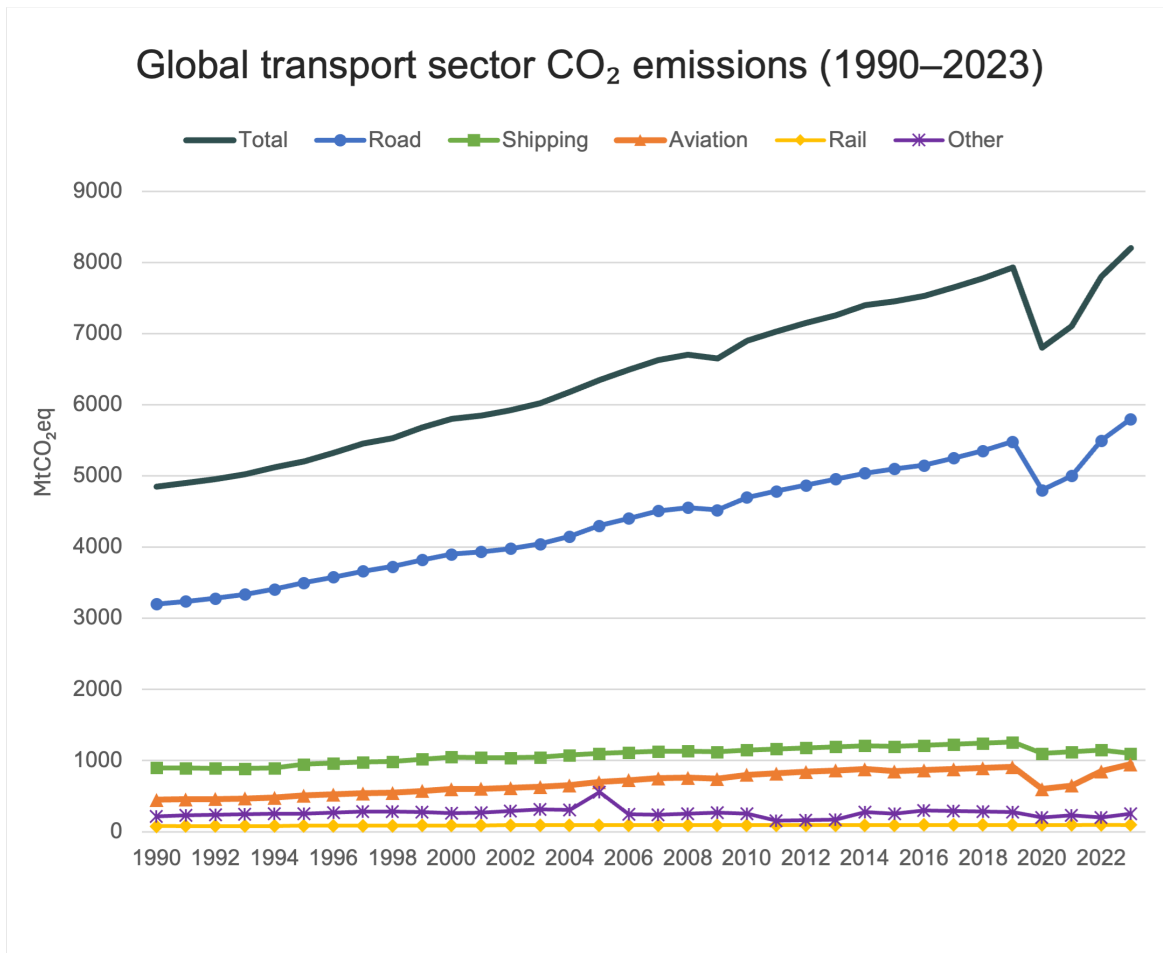


Figure 2.2: Evolution of global CO₂ emissions from transport by mode (1990–2023), demonstrating road transport’s overwhelming dominance and the persistent growth trajectory across all categories despite technological advances. Source: adapted from International Energy Agency (2024) and Intergovernmental Panel on Climate Change (2023).

2.1.2 Mobility in cities and the influence of private vehicles

Urban mobility concentrates both the challenge and the solution for transport decarbonisation. Cities, while occupying only 3 % of Earth’s surface, generate 80 % of global emissions and will host two-thirds of the world’s population by 2050 (UN-Habitat 2020). This concentration creates leverage points where targeted interventions can achieve disproportionate climate impact through systematic mobility transformation.

This trend is mirrored in the transport sector, with road transport being the primary contributor to pollution. An estimated 73 % of transport-related emissions originate from road vehicles, including passenger and freight transport (European Environment Agency 2024). The widespread use of private vehicles in urban centres is a major pollution factor. In 2019, cars accounted for over 61 % of transport-related greenhouse gas emissions in Europe (European Environment Agency 2023b), remaining the predominant mode of transport in many European cities.

The scale of European car dependency is quantified through vehicle density: 257 million registered motor vehicles in 2023, representing 571 cars per 1 000 inhabitants (Eurostat 2023c).

With average occupancy rates of 1.6 passengers per vehicle, this translates to approximately 1.16 t of CO₂ per year (Our World in Data 2023)—representing roughly 25 % of individual carbon budgets compatible with 1.5 °C targets.

Beyond greenhouse gas emissions, private vehicles generate cascading impacts across urban systems. Fine particulate matter (PM), one of the most harmful urban pollutants, increases the incidence of cardiovascular and respiratory diseases (World Health Organization 2021b). Private cars remain one of the leading contributors to air pollution in cities; they are responsible for 15 % of PM emissions in European urban areas (Joint Research Centre, European Commission 2023). According to the European Commission, air pollution contributes to approximately 300 000 premature deaths annually in Europe (European Commission 2023a).

While private car use is primarily an individual choice, it is strongly influenced by the characteristics of urban environments and the quality of transport infrastructure. Inefficient public transport systems, poorly designed urban spaces without cycling or pedestrian-friendly infrastructure, and the geographic features of cities all contribute to reinforcing private vehicle dependency while undermining the development and uptake of more sustainable alternatives.

2.1.3 European car dependency: patterns and intervention implications

European car dependency patterns reveal systematic relationships between urban characteristics and sustainable mobility adoption that determine intervention requirements. Car use accounts for 57 % to 81 % of the total distance travelled daily in several EU Member States, with higher usage rates in eastern and southern Europe (Eurostat 2023d). This variation correlates directly with infrastructure development patterns and economic factors.

Cities achieving below 40 % car modal share (Copenhagen, Amsterdam, Vienna) demonstrate consistent features: integrated public transport networks, comprehensive cycling infrastructure, and mobility management policies implemented systematically over decades (Gehl 2010). These cities typically fall within the lower range of the EU car dependency spectrum.

Conversely, car-dependent contexts (>70 % modal share) typically exhibit lower urban density, limited multimodal integration, and infrastructure investments historically prioritising private vehicle access. This variation establishes differential intervention requirements: high-dependency contexts require fundamental behavioural transformation strategies, while integrated systems can optimise existing sustainable patterns through digital enhancement approaches.

Understanding these patterns becomes critical for designing effective interventions, as the same digital tools may generate vastly different outcomes depending on underlying urban mobility infrastructure and cultural contexts.

2.1.4 Direct and indirect impacts

Private vehicle dependency generates cascading impacts across urban systems through complex interaction effects that extend far beyond immediate users. Understanding these impacts requires systematic analysis across two critical dimensions: their temporal manifestation (direct vs. indirect) and their distributional scope (individual vs. collective effects). This analytical framework, adapted from transportation economics literature (Litman 2021), enables precise identification of intervention leverage points where behavioural change can generate maximum system-wide benefits while informing the design of ICT-enabled solutions.

The matrix in Figure 2.3 visualises the externalities of private car use along two dimensions within the four impact quadrants.

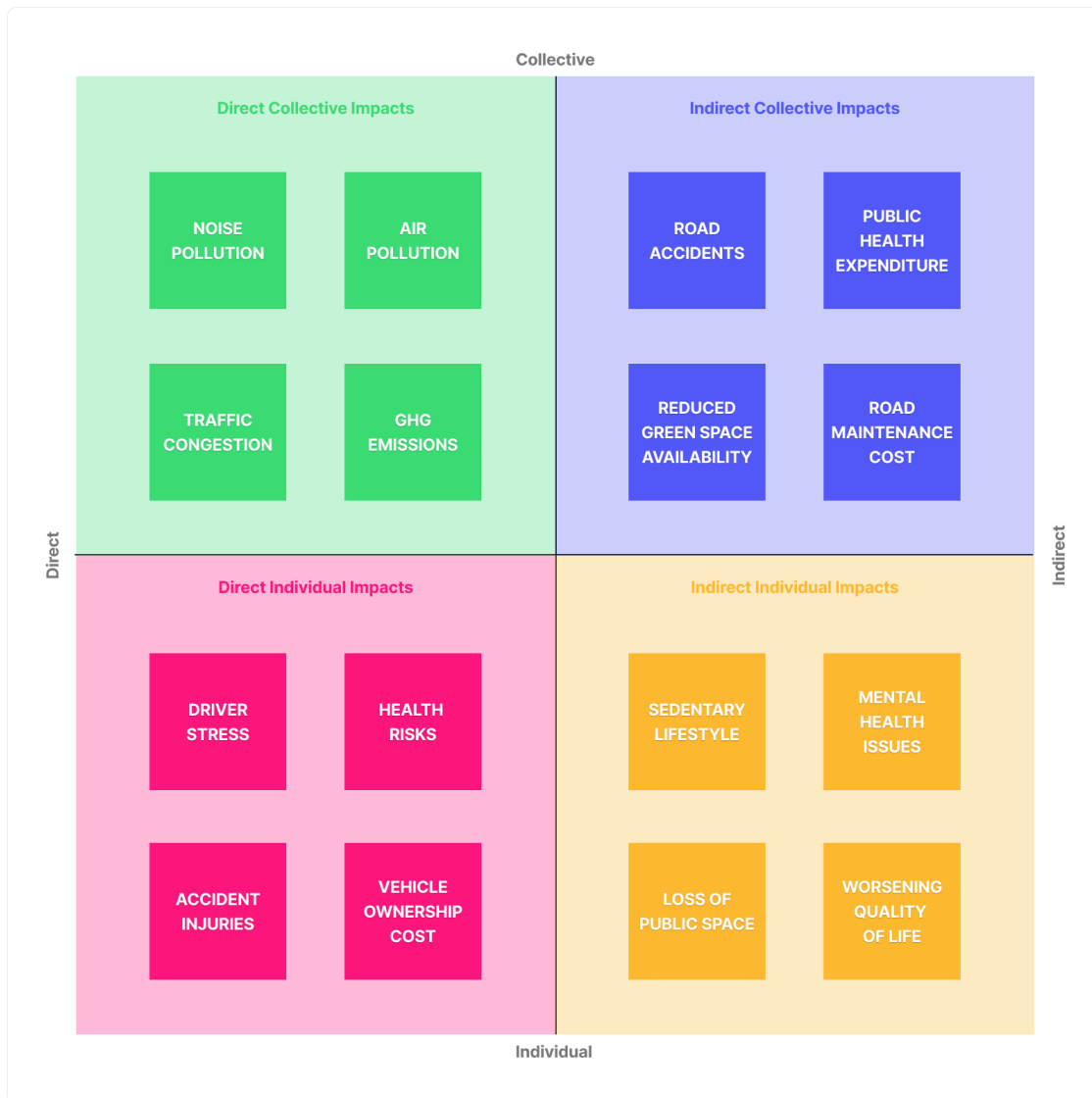


Figure 2.3: Systematic categorisation of private vehicle externalities by temporal nature (direct vs. indirect) and distributional scope (individual vs. collective). It highlights the broad spectrum of impacts generated by car dependency. Source: adapted from Litman (2021).

This impact matrix reveals critical insights for intervention design. Traditional policy approaches typically address only direct collective impacts (emissions, congestion) through regulatory mechanisms, missing the individual and indirect dimensions determining behavioural compliance and long-term sustainability.

The framework also illuminates why purely technological solutions frequently fail to achieve expected adoption rates: addressing direct impacts through better vehicles or infrastructure leaves the individual motivational drivers and social contexts that sustain car dependency patterns unchanged. This systematic analysis establishes the theoretical foundation for ICT-enabled behavioural interventions that can systematically address multiple impact dimensions through personalised engagement, social reinforcement, and collective awareness mechanisms.

2.1.4.1 Direct collective impacts

These are primarily associated with pollution and traffic. Beyond the well-documented contributions of cars to air pollution and greenhouse gas emissions, noise pollution is another significant, albeit often underestimated, impact. Defined as noise levels exceeding 55 dB from anthropogenic activities, this form of environmental degradation adversely affects ecosystems, impedes the enjoyment of public spaces, and impacts public health. In 2023, more than 113 million Europeans were chronically exposed to road traffic noise levels above 55 dB, a threshold considered harmful by the WHO (World Health Organization 2018). Such exposure is linked to insomnia, stress, cognitive decline, and cardiovascular diseases. It causes an estimated 12 000 premature deaths in Europe annually, with over 6.5 million individuals experiencing chronic sleep disorders (European Environment Agency 2020a).

Road traffic also contributes to significant accidents. In 2023, there were approximately 20 400 severe injuries and 46 road fatalities per one million inhabitants across the EU (European Commission 2024). Although the incidence has declined since 2014, when road fatalities reached 25 700, the EU target of zero road deaths and serious injuries by 2050 remains a distant objective (International Transport Forum (OECD) 2022).

2.1.4.2 Direct individual impacts

The physical and psychological toll of driving under stressful urban conditions is substantial for individuals. Prolonged waiting times, congestion, and delays elevate stress and anxiety levels and can provoke aggressive behaviour, increasing the risk of accidents (Evans and Wener 2006). Physical injuries from road accidents have further consequences, including diminished productivity and increased healthcare expenditures.

The economic implications are also considerable. In 2022, the average cost of vehicle ownership in Europe amounted to € 616 per month (€ 7 392 per year), encompassing depreciation, fuel, insurance, maintenance, parking, and tolls (Statista 2024).

2.1.4.3 Indirect collective impacts

The public health burden associated with air and noise pollution is overwhelming. Cardiovascular and respiratory diseases, as well as sleep disorders, place additional strain on national health systems (World Health Organization 2021a). Road traffic accidents alone cost the EU economy approximately € 120 B annually, including both healthcare expenses and productivity loss (European Commission 2020e). High car dependency also serves as a disincentive for physical activity, contributing to sedentary behaviour and increasing the risk of chronic health conditions such as obesity, cardiovascular disease, and diabetes (World Health Organization 2022). These combined factors result in higher public healthcare expenditure and reduced efficiency of medical service provision.

Furthermore, urban planning also plays a role: many cities still prioritise private car use, dedicating substantial portions of urban space to road infrastructure. This process of cementification requires high maintenance costs and generates environmental consequences, such as soil sealing and ecosystem fragmentation, as well as social ones, including reduced green space availability and diminished urban liveability (UN-Habitat 2020; Gehl 2010). In recent years, several European cities have begun rethinking space allocation. A notable example is Paris, where, in the last decade, approximately 50 000 parking spaces have been repurposed as pedestrian areas, green zones, and bicycle lanes. This transformation has led to a 40 % reduction in air pollution (The Guardian 2023).

2.1.4.4 Indirect individual impacts

Individuals experience long-term health consequences from vehicular pollution, including elevated risks of chronic respiratory and cardiovascular conditions such as asthma and bronchitis (World Health Organization 2021a). Sedentary lifestyles exacerbated by car dependency increase the incidence of metabolic disorders such as obesity and diabetes (World Health Organization 2022). Moreover, mental health may be adversely affected by post-traumatic stress following accidents or by prolonged noise exposure, potentially leading to anxiety, depression, and other psychological disorders (Jafari et al. 2015).

Addressing these multidimensional challenges necessitates transformation strategies that simultaneously target multiple impact quadrants through holistic approaches combining regulatory frameworks with individual engagement mechanisms, thereby reducing car dependency while mitigating its deleterious consequences on public health, environment, and social equity. This analytical framework establishes the foundation for examining how ICT solutions can systematically address these diverse impact dimensions, as explored in the following section.

2.2 ICT solutions for sustainable mobility

The systematic analysis of car dependency impacts reveals that effective transformation requires interventions simultaneously addressing direct and indirect effects across individual and collective dimensions. Information and communication technologies emerge as uniquely positioned to meet this challenge through integrated capabilities that traditional approaches cannot match: real-time personalisation for individual users, system-wide optimisation for collective benefits, immediate behavioural feedback, and data-driven policy support for systemic change (International Association of Public Transport 2022; ERTICO 2025).

Digital technologies now constitute fundamental components of all mobility services, serving as the foundation for advanced solutions that collect, process, and exchange information to enable predictive analysis, intelligent decision-making, and efficient collaboration (Batty et al. 2012). Through their capacity to optimise resource utilisation, reduce emissions, and enhance transport system efficiency, ICT demonstrates significant potential for sector-wide sustainability transformation.

The following subsections examine key ICT mobility innovations contributing to this transformation potential.

2.2.1 MaaS platforms

Mobility as a Service (MaaS) represents a paradigm shift toward urban, multimodal, and integrated mobility, enabling users to access diverse transport services (such as public transport, sharing services, and taxis) through seamless unified experiences where single platforms facilitate planning, booking, and payments. MaaS integrates public and private transport services into user-friendly interfaces, typically mobile applications, managing multimodal travel through unified accounts (Sochor et al. 2018).

The primary advantage lies in flexibility and the capacity to address varied traveller needs through customised solutions that reduce private vehicle dependency. MaaS platforms aim to decrease car usage and ownership while incentivising public transport utilisation and sustainable mobility adoption (Kupfer et al. 2015). Resultant impacts include reduced road congestion with aforementioned associated health and environmental benefits, plus enhanced public transport efficiency and centrality.

Implementation experiences highlight both the potential and the challenges of MaaS deployment. *Whim*, launched in Helsinki and later expanded to several European cities, showcased the promise of subscription-based multimodal access but ultimately ceased operations, exposing critical issues in business model viability. In contrast, *Moovit*, active in over 3 400 cities, has achieved greater longevity by focusing on journey planning and real-time transit information rather than full integration. These contrasting outcomes demonstrate that while integrated digital solutions can effectively unify diverse mobility options, long-term success hinges on economic sustainability and market adaptability.

2.2.2 Intelligent Transport Systems

Intelligent Transport Systems (ITS) encompass diverse tools for enhanced safety, coordination, and management of transport networks, spanning advanced traffic management systems, sophisticated public transport optimisation, and user information services. These applications utilise sensors, cameras, and algorithms to monitor traffic flows in real time while implementing adaptive routing and logistics solutions (ERTICO 2025).

The evolution toward connected vehicles has enabled the *Internet of Vehicles* (IoV), serving as an enabler for the *ACES* paradigm—Autonomous, Connected, Electric, and Shared mobility (B. Chen et al. 2021). Through *Vehicle-to-Everything* (V2X) communication technology, encompassing both *Vehicle-to-Vehicle* (V2V) and *Vehicle-to-Infrastructure* (V2I) communication, each vehicle becomes a network node capable of exchanging real-time information about road conditions, traffic density, accidents, and optimal routes. This creates intelligent networks facilitating safer and more efficient mobility experiences.

The development of *Collaborative ITS* (C-ITS) represents a fundamental step toward autonomous mobility and safer, more efficient transport solutions (European Commission 2021a), exemplified by the C-Roads Platform’s European cooperation in implementing standardised, interoperable intelligent transport systems across borders.

2.2.3 Data analytics and big data for mobility planning

Connected vehicles have dramatically expanded mobility data availability, enabling real-time analysis of citizen travel behaviours through mobile devices, applications, and sensors. This enhanced information supports *big-data analysis* techniques for developing predictive mobility models and simulations (Y. Zhang et al. 2022), optimising infrastructure efficiency and informing urban planning and public policies. Data access and sharing become crucial for monitoring transport activities and generating value across sectors, including insurance and healthcare (European Commission 2020d).

However, the transformative potential of mobility big data remains limited by citizen engagement. Although technical capabilities allow advanced analysis, insight quality depends fundamentally on user participation in data generation processes, underscoring the need for behavioural mechanisms that make data contribution meaningful for individual users while generating policy-relevant insights for institutional stakeholders.

2.2.4 Electric mobility

The *ACES* paradigm (Autonomous, Connected, Electric, and Shared Mobility) represents the major technology-driven transformation of personal and freight transportation, intrinsically linked to electric vehicle industry growth. European projections indicate battery electric cars will constitute nearly 25 % of new vehicle sales by 2025 (Transport & Environment 2024), driven by expanded affordable model ranges, improved competitiveness versus internal combustion vehicles, and proliferating charging infrastructure.

Public transport electrification shows significant progress, with 42 % of European city buses being electric in 2023, representing 15.9 % of total registered buses. Forecasts indicate that new bus registrations by 2030 should reach between 63 % and 76 % of new vehicles on the road, reaching 100 % by 2050 (ACEA 2023).

Despite technological advances, electric mobility adoption faces systematic barriers, revealing the critical role of behavioural intervention mechanisms. Range anxiety, charging accessibility, and cost perceptions persist as constraints even as technical capabilities improve, demonstrating that technological solutions require integrated approaches bridging capability-acceptance gaps through targeted engagement, community-based adoption support, and systematic behavioural reinforcement mechanisms.

Table 2.1 presents a comparative overview of four predominant ICT-based solutions currently implemented in urban mobility, highlighting their complementary approaches to sustainability transformation. While each solution addresses distinct facets of the transportation system, modal integration, traffic optimisation, evidence-based planning, and decarbonisation, their collective analysis reveals systematic patterns in technological capabilities and implementation challenges that inform intervention design strategies.

Table 2.1: Overview of ICT-based solutions for sustainable urban mobility.

Solution	Main purpose	Impact	Technology	Examples
MaaS	Modal integration	Vehicle reduction	Mobile apps, APIs	Whim, Moovit
ITS	Traffic optimisation	Safety	IoT, V2X	C-Roads
Big Data	Mobility planning	Policy support	AI, Cloud	Telraam
E-mobility	Decarbonisation	Emission cut	EVs, Smart grids	Ebusco

2.2.5 Integration imperatives: toward comprehensive behavioural-technical systems

Cross-analysis of ICT solutions reveals three convergent opportunities for next-generation mobility interventions. First, the *effectiveness-adoption gap* indicates that high-impact solutions face behavioural barriers requiring engagement strategies beyond traditional economic or regulatory approaches. Second, the *individual-system integration challenge* demonstrates that personal mobility choices aggregate to system-level outcomes, yet existing tools lack mechanisms connecting individual actions to collective transformation. Third, the *evidence-policy gap* shows that urban planning requires granular mobility data, while citizens lack meaningful policy development participation tools.

These convergent opportunities establish the empirical motivation for integrated behavioural-technical interventions that can simultaneously achieve high individual engagement, measurable emission reductions, and policy-relevant data generation.

2.2.6 Integration of digital mobility solutions

While individual technological solutions offer significant benefits, their integration into comprehensive digital mobility ecosystems substantially amplifies their potential.

Cities like Amsterdam and Vienna have demonstrated how layered implementation of complementary technologies—connecting MaaS platforms with real-time ITS data, electric vehicle infrastructure, and participatory planning tools—creates synergistic impacts greater than the sum of individual interventions (Amsterdam Smart City 2023).

These integrated approaches enable what Paiva et al. (2021) describe as a coordinated orchestration of urban mobility systems, where diverse technologies converge to create intelligent transport networks that respond dynamically to changing conditions. This concept extends beyond mere technological integration to encompass a fundamental shift in how urban mobility is conceptualised and managed.

Musolino et al. (2022) further develop this perspective in their research on MaaS design models, highlighting how the effectiveness of digital mobility solutions depends on their integration into cohesive systems that optimise across different transport modes. Such orchestration allows cities to address complex mobility challenges holistically while providing users with seamless, multimodal experiences that can effectively compete with private vehicle ownership. However, the sustained behavioural change required for mobility transformation demands approaches that extend beyond technological integration to systematic individual engagement, which is the focus of the following chapter.

2.3 Towards a digital and sustainable mobility ecosystem: challenges and enablers

The ICT solutions examined offer strong potential to transform urban mobility, yet systemic barriers still hinder widespread adoption and limit overall impact. Despite technological maturity, the necessary enabling conditions for full-scale transition remain inadequate (International Transport Forum 2023), with structural and operational constraints slowing sector-wide uptake.

Identifying these barriers and the corresponding enablers is essential to designing interventions that bridge technological capabilities with behavioural adoption at scale. A critical understanding of these factors clarifies the main obstacles and highlights emerging opportunities for advancing sustainable urban mobility.

2.3.1 Key challenges in the ICT-driven mobility transition

Cross-analysis of MaaS, ITS, data analytics, and e-mobility implementations reveals four systematic constraint categories that limit transformation potential despite technological sophistication.

Behavioural inertia and adoption barriers remain the most persistent obstacles. Resistance to mobility change, particularly car dependency (S. Cairns et al. 2010), stems from multiple psychological mechanisms: status quo bias, loss aversion, and habitual automation (Samuelson and Zeckhauser 1988; Kahneman 2011). Even advanced solutions face systematic adoption hurdles, including user interface complexity, fragmented payment systems, and limited interoperability (Sochor et al. 2018), confirming that technology alone is insufficient to trigger behavioural shifts.

Digital divides and accessibility constraints limit inclusive participation. Segments of the population face barriers due to limited digital literacy, lack of smartphone access, or absence of payment cards required for mobility services (Durand et al. 2021). This digital exclusion contradicts sustainability principles requiring broad-based participation for systemic impact.

Data fragmentation and interoperability deficits constrain system-wide optimisation. Mobility data often remains fragmented, inaccurate, or deliberately withheld by service providers for competitive reasons (Tempelmeier et al. 2019). The absence of shared standards complicates interoperability across platforms and operators, preventing the seamless experiences that could motivate sustained usage (Thakuriah et al. 2017).

Environmental costs of digital infrastructure create sustainability paradoxes. ICT systems' energy consumption and electronic waste must be systematically addressed to ensure net positive environmental impact (Belkhir and Elmeligi 2018). As discussed in Section 1.4, this challenge requires "green ICT" approaches that align technological deployment with climate neutrality goals.

Notwithstanding these challenges, digital technologies possess considerable transformative potential—provided they are deployed within inclusive, interoperable, and environmentally responsible frameworks (OECD Secretariat 2024). This potential motivates systematic analysis of strategic enablers that can overcome identified constraints.

2.3.2 Strategic enablers and opportunities for sustainable transport innovation

Despite these challenges, emerging technological, social, and policy innovations offer promising pathways to foster more inclusive and sustainable mobility ecosystems that can overcome identified constraints.

AI-driven personalisation and adaptive systems represent the next frontier in addressing behavioural barriers. Through machine learning algorithms and data analysis capabilities, platforms can provide tailored mobility offerings that continuously optimise based on individual patterns and contextual factors (Zhao et al. 2019). This approach advances from static rule-based systems toward intelligent behavioural infrastructures, demonstrating superior effectiveness in sustaining long-term engagement compared to universal design strategies.

Inclusive and collaborative design principles can systematically address digital divide challenges. Implementing “privacy by design,” “accessibility by design,” and participatory development approaches enables more equitable service provision (Badu-Marfo et al. 2023). Community-based co-design processes ensure digital solutions reflect diverse mobility needs rather than privileging technologically sophisticated early adopters.

Behavioural engagement and gamification mechanisms offer systematic approaches to activation and retention. Feedback systems, social dynamics, and game-based interventions can guide individuals toward sustainable choices while intrinsically rewarding participation (Avril et al. 2024). These approaches address the fundamental challenge that technological solutions often lack motivational frameworks for sustained change.

Evidence-based policy integration enables individual actions to contribute to systemic transformation. Digital platforms that generate policy-relevant mobility data while engaging citizens in sustainable choices can bridge the gap between personal behaviour change and urban planning requirements. This integration approach positions individual engagement tools as infrastructure supporting evidence-based decision-making rather than isolated interventions.

2.3.3 Synthesis: from barriers to integrated solutions

Table 2.2 summarises the key challenges hindering the widespread adoption of ICT-based urban mobility solutions alongside the corresponding strategic enablers that can ease their resolution. This synthesis highlights how social, technical, and environmental barriers may be addressed through inclusive design, policy innovation, and emerging digital capabilities.

Table 2.2: Systematic mapping of barriers constraining ICT-driven mobility transformation alongside corresponding strategic enablers that can overcome these limitations.

Barriers	Strategic enablers
Resistance to behavioural change	Behavioural nudging (gamification, feedback systems, etc.)
Digital divide	Inclusive design (accessibility by design, etc.)
Fragmented/inaccessible data	Interoperability standards and open data policies
Environmental cost of ICT	Green ICT regulations and energy-aware design
Platform fragmentation	API integration and cross-provider governance

The successful implementation of these enablers requires platforms that combine technological components with insights from behavioural science and concepts of accessibility and interoperability, as demonstrated by digital services that achieve measurable emission reductions through engagement via games and community-based interventions. When implemented systemically and with a strong user-centric orientation, these levers can catalyse the development of behavioural infrastructures that support digital and sustainable mobility ecosystems, creating equitable, efficient, and climate-aligned urban transformation.

The analysis reveals sustainable urban mobility transformation requires approaches that systematically integrate technological capabilities with behavioural science principles, inclusive design methodologies, and policy-relevant data generation. While demonstrating significant technical potential, traditional ICT solutions cannot achieve systemic impact without addressing the behavioural, social, and institutional factors that determine adoption and sustained usage.

This integration imperative motivates the development of *behavioural infrastructure*—digital systems designed to simultaneously engage individuals in sustainable mobility choices while generating valuable data for evidence-based planning. Such systems must address three critical requirements identified through this analysis:

- **Sustained engagement mechanisms** that transcend temporary technological novelty to create lasting behavioural change through systematic activation of intrinsic motivation, social reinforcement, and progressive skill development.
- **Contextual adaptation capabilities** that account for diverse urban environments, demographic characteristics, and institutional settings without losing effectiveness or requiring complete redesign for each implementation context.
- **Systemic integration approaches** that connect individual mobility choices to collective outcomes through data generation, policy support, and institutional engagement, enabling personal actions to contribute sensibly to urban transformation processes.

The following chapter examines how these requirements can be operationalised through systematic integration of behavioural science, game design, and ICT architecture, using the MUV platform as a case study for developing and validating comprehensive behavioural infrastructure for sustainable urban mobility.

Chapter 3

Designing Behavioural Change for Sustainable Mobility: The MUV Case Study

This chapter explores how MUV leverages behavioural design, gamification, and technology to foster sustainable mobility. It examines psychological barriers to change and the role of nudging, positive reinforcement, and game mechanics in shaping long-term habits. MUV reimagines urban mobility as a sport, engaging users through training sessions, challenges, and tournaments, combining intrinsic and extrinsic motivations. The platform's data-driven approach demonstrates its impact in reducing CO₂ emissions and promoting active travel. The chapter also details MUV's technological infrastructure, including its cloud-native backend, mobile application, and web dashboard. It outlines trip validation algorithms, point calculation, and CO₂ savings measurement (ISO 14064-2), ensuring scalability, efficiency, and sustainability.

3.1 Behavioural design in sustainable mobility

As outlined in Chapter 1, the pathway to climate neutrality hinges not only on systemic transformations but also on deep changes in individual and collective behaviours. This is particularly evident in urban mobility, where personal travel routines and modal choices significantly influence emissions, congestion, and quality of life. Urban mobility patterns are largely habitual: according to Eurostat (2025), 65 % of Europeans use private cars for commuting to work, even though 70 % of urban trips are shorter than 5 km (European Parliament 2015). These data highlight a persistent reliance on private vehicles even for short, easily walkable or bikeable journeys.

Although ICT plays a crucial role in optimising transport systems, technology alone cannot guarantee widespread adoption of sustainable transport habits. Behavioural design offers a complementary approach that targets the psychological, contextual and social factors underlying mobility choices, fostering long-term habit transformation through targeted techniques such as nudging, positive reinforcement, personalisation, and gamification.

3.1.1 Why behaviour matters in mobility

The dominance of private transport (particularly car usage) across European cities contributes directly to greenhouse gas emissions, atmospheric and noise pollution, traffic congestion, and diminished urban liveability. Transforming mobility patterns thus requires more than infrastructure provision: it demands deliberate behavioural intervention strategies.

3.1.1.1 Psychological barriers to mobility behavioural change

Behavioural change in mobility faces strong psychological and structural barriers. Research on behavioural inertia shows that individuals resist change even when alternatives offer clear benefits (Samuelson and Zeckhauser 1988). This resistance stems from several factors:

- **Habitual reliance on private cars:** Commuting habits operate largely on autopilot. Travel mode choices become habitual and resistant to change unless disrupted by external interventions or major life events (Verplanken, Aarts, et al. 1997).
- **Cognitive load and decision fatigue:** Choosing new transport modes requires mental effort. Dual-process theory suggests individuals rely on fast, automatic thinking in daily routines, favouring familiar car-based behaviours over deliberate and rational consideration of alternatives (Kahneman 2011).
- **Status quo bias and loss aversion:** Individuals exhibit strong preferences for existing behaviours even when better options are available (Samuelson and Zeckhauser 1988). Moreover, loss aversion further amplifies perceived costs of change, overestimating the inconvenience of relinquishing car use while deterring transitions to sustainable options (Tversky and Kahneman 1991).
- **Social norms and peer influence:** Behavioural choices are strongly influenced by perceived norms. Descriptive norms (*what others do*) and injunctive norms (*what others approve of*) can steer mobility choices (Cialdini et al. 1990; Schultz et al. 2007). For example, if car use is perceived as a social norm, alternatives like cycling may be dismissed as inconvenient or stigmatised. Similarly, exposing individuals to evidence of widespread sustainable mobility adoption (e.g., demonstrating that “most people in your area use public transport”) can positively influence such uptake.
- **Perceived safety and convenience barriers:** Many users associate public transport or active modes with discomfort, unreliability, or risk, especially among vulnerable groups such as older people, women, parents with young children, or people with reduced mobility (Anable 2005).

These barriers illustrate the complex web of psychological, social, and structural factors that sustain unsustainable mobility behaviours. Addressing them requires multidimensional strategies capable of reducing friction, increasing perceived value, and activating latent motivations.

3.1.1.2 Leveraging behavioural design to facilitate sustainable mobility choices

Behavioural design examines how internal factors (personal traits, beliefs, self-efficacy) and external factors (environmental conditions, relationships, resources) affect human behaviour (Steg and Vlek 2009; Service et al. 2014). In urban commuting, external factors include journey constraints, transport availability, and associated costs. Internal factors represent established habits, values, and personal characteristics. Effective interventions might include incentives such as discounts for sustainable transport use, feedback mechanisms demonstrating CO₂ impacts of mobility choices, or communication campaigns fostering community benefits of sustainable behaviour (Bamberg et al. 2011; Thøgersen and Møller 2008).

These strategies often rely on activating pro-environmental norms and appealing to users' intrinsic motivations. Research demonstrates that normative messages significantly affect sustainable choices when framed as widely adopted and socially approved (Cialdini 2003).

By strategically applying behavioural insights, urban mobility services can become powerful social and environmental change instruments, moving beyond efficiency improvements to actively shape travel choices and community norms.

3.1.2 Key techniques for shaping sustainable mobility behaviours

Effective behavioural change in mobility requires strategic interventions that guide individuals towards optimal decision-making while preserving freedom of choice. This user-centred approach aligns with Herbert Simon's concept of design as a science of the artificial, aimed at structuring environments that facilitate effective decision-making (Simon 1996).

Several theoretical models provide structured frameworks for understanding and designing behavioural change interventions. The *Behaviour Change Wheel* (BCW), developed by Susan Michie, delineates a structured approach based on three core components:

- **Capability:** an individual's physical and mental ability to perform a behaviour.
- **Motivation:** psychological and emotional factors that influence action.
- **Opportunity:** external factors that facilitate or constrain a behaviour.

This approach posits that successful interventions must simultaneously address all three components (Michie et al. 2011).

Fogg's Behaviour Model (FBM) postulates that behaviour occurs when three factors—Motivation, Ability, and Prompt—converge simultaneously. Fogg asserts that behavioural change is most efficacious when an individual possesses sufficient motivation, perceives the action as easily executable, and is triggered by an external prompt. This model is particularly relevant for digital mobility applications, as notifications, personalised incentives, and progress tracking can be effective prompts (Fogg 2009).

Table 3.1 compares three behavioural models used to guide the design of digital interventions for sustainable mobility.

Table 3.1: Comparison of key behavioural models and how they support digital mobility design.

Model	Components	Application in mobility design
Behaviour Change Wheel (BCW)	Capability, Motivation, Opportunity	Design of comprehensive behavioural interventions
Fogg's Behaviour Model (FBM)	Motivation, Ability, Prompt	Triggering user action via application-based prompts
Self-Determination Theory (SDT)	Autonomy, Competence, Relatedness	Sustaining motivation through gamification and user engagement

3.1.2.1 Nudging

Nudging, a concept in behavioural science, posits that subtle supports, suggestions or indirect cues can steer individual and collective decisions more effectively than direct instructions, obligations, or prohibitions (Thaler and Sunstein 2008). Rather than restricting choice, nudges reshape decision-making contexts to favour desirable outcomes.

In mobility, effective strategies include setting low-impact modes as defaults in travel-planning applications, using social proof to highlight widespread adoption of sustainable choices, and displaying environmental impacts to raise awareness. Research demonstrates that even simple interventions, such as reordering interface elements or providing comparative feedback, can significantly influence modal choices, making nudging particularly suited for voluntary behavioural change.

3.1.2.2 Positive reinforcement

Positive reinforcement involves providing rewards for specific behaviours to encourage future repetition. Various reinforcer types can be employed depending on context, behaviour to be reinforced, and the target individual. A distinction is made between: natural reinforcers (direct consequences of behaviour), social reinforcers (gratitude, appreciation, recognition), tangible reinforcers (physical rewards), and token reinforcers (points exchangeable for value) (Osbaldiston and Schott 2012).

Mobility applications commonly implement point systems, badges for sustainable choices, or financial incentives such as mileage reimbursements for employees who walk or cycle to work, creating tangible motivation for sustained behaviour change.

3.1.2.3 Personalisation

Personalisation adapts interventions to individual needs, interests, and behaviours, providing more engaging and effective services. Elements include customised content, personalised recommendations, and adaptive interfaces that modify according to user preferences and previous interactions. This approach enhances engagement probability and enables incremental, guided changes based on longitudinal behavioural measurements, with comparative research demonstrating that personalised game-based interventions achieve superior outcomes compared to generic approaches (R. Orji et al. 2017; Rita Orji and Ndulue 2023). In

the field of interaction design, behavioural design is also seen as essential to support habit formation and long-term engagement through iterative, user-centred adaptation (Interaction Design Foundation 2023).

In mobility contexts, personalisation manifests through profiling functionality in Mobility as a Service platforms, enabling users to specify travel preferences and recurring journeys for integration into trip planning or personalised step targets in health monitoring applications.

3.1.2.4 Gamification

Gamification incorporates game design elements within non-game contexts. When appropriately designed, integrating rewards, leaderboards, levels, quizzes, competitions, and badges can create more engaging travel experiences. Game design involves crafting systems of rules and feedback that produce meaningful play (Salen and Zimmerman 2003).

Gamification strategies can promote the adoption of public transport, active mobility, or sharing services while reducing personal carbon footprints. Beyond improving user engagement and motivation, these approaches enhance customer loyalty and facilitate the collection of valuable insights into user preferences (Deterding et al. 2011). For instance, the eco-driving score calculated for certain hybrid vehicles and displayed to the driver after each journey supports adopting a driving style more suited to the vehicle type to minimise consumption. A conceptual model summarising how game elements influence motivation and behaviour is illustrated in Figure 3.1, outlining four interconnected dimensions from structured mechanics to long-term behavioural outcomes.

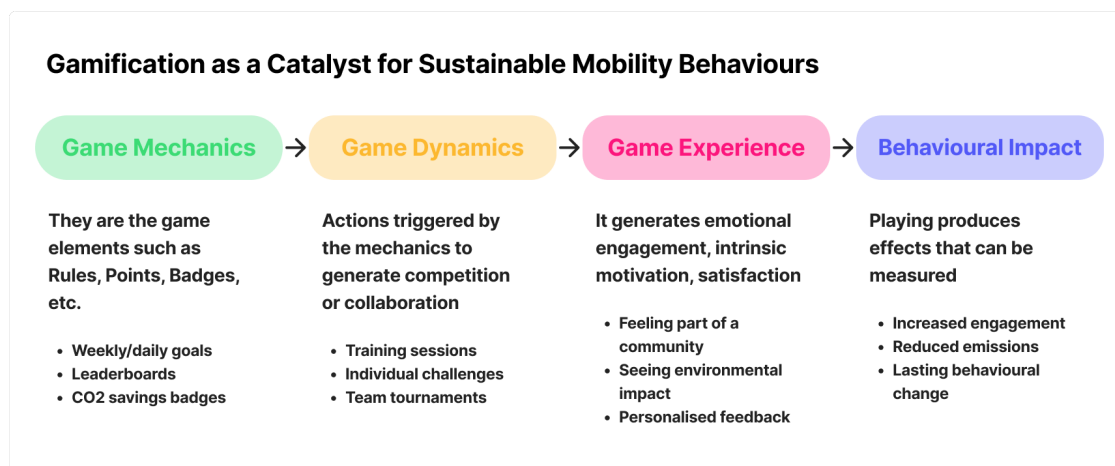


Figure 3.1: Framework illustrating the interaction between Game Mechanics, Game Dynamics, Game Experience, and Behavioural Impact in gamified systems.

These behavioural design techniques are frequently combined within mobility services to maximise effectiveness, creating comprehensive and engaging user experiences that facilitate informed mobility choices while reinforcing the role of digital services as enablers of sustainable urban transformation.

3.1.3 Game design as a tool for behavioural transformation

Game design has evolved beyond entertainment to become a strategic tool for addressing complex societal challenges, including education, sustainability, and urban mobility. By leveraging psychological principles underlying habit formation and behaviour change, games can effectively motivate users to adopt new mobility patterns.

This evolution reflects a fundamental shift from traditional gamification approaches to comprehensive game design that creates new, sustainable experiences (Schillaci, Di Dio, et al. 2022). Rather than making unsustainable behaviours more engaging through superficial mechanics, this approach redesigns interaction paradigms to make sustainable choices inherently rewarding and meaningful.

3.1.3.1 From *habit loops* to *game loops*: driving behaviour change

Games represent effective strategies for facilitating behavioural change because their underlying mechanisms share striking similarities with habit formation processes. Habits operate through a neurological cycle known as the *habit loop*, which consists of three elements: cue (stimulus triggering the habit), routine (response to cue), and reward (result reinforcing behaviour) (Duhigg 2012). Modifying habits requires targeted interventions within this cycle, such as introducing alternative cues or altering reward structure.

Similarly, games rely on a *game loop* composed of challenge, reward, and expansion. Players engage with challenges that yield rewards upon completion, often unlocking new opportunities, enabling skill development and progression. Between reward and expansion lies *anticipation*, a pivotal moment marked by dopamine release that elicits engagement and sustains participation. This cycle motivates players and mirrors the habit-forming process, making games powerful tools for promoting behavioural change.

An illustrative example is the mobile application *Zombies, Run!*, which embeds game elements into fitness routines through storytelling and immersive gameplay. Players complete missions by running or walking to escape virtual zombies and collect supplies. Each mission provides narrative progress and virtual rewards, fostering anticipation and sustaining motivation. Over time, users unlock new content and develop consistent exercise habits. A recent study confirmed the gamified narrative and reward mechanisms' effectiveness in promoting physical activity and long-term engagement (Watson et al. 2022), showing how game mechanics can transform routine behaviours, even in mobility contexts, into enjoyable and lasting habits.

Figure 3.2 illustrates the conceptual similarity between habit and game loops, highlighting their shared cyclical nature that reinforces behaviour over time. This parallel forms the foundation for game-based systems that promote sustainable mobility habits.

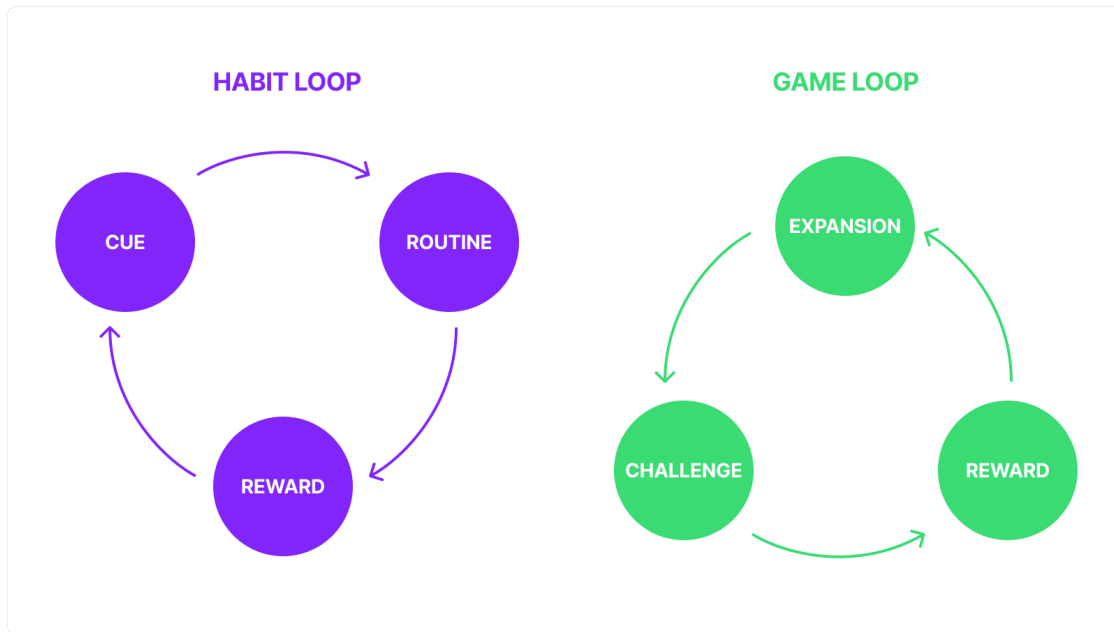


Figure 3.2: Comparison between the Habit Loop and the Game Loop, highlighting their shared structure of cue/challenge, reward, and repetition. This similarity underpins many game-based strategies for behaviour change.

3.1.3.2 Essential game elements for sustainable mobility

Effective mobility-focused games require precise design of core components to ensure clear mechanics, smooth gameplay, and optimal user experience. Academic research has extensively studied game design for behavioural change, particularly its relation to motivational psychology and habit formation.

Self-Determination Theory (SDT), one of the most prevalent contemporary social-cognitive motivational theories developed by Deci and Ryan (1985, 2000), states that intrinsic motivation is driven by three psychological needs:

- **Autonomy:** the need to feel in control of one's actions.
- **Competence:** the desire to improve and master skills.
- **Relatedness:** the need to feel connected to others.

Effective game design incorporates these principles through goal-oriented challenges (competence), decision-making freedom (autonomy), and social interactions via leaderboards and competitions (relatedness).

Yu-kai Chou's *Octalysis Framework* (2016) provides structured gamification approaches identifying eight core drives motivating human behaviour, including development and accomplishment, social influence, and empowerment of creativity. Games incorporating missions appeal to users' sense of accomplishment, while community-based competitions leverage social influence.

Essential game elements for mobility applications include:

- **Goal:** Clear, tailored, attainable objectives providing meaningful participation purpose.
- **Feedback system:** Real-time progress updates enabling users to ascertain proximity to success.
- **Increasing challenge:** Gradually increasing complexity, maintaining engagement without boredom or frustration.
- **Rewards:** Virtual or tangible incentives provide immediate gratification and reinforce desirable behaviours.
- **Social component:** Leaderboards or group challenges foster competition and collaboration while enhancing a sense of belonging and mutual motivation.

When effectively integrated, these elements create comprehensive frameworks for influencing mobility behaviour positively and enjoyably.

A notable example is *STEPN*, which exemplifies strategic game element integration for behaviour change. This web3 application rewards physical activity through GPS tracking. To play, users need to purchase virtual sneakers, earning in-game currency that can be used for upgrades or exchanged for real value. The platform combines clear goals (active lifestyle integration), robust feedback (distance, calories, tokens), progressive challenges (daily/weekly missions), tangible rewards (digital tokens), and social components (community competition). Research demonstrates the effectiveness of move-and-earn mechanisms in promoting sustained physical activity (Lee et al. 2023).

3.1.3.3 Transformational games: from awareness to action

Transformational games generate profound individual and collective changes by reshaping beliefs and values and inspiring conscious real-world action. Games can serve as persuasive media, expressing systems and shaping behaviour by embedding real-world logics into game mechanics (Bogost 2007).

Defining characteristics include purpose-oriented play transcending entertainment to address societal goals, empowerment through tools and motivation for achieving objectives, and real-world impact where in-game actions translate into tangible outcomes such as reducing carbon footprints or improving health metrics.

Pokémon GO is a widely recognised example of transformational games' scale potential. This augmented reality game encourages exploration and walking in search of virtual creatures, attracting 87.9 M monthly users at peak (with 23.7 M users playing in a single day). Research demonstrates that highly engaged players increased daily activity by 1 473 steps (25 % improvement), with systematic reviews confirming significant short-term physical activity increases across age groups (Althoff et al. 2016; Hino et al. 2019).

Similarly, *Charity Miles* illustrates the alignment between personal health and societal benefit, converting physical activity into charitable donations per kilometre covered and linking fitness efforts to broader civil causes (Mah 2016).

These examples highlight transformational games' potential to influence collective behaviours through intrinsic motivation, community collaboration, and technological innovation. Such games can catalyse reduced car dependency in urban mobility contexts, promote public transport adoption, and encourage active mobility solutions.

The power of transformational games lies in their ability to mobilise collective optimism and individual motivation toward real-world impact (McGonigal 2011). By seamlessly merging game mechanics with meaningful objectives, they transform awareness into actionable change, addressing global challenges like climate change and urban sustainability.

3.1.4 From design to deployment: scaling behavioural impact

The insights presented in this section underscore the critical importance of designing mobility services that extend beyond mere functionality, incorporating behavioural strategies to foster sustainable routines over time. By integrating psychological models, motivational principles, and game design frameworks, it is possible to engineer digital experiences that gently encourage individuals to make more responsible mobility decisions without resorting to coercion or prescriptive constraints.

However, translating these theoretical principles into real-world solutions necessitates carefully balancing behavioural effectiveness, technological feasibility, and contextual relevance. Designing for behavioural transformation entails not only identifying optimal combinations of incentives, feedback, and social mechanisms but also seamlessly embedding them within users' daily routines and digital habits.

3.1.4.1 Design principles for scalable interventions

Effective deployment of behavioural design in mobility requires adherence to several key principles. User autonomy must be preserved throughout the intervention, ensuring that sustainable choices feel empowering rather than imposed. Contextual adaptability enables interventions to respond to diverse urban environments, mobility infrastructures, and cultural contexts without losing effectiveness.

Progressive engagement gradually allows users to develop competence, moving from simple awareness-building activities to complex behavioural commitments. Social integration leverages existing community structures and peer networks to amplify individual motivation through collective action and social validation.

Measurable impact ensures that interventions generate verifiable outcomes that inform iterative improvements and demonstrate value to stakeholders across individual, organisational, and policy levels.

3.1.4.2 From theory to practice: the MUV framework

The *MUV (Mobility Urban Values)* platform (MUV Srl SB 2021) is a quintessential illustration of these theoretical principles in practice. Operating at the intersection of habit loops and game loops, MUV converts routine mobility decisions into engaging and rewarding experiences through several essential design elements:

- **Clear and meaningful objectives** through targeted training sessions and challenges corresponding to quantifiable sustainability goals.
- **Real-time feedback** on mobility activities and their environmental impact, implementing immediate reinforcement principles.
- **Progressive competition structure** maintaining interest and motivation, aligned with the SDT principles.
- **Balanced incentives** combining intrinsic rewards (personal satisfaction, environmental awareness) with extrinsic ones (badges, tangible prizes).
- **Social dimension** leveraging competitions between communities to activate social norms and collective identity.

MUV exemplifies a transformational game that transcends simple gamification to generate concrete, measurable impact on urban mobility. Rather than merely overlaying game elements onto existing behaviours, it fundamentally reimagines the urban mobility experience as a collective sporting activity, altering how people perceive and engage with daily travel choices while demonstrating how behavioural design can become a critical component supporting sustainable transformation through citizen engagement.

3.2 The MUV Game: turning sustainable mobility into a sport

Building upon the theoretical foundations of behavioural design discussed in Section 3.1, this section examines the comprehensive design, implementation, and evaluation of MUV, a novel digital platform that advances sustainable mobility through the systematic application of behavioural change principles.

MUV represents more than a technological solution; it embodies a theoretical framework that integrates sport metaphors, multi-modal gamification, and scientifically validated impact measurement to address fundamental challenges in urban mobility transformation. The platform demonstrates how abstract behavioural science principles can be operationalised into scalable, measurable interventions that achieve both individual engagement and collective environmental impact.

The analysis encompasses three interconnected dimensions:

1. **Theoretical innovations** that distinguish MUV's approach from existing mobility gamification strategies.
2. **Practical implementation** of these principles through specific design choices and technical architectures.
3. **Empirical validation** of the framework's effectiveness alongside critical assessment of limitations and scalability challenges.

The platform emerged from extensive empirical research conducted through the European MUV2020 project (2017-2020) (European Commission 2020c), funded under the Horizon 2020 programme, which engaged over 5 000 citizens across six pilot cities in co-designing and testing gamified mobility interventions. Following demonstrated effectiveness, including 32 % average reductions in participants' carbon footprints, the approach was transitioned to commercial application through MUV Srl SB, established in 2020 as an academic spinoff of the University of Palermo. The technological evolution involved comprehensive re-design to enhance gaming experiences and refine tracking algorithms following established gamification design frameworks (Morschheuser et al. 2018).

A distinctive methodological feature is MUV's integration of rigorous scientific measurement with practical market deployment. The platform's CO₂ emission reduction methodology has been validated by RINA in accordance with ISO 14064-2 standards, ensuring that environmental impact claims meet international scientific standards while supporting commercial sustainability goals (International Organization for Standardization 2019).

Figure 3.3 illustrates MUV's visual identity, which reflects the platform's core values of participation, dynamism, and playfulness within a coherent sporting metaphor.



Figure 3.3: Logo of *MUV Srl SB* in a double version. The brand is a registered trademark.

3.2.1 Theoretical foundations and design innovations

MUV represents an original synthesis of behavioural change theory, game design, and sustainable mobility intervention that advances beyond traditional gamification approaches through three key theoretical contributions.

3.2.1.1 Sport-as-metaphor framework for behavioural transformation

The primary theoretical innovation lies in the systematic application of sport as a metaphor for sustainable mobility transformation. Unlike conventional gamification that overlays game elements onto existing activities, this approach fundamentally reframes the entire mobility experience within a coherent athletic paradigm (Schillaci, Di Dio, et al. 2024).

This framework addresses a critical gap in mobility behavioural interventions: the need to transform routine, often unconscious travel decisions into conscious, motivated choices. Sport provides an ideal metaphor because it naturally integrates the three psychological needs identified in Self-Determination Theory—autonomy (choice in training methods), competence (progressive skill development), and relatedness (team membership and competition)—as established in Section 3.1.2.

The sport-as-metaphor approach operationalises through narrative transformation where individual trips become "training sessions," modal choices represent different "athletic disciplines," communities form "teams" with shared performance goals, and environmental impact becomes measurable "athletic achievement." This conceptual reframing activates intrinsic motivational drivers that research demonstrates are more sustainable than extrinsic incentives alone (Deci and Ryan 2000). By positioning sustainable mobility as athletic participation rather than environmental obligation, the framework reduces psychological resistance while enhancing engagement durability, addressing fundamental challenges in long-term behavioural change (Verplanken and Wood 2006).

3.2.1.2 Multi-modal gamification architecture

The second theoretical contribution involves the development of a comprehensive gamification architecture that accommodates diverse transport modes within a unified competitive framework. Existing mobility gamification approaches typically focus on single modes or generic categories that fail to reflect the complexity of urban mobility ecosystems.

MUV's architecture advances behavioural intervention theory through three innovations:

- **Hierarchical point systems** that reflect actual environmental impact rather than arbitrary game mechanics. The scoring algorithm incorporates mode-specific sustainability coefficients validated against ISO 14064-2 standards, ensuring game rewards align with genuine ecological benefits rather than engagement metrics alone.
- **Progressive competition structures** that systematically build from individual habit formation through peer competition to complex team dynamics. This progression

mirrors established models of behavioural change that emphasise gradual skill-building and social integration.

- **Contextual multiplier systems** that reward behaviours facing higher barriers or generating greater impact. This approach operationalises behavioural economics insights about loss aversion and effort justification (Kahneman 2011). Additionally, it implements variable ratio reinforcement schedules that research demonstrates maintain long-term engagement (Hamari et al. 2014).

3.2.1.3 Integrated measurement and feedback systems

The third theoretical contribution addresses the challenge of connecting individual behavioural change to collective environmental impact through scientifically validated measurement frameworks. Traditional mobility interventions struggle to demonstrate causality between individual actions and systemic outcomes, limiting their policy relevance and user motivation.

MUV's integrated approach advances measurement theory through personalised baseline establishment that accounts for individual mobility patterns rather than applying generic assumptions, enabling accurate attribution of behavioural change to specific interventions while maintaining privacy through anonymisation and aggregation.

Real-time feedback loops close the gap between action and outcome awareness, providing immediate point feedback, weekly impact summaries, and long-term trend analysis. This implements principles from habit formation research about the importance of proximate reinforcement (Duhigg 2012).

Multi-level impact aggregation demonstrates how individual choices contribute to organisational and urban sustainability goals, addressing collective action problems in environmental behaviour by making personal contributions visible within larger impact narratives.

3.2.1.4 Empirical validation methodology

The theoretical framework was developed through iterative innovation methodology combining user co-design, behavioural testing, and impact measurement across diverse European urban contexts (Vesco et al. 2020). The development process integrated multiple theories of change through extensive stakeholder engagement, enabling accommodation of diverse mobility contexts while ensuring robust intervention design (Barroca et al. 2023).

Empirical validation with over 5 000 European citizens demonstrated framework effectiveness: 32 % average carbon footprint reduction, 260 000 sustainable kilometres tracked, and sustained engagement exceeding mobile application benchmarks.

This empirical foundation successfully transitioned from research prototype to commercial implementation through MUV Srl SB, established in 2020 to transform theoretical principles into market-viable solutions through sustainable business models targeting organisational clients.

3.2.2 Implementing the sport-as-metaphor framework

The sport-as-metaphor framework outlined in Section 3.2.1.1 requires systematic translation from theoretical principles into concrete user experiences. This section examines how the sporting paradigm is implemented through specific design choices that create authentic athletic engagement with sustainable mobility.

3.2.2.1 Narrative transformation and user identity

The theoretical foundation draws from narrative psychology research demonstrating that metaphorical reframing can fundamentally alter behavioural engagement (Lakoff and Johnson 1980). Unlike surface-level gamification that adds competitive elements to existing activities, the sport-as-metaphor creates complete identity transformation where users adopt athletic personas in mobility contexts.

The implementation transforms routine mobility into measurable athletic performance through systematic reframing of travel activities. Individual sustainable trips become recorded performances with quantifiable metrics (distance, duration, environmental impact), creating personal athletic profiles that demonstrate progression over time. The system implements a sustainability hierarchy where active mobility (walking, cycling) earns the highest performance scores, followed by public transport, electric vehicles, and shared modes, mirroring athletic scoring systems that reward higher skill levels.

For example, a commuter cycling to work might earn points for choosing an active transport mode, receive bonus multipliers for travelling during adverse weather conditions, and contribute to their team's position in an ongoing tournament—all within a single journey, creating tangible athletic experiences with immediate feedback and social recognition.

Performance recognition operates through multiple achievement dimensions that accommodate diverse motivational orientations identified in achievement goal theory (Hulleman et al. 2020). The system provides mastery-oriented pathways through individual personal records (longest distance, most consistent performance), performance-oriented recognition through comparative achievements (ranking among peers), and cooperative recognition through collective contributions (team performance enhancement). This multi-dimensional approach ensures that users with different achievement orientations find appropriate motivational support within the sporting framework.

3.2.2.2 Progressive engagement architecture

The sporting metaphor is implemented through progressive competition structures that accommodate varying athletic commitment and capability levels. Rather than prescriptive phases, the system offers flexible pathways that enable users to engage at their preferred competitive intensity. Users can progress through three types of competitions:

- **Individual training sessions:** Personal challenges focused on skill-building and habit formation, similar to athletic training regimens. These competitions emphasise

self-improvement and competence development without requiring social comparison.

- **Peer-based challenges:** Direct competitive or collaborative engagement with similar-level participants, mirroring local sports events. These competitions activate social motivation while maintaining accessible entry requirements and low complexity.
- **Team-based tournaments:** Complex competitions featuring strategic coordination, extended timelines, and sophisticated scoring systems. They replicate professional sports with elimination rounds, strategic team composition, and collective recognition.

The progressive architecture enables natural advancement based on user preference and capability rather than mandatory progression, maintaining autonomy while providing clear pathways for increased engagement. Figure 3.4 illustrates this architecture.



Figure 3.4: Visual representation of MUV's game dynamics structured as a progressive ladder. Training sessions build individual habits, challenges introduce peer-based competition or collaboration, and tournaments culminate in structured team-based gameplay.

3.2.2.3 Motivational integration across psychological needs

The sport-as-metaphor implementation activates both intrinsic motivations (enjoyment, physical well-being benefits, satisfaction from skill mastery) and extrinsic motivations (social recognition, competitive achievement, team belonging) through systematic integration of the three core needs of SDT:

- **Autonomy support:** Users maintain complete control over participation timing, intensity, and competitive involvement. The voluntary tracking system requires deliberate activation, ensuring that sustainable choices feel self-directed rather than externally mandated. Competition registration operates on opt-in basis, preserving user agency while creating opportunities for deeper engagement.
- **Competence development:** The progressive architecture enables users to develop mastery through increasing challenge complexity. Training sessions provide immediate feedback on skill development, while competitions offer opportunities to demonstrate competence against meaningful standards. The point system reflects genuine achievement in sustainable mobility adoption rather than arbitrary game mechanics.
- **Relatedness cultivation:** Team structures, social leaderboards, and collaborative challenges create multiple pathways for social connection. The platform leverages existing community structures (workplaces, educational institutions) while providing mechanisms for organic relationship formation through shared sustainable mobility goals.

3.2.2.4 Cultural adaptation and universal appeal

The sport metaphor's effectiveness across different cultural contexts requires careful consideration of varying sporting traditions and motivational preferences. Preliminary evidence from implementations in Italy, Luxembourg, and other European countries suggests potential adaptability, though systematic cross-cultural validation remains an area for future research.

The framework incorporates design elements that may accommodate cultural variation, including flexible competition formats that emphasise individual achievement or collective success depending on cultural preferences, rewarding systems that reflect diverse cultural values around public acknowledgement versus private accomplishment, and messaging approaches adaptable to different cultural communication styles.

However, the universal applicability of sport-as-metaphor requires validation across broader cultural contexts beyond European implementations.

3.2.2.5 Integration with existing mobility infrastructure

The framework operates as a motivational enhancement layer that complements rather than replaces existing mobility infrastructure. The platform functions independently of available transport options while increasing the utilisation of sustainable alternatives through enhanced motivation.

What distinguishes this framework from conventional gamified mobility platforms is its integration of behavioural intervention with policy-relevant data generation. The mobility data collected through the application serves multiple purposes beyond individual gameplay: it reinforces intrinsic motivations by visualising personal progress, enables organisations to develop evidence-based mobility management plans, and provides valuable insights for urban mobility policies and *Sustainable Urban Mobility Plans* (SUMP) (European Commission 2019a).

This dual approach—combining bottom-up behavioural change with top-down policy formulation—establishes a reinforcing loop in which individual actions inform systemic improvements, promoting more sustainable behaviours. The framework thus transcends individual behavioural change to become an instrument for evidence-based urban planning, where citizen engagement generates data that informs infrastructure investment, policy development, and mobility service design.

The sport-as-metaphor demonstrates broad applicability across diverse transport modes—from public transit systems to active mobility infrastructure—without requiring specific technological integration or infrastructure modification. This infrastructure-agnostic approach ensures broad applicability while maintaining focus on behavioural transformation rather than technological dependency.

By positioning sustainable mobility as athletic participation rather than environmental obligation, the implementation reduces psychological resistance while enhancing intrinsic motivation for continued engagement beyond formal competition periods. The resulting data ecosystem supports individual behaviour change and collective planning processes, simultaneously creating value for users, organisations, and urban policymakers.

These theoretical implementation principles are translated through specific game mechanics and dynamics, described in detail in the following section, before empirical validation in Chapter 4.

3.2.3 Game mechanics and dynamics

The MUV sports paradigm is conceptualised through a thoroughly crafted game mechanics and dynamics system that embodies behavioural change principles. According to the *MDA* (Mechanics, Dynamics, and Aesthetics) framework (Hunicke et al. 2004), game mechanics define fundamental rules and systems structuring player interaction, while dynamics emerge from how these mechanics are experienced through play.

MUV employs a straightforward yet effective mechanic at its operational core: participants track sustainable travel via the mobile application and earn points based on mobility choices. Points awarded depend on journey length and transport mode, following a sustainability hierarchy that explicitly rewards the most environmentally beneficial options. Soft mobility (walking, cycling) receives the highest scores, followed by collective transport, electric vehicles, and shared modes.

This system requires deliberate user action to initiate and conclude trip tracking, fostering *voluntary participation*—a fundamental principle of sustainable behavioural change. MUV’s tracking system promotes multimodality, allowing users to switch between transport modes within trips while maintaining privacy control through selective tracking activation. By empowering users to determine participation timing and intensity, MUV strengthens intrinsic motivation and ensures authentic, sustained engagement.

Accumulated points become the foundation for MUV’s three game dynamics: training sessions, challenges, and tournaments. These competitions accommodate both open participation and community-specific implementations, designed to provide diverse engagement experiences that address varying motivational preferences and competitive orientations.

3.2.3.1 Training sessions

Training sessions form the foundational layer of MUV’s game dynamics, directly targeting the competence need identified in SDT. Unlike other competition modes, these sessions emphasise personal improvement rather than social comparison, fostering the intrinsic motivation crucial for long-term behavioural change (Ryan and Deci 2007). By challenging users to measure themselves against their own previous performance, training sessions create the psychological conditions for habit formation—a process that requires consistent repetition and progressive skill mastering.

These sessions consist of structured missions with increasing difficulty levels that mirror athletic training programs, ranging from basic onboarding tasks to advanced engagement challenges. Each completed mission earns virtual rewards in the form of badges, providing immediate positive reinforcement and a visible record of achievement.

MUV’s training architecture includes two complementary categories: *one-time activities* and *recurring missions*. One-time activities serve as an onboarding mechanism, familiarising users with the system’s features while encouraging exploration of sustainable mobility options. These missions are organised into six main categories, each targeting specific aspects of user engagement and platform adoption.

Table 3.2 provides an overview of these categories, their objectives, and representative mission examples.

Table 3.2: One-time training sessions in MUV, organised by category and objective.

Category	Objective	Mission Examples
Onboarding	Initial platform familiarisation	Register your first trip
Mobility exploration	Test diverse transport modes	Walking, cycling, public transport, electric vehicles, carpooling, multimodal trips
Temporal engagement	Encourage time-varied usage	Morning, afternoon, evening, night, weekend trips
Profile customisation	Enhance personalisation and data quality	Complete profile, add frequent trip, set up garage, verify email, update avatar
Social interaction	Foster user engagement and network expansion	Add friend, invite friend, send feedback, rate MUV on app store
Game discovery	Introduce competitive dynamics	Get first badge, win reward, sign up for challenge/tournament

Recurring activities implement progressive achievement system that guides users toward increasingly ambitious goals across multiple domains. These missions employ a bronze-silver-gold progression structure, with thresholds designed to maintain long-term engagement while building competence in different aspects of sustainable mobility.

Table 3.3 categorises these recurring missions by their primary focus areas and underlying behavioural objectives.

Table 3.3: Recurring training sessions in MUV, organised by category and objective.

Category	Objective	Mission Examples
Trip activity	Foster consistent sustainable travel	Total trips, consecutive tracking days, frequent trip usage
Point achievement	Promote long-term participation	Accumulate total points, maintain weekly point targets
Distance & health	Highlight physical activity benefits	Track total kilometres, achieve daily step goals, monitor calories expended
Environmental impact	Demonstrate sustainability outcomes	Calculate CO ₂ savings, measure emission reductions
Competition engagement	Encourage competitive participation	Join challenges and tournaments, achieve best player recognition

Complete technical specifications for all training sessions, including detailed progression thresholds and specific parameters, are provided in Appendix A.2.

By enabling users to surpass their own limits and achieve ever-new goals, the training sessions establish the psychological conditions for long-term habit formation.

3.2.3.2 Challenges

While training sessions focus on self-improvement, challenges expand the motivational framework by introducing social dimensions, addressing the relatedness component of SDT. These structured competitions activate social mechanisms, including peer influence, normative comparison, and community identification, that have been shown to significantly impact behavioural decisions (Cialdini et al. 1990).

MUV challenges fall into two categories: *competitive challenges* that tap into rivalry and performance comparison, and *collaborative challenges* that harness group cohesion and collective purpose. Both formats typically run for four weeks, although this duration can be customised for specific events or organisational needs.

Challenges gain their versatility by applying specific criteria that define participation parameters. These criteria create focused experiences around particular mobility modes, trip types, geographic areas, or time periods. Combining these four criteria in different configurations allows MUV to generate diverse experiences that keep engagement fresh while targeting specific mobility behaviours or contexts. Table 3.4 summarises the criteria used to define challenges.

Table 3.4: Criteria used to define MUV challenges, including mobility options, trip types, geographic areas, and time ranges.

Criteria	Description	Examples
Mobility options allowed	Only trips travelled by specific mobility modes are valid	Walking and cycling trips, Only public transportation trips
Trip type	Only trips with specific origins and/or destinations are valid	Home-to-work trips, Trips to an event venue
Geographic area	Only trips travelled within a given geographic boundary are valid	Trips within Italy, Trips in the Palermo area
Time range	Only trips within one or more specific time intervals are valid	Trips during specific events, Trips on weekends

Competitive challenges create individual rivalry through leaderboard rankings, rewarding top performers. Collaborative challenges emphasise collective achievement through bronze-silver-gold thresholds, where participants work toward shared goals with rewards based on community contribution levels.

Both formats offer tangible individual rewards (gift cards, vouchers) through drawings among top performers. At the same time, collaborative challenges may include collective community awards, such as charitable donations upon reaching the highest threshold.

3.2.3.3 Team tournaments

Team tournaments represent MUV's most sophisticated game dynamic, synthesising competitive and collaborative elements to address all three psychological needs in SDT. The core innovation lies in the balanced scoring mechanism: team performance combines designated "best players" scores with the mean contribution of all members, ensuring every participant's effort matters while recognising exceptional performances. The number of these best players is dynamically adjusted according to the size of the teams in a tournament, ensuring fair competition between groups of different composition.

This scoring approach serves multiple psychological functions: it maintains high motivation across all skill levels, prevents disengagement among less active participants, and creates a sense of collective responsibility without eliminating the recognition of exceptional individual achievement. These principles directly apply insights from organisational psychology about balancing individual recognition with team cohesion (Tjosvold et al. 2004).

These events bring together diverse groups, enabling competitions between cities, universities, corporations, or smaller organisational units. Tournaments typically span six to twelve weeks and comprise three distinct phases that can be combined optimally for each scenario:

- **Preliminary or ranking phase:** Teams are divided into divisions and compete on a

leaderboard updated weekly based on accumulated points. The highest-performing teams progress to the subsequent phase.

- **Intermediate or group phase:** Teams are divided into groups and compete against teams from the same group in weekly one-on-one matches. The teams with the most wins in the round advance to the final phase.
- **Final or playoff phase:** Teams are placed on a knockout board, engaging in weekly matches, with winners advancing until the final champion is crowned.

Table 3.5 summarises the characteristics of these phases.

Table 3.5: Tournament phases in MUV, including duration, competition type, mechanics, and team involvement.

Phase	Duration	Competition type	How it works	Teams involved
Ranking	1 to 3 weeks	Leaderboard	Teams are split into divisions; the highest-scoring teams in each division advance	8 to 1 024
Group	3 to 5 weeks	Weekly one-on-one matches	Teams compete within groups; the teams with the most wins in each round advance	4 to 192
Playoff	2 to 4 weeks	Weekly one-on-one knockout matches	Teams progress through a knockout board, with the final match deciding the champion	4 to 32

A tournament should ideally comprise three phases, progressing from the preliminary through the intermediate phase to the final. However, to ensure flexibility and suitability for diverse contexts, competitions based on one or more phases can be defined (e.g., combining group and playoff phases or providing only a preliminary phase with free ranking).

This structure ensures that tournaments are inclusive and engaging for teams of varying sizes and skill levels. Additionally, the ability to customise phases enables organisers to tailor the tournament to specific contexts, such as duration, number of participants, or competitive intensity. This flexibility not only keeps tournaments dynamic but also fosters sustained team participation and enthusiasm across diverse scenarios.

Tournaments incorporate tangible rewards for the best players. Two types of rewards are provided: those drawn among all the best players of the participating teams and those reserved exclusively for the best players of the winning team. Moreover, collective rewards are allocated to the winning team, as in collaborative challenges.

This comprehensive system of game dynamics of MUV creates a progressive engagement pathway that emulates the experience of athletes. Users typically begin with basic training

sessions to build foundational habits, advance to challenges that introduce social dimensions, and ultimately participate in tournaments that offer the richest and most complex experience. This structured progression systematically develops both individual competencies and social connections combining intrinsic and extrinsic motivational drivers.

Table 3.6 provides a comparative overview of MUV's game dynamics, highlighting how each type creates different engagement patterns through varied forms of interaction, participation structures, motivational drivers, and reward systems.

Table 3.6: MUV game dynamics with their interaction types, participation modes, motivational drivers, and rewards.

Dynamic	Interaction	Participation	Motivation	Reward
Training sessions	Competitive	Individual-level	Intrinsic (self-improvement)	Virtual, individual (badges)
Competitive challenges	Competitive	Peer-to-peer	Extrinsic (outperforming other players)	Real, individual (gift cards, vouchers)
Collaborative challenges	Collaborative	Community-level	Mixed (community impact and recognition)	Real, community (donations) Real, individual (gift cards, vouchers)
Team tournaments	Competitive/ Collaborative	Team-based	Mixed (team collaboration and rewards)	Real, winning team (donations) Real, best players (gift cards, vouchers) Virtual, best players (victory badges)

By integrating these diverse dynamics, MUV creates a compelling and varied gaming experience, motivating users to adopt sustainable mobility behaviours while fostering community engagement, commitment, and personal awareness.

Furthermore, in contrast to other mobility gamification platforms such as *Strava* (Strava 2024) or *Ciclogreen* (Ciclogreen 2024), MUV incorporates multiple transport modes and directly aligns with institutional planning requirements. Whilst platforms like Strava predominantly focus on cycling and running, MUV's multimodal approach favours a more extensive impact on urban mobility patterns.

3.2.4 Complementary engagement mechanisms

While the core game dynamics described in the preceding section form the structural backbone of MUV, the effectiveness of any gamified system depends on complementary elements that maintain player engagement and reinforce desired behaviours. Drawing on principles from both behavioural psychology and game design, MUV integrates a series of additional game elements that work synergistically with the main dynamics to create a comprehensive motivational framework.

These elements serve specific psychological functions: incentives establish clear value associations, bonuses provide variable rewards that increase engagement, leaderboards activate social comparison mechanisms, feedback systems close the action-outcome loop, and social interaction features leverage the power of community norms.

Table 3.7 summarises these elements, highlighting their behavioural purpose and specific implementation within MUV.

Table 3.7: Additional game elements in MUV, categorised by purpose and implementation.

Category	Purpose	Implementation in MUV
Incentives	Motivate players and maintain active participation	Badges, Gift cards, Donations
Bonuses	Rewards additional efforts and virtuous choices under specific conditions	Score multipliers, Steps, Quizzes
Feedback	Provide real-time updates to inform decisions	Push notifications, Feed notifications
Social interaction	Foster collaboration, competition and community engagement	Weekly leaderboards, Friends, Invitations

3.2.4.1 Incentives and reward structure

MUV employs a multi-layered incentive system combining virtual and tangible rewards to sustain player motivation. Empirical studies confirm that these reward systems can significantly enhance engagement and behavioural outcomes in gamified contexts (Hamari et al. 2014).

Virtual badges highlight achievements and competition participation, offering players a sense of accomplishment and competence that satisfies psychological needs for mastery. These rewards serve primarily as progress markers and skill development indicators, implementing positive reinforcement principles discussed in Section 3.1.2.2.

Tangible rewards, such as gift cards or vouchers, are awarded to the most active participants in challenges and tournaments. These incentives, predominantly themed around sports, sustainability, and culture, are provided by companies aligned with MUV’s values, creating a value-congruent reinforcement system that extends beyond the platform itself.

3.2.4.2 Dynamic bonuses and personalisation

Bonuses function as a dynamic reward mechanism that amplifies the basic point system, creating additional motivation through variability in timing and magnitude. They operate via two channels: direct multipliers applied to trips and indirect bonuses earned through supplementary activities. MUV's scoring framework defines five direct multiplier categories that incentivise behaviours facing higher barriers or generating greater impact: weather-based incentives for travelling in adverse conditions, peak-hour bonuses during congested periods, frequency multipliers for consistent app usage, routine trip recognition for regular commuting patterns, and altitude adjustments for physically demanding active mobility. Full technical specifications for all multiplier categories are detailed in Appendix A.4.2.

A particularly significant component is the multiplier for frequent journeys. Users can add regular trips, such as home-to-work or home-to-school, which the system automatically recognises and rewards. This feature enables targeted competitions based on recurring travel and offers consistent incentives that foster conscious mobility habits, directly supporting the habit formation principles discussed in Section 3.1.3.1.

Beyond trip-based multipliers, MUV incorporates supplementary indirect bonus mechanisms, including step-counting integration with mobile health platforms (*Google Health Connect* for Android, *Apple HealthKit* for iOS) and interactive quiz features that provide learning-oriented bonus opportunities. Both incentives translate into extra points, creating additional elements that reinforce daily app use. This integrated architecture aligns with personalisation principles, enhancing user knowledge and context adaptation while supporting behavioural and cognitive engagement (Lameras et al. 2017).

3.2.4.3 Feedback systems and reinforcement loops

Effective feedback systems are essential for learning and habit formation, closing the loop between action and outcome in the behavioural change framework. MUV's feedback system provides real-time updates and progress tracking to keep users informed, operating through two main components: push notifications and feed cards.

Push notifications function as reminders and game updates, serving as the "cue" element in the habit loop model. They prompt users to engage with sustainable mobility while providing timely updates on competition results, achievements, and system interactions. Users can also set personalised reminders to activate tracking at specific times, creating customised cues that can be integrated into their daily routines.

Feed cards offer immediate acknowledgement of progress and accomplishments, implementing positive reinforcement principles while maintaining user awareness of ongoing activities and opportunities. Displayed on the home screen for easy access, they enable direct navigation to relevant app sections with a single click.

This integrated feedback approach enhances user participation and fosters proactive, sustainable mobility engagement, making gameplay more satisfying while directly engaging relevant psychological needs for competence and progress recognition.

3.2.4.4 Social features and community engagement

The social dimension of behaviour change is central to MUV's effectiveness, particularly regarding the impact of social norms and peer influence on individual choices. MUV promotes collaborative play and community engagement through features that create meaningful social connections between users, primarily targeting pre-organised communities where recognition and belonging already exist.

Weekly leaderboards activate the power of social comparison—a fundamental psychological mechanism that drives behavioural change through peer influence and normative pressure, fostering competition among all users by ranking them based on their points.

The friendship feature enables personal connections and friendly competition at more intimate scales. The invitation system encourages users to share competitions and introduce new participants, leveraging social diffusion principles where behaviour change spreads through peer networks and social influence.

These social mechanisms activate the relatedness need in SDT and establish accountability structures that sustain engagement beyond individual motivation. By focusing on existing communities, the service builds on established social bonds, promoting behaviours that are visible and valued within peer groups (Cialdini et al. 1990).

Combining these complementary elements with core game dynamics, MUV creates a holistic behavioural intervention system that targets multiple psychological drivers simultaneously. This integrated approach boosts individual motivation, reinforces community ties, and connects personal actions to collective impact, which is key to addressing the complex social and environmental challenges of urban mobility.

3.2.5 Insights from data: measuring MUV success

The data-driven nature of MUV represents a critical bridge between theoretical behavioural principles and practical implementation. By systematically collecting, analysing, and applying user data, MUV transforms abstract behavioural science concepts into measurable outcomes and actionable insights. This evidence-based approach validates the efficacy of gamification strategies while enabling continuous system refinement through feedback loops that connect user behaviour to design decisions.

3.2.5.1 Data collection and analysis framework

MUV's data ecosystem serves three fundamental purposes: understanding community mobility patterns for targeted interventions, measuring environmental and health impacts of behavioural changes, and evaluating user engagement across different game dynamics to optimise motivational frameworks.

The platform collects data across five interconnected categories:

- **Registration and personal data:** Essential account information (name, email, username) with optional demographic data (age, gender, height, weight) to enable per-

sonalised experiences and accurate impact calculations while adhering to GDPR data minimisation principles.

- **Mobility data:** User-declared baseline habits (typical travel patterns, frequent trips, available vehicles) combined with real-time tracked sustainable travel activity, enabling precise calculation of behavioural change and CO₂ savings through comparative analysis.
- **Game data:** Metrics of interaction with game elements, including points accumulation, competition participation, training session progress, social connections, achievements, and interaction patterns that reveal which motivational mechanisms generate the strongest engagement across different user segments.
- **Impact data:** Environmental and health outcomes translated from behavioural activity through four key metrics—CO₂ saved using ISO 14064-2 certified methodology, modal shift percentages, calories expended, and daily steps synced with mobile health platforms.

Table 3.8 provides an overview of the key data elements collected within the MUV ecosystem, illustrating the essential components that enable both gamification functionality and impact measurement while maintaining strict privacy compliance and user control.

Table 3.8: Overview of key data elements collected by MUV, categorised by type and operational purpose.

Category	Key Elements	Type	Source	Primary Purpose
Registration data	Email, Username, User ID	Mandatory	User/System	Account creation and identification
Personal data	Name, Demographics (optional)	Mixed	User	Personalisation and compliance
Mobility data	Tracked trips, Modal split, Baseline habits	Mixed	User/Computed	Behavioural analysis and CO ₂ calculation
Game data	Points, Competition participation, Social connections	Computed	System	Engagement tracking and motivation
Impact data	CO ₂ savings, Modal shift, Health metrics	Computed	System	Environmental and health impact measurement

A thorough technical inventory of all data elements is provided in Appendix A.1 for implementation reference and privacy compliance assessment.

3.2.5.2 Key performance indicators and outcomes

Empirical evidence demonstrates MUV's effectiveness across both engagement and impact dimensions. From an engagement perspective, the platform achieved a *Daily Active Users to Monthly Active Users (DAU/MAU)* ratio of 14.9 % over the 2022–2024 period, substantially exceeding the 10 % threshold widely recognised in mobile application analytics as indicative of strong user retention (A. Chen 2015). The presence of active competitions correlated with a 41.84 % increase in user participation, confirming the effectiveness of game dynamics.

From an impact perspective, MUV users demonstrated an average 33.82 % reduction in CO₂ emissions based on comparisons between initial mobility baselines and subsequent modal shifts. These outcomes are particularly notable compared to traditional urban interventions such as *Low Emission Zones (LEZs)* and *Limited Traffic Zones (LTZs)*. For instance, Milan's expansion of Area B and Area C delivered significant results through regulatory means, reducing high-emission vehicles and avoiding over 150 t of NO_x between 2022 and 2023 (AMAT 2023). Similarly, London's *Ultra Low Emission Zone (ULEZ)* extension in 2023 produced measurable air quality improvements (Greater London Authority 2025).

While these regulatory approaches operate through access restrictions and penalties, MUV's approach generates multidimensional value beyond emission reductions: enhancing user agency by transforming sustainable choices into rewarding experiences, fostering positive associations with mobility behaviours, and building communities through shared objectives.

These comparative advantages suggest that gamified, incentive-based approaches can serve as valuable complements to traditional urban policies, particularly in contexts where regulatory approaches face political or practical implementation challenges.

3.2.5.3 Data-enabled applications

The data collected through MUV generates value across multiple contexts, from individual user experiences to urban planning decisions. The applications of this data ecosystem extend in two key directions.

Internal service optimisation enables continuous evolution by monitoring feature effectiveness and identifying engagement barriers. At the same time, external policy support provides evidence-based input for institutional mobility planning, supporting the development of corporate mobility management plans and informing municipal Sustainable Urban Mobility Plans (SUMP) through granular insights that reveal actual mobility patterns and behavioural responses to incentives.

This bidirectional value creation creates a virtuous cycle where better data leads to improved experiences, which generate more robust data. By connecting individual mobility choices to collective outcomes through data collection and analysis, MUV bridges the gap between theoretical behavioural principles and practical urban transformation.

3.2.6 The B2B model: ensuring scalability and sustainability

The behavioural and data-driven approaches described in previous sections are operationalised through a business model designed to ensure both economic sustainability and scalable impact. Unlike many gamified applications that rely on direct-to-consumer monetisation strategies, MUV adopts a *business-to-business (B2B)* approach, targeting organisations such as companies, universities, and public administrations interested in implementing sustainable mobility initiatives at scale.

Through subscription, clients acquire a licence that enables the creation of a dedicated community within the mobile application where their employees, students, or citizens can participate in customised mobility challenges and tournaments. Beyond access to the gamification platform, clients receive valuable analytical capabilities through real-time web dashboards, detailed sustainability reports, anonymised mobility datasets, and support for developing mobility management plans.

The value proposition resonates across diverse client segments through its unique combination of engagement and data-driven insights. For private companies, MUV offers a non-coercive approach to reducing corporate carbon footprints while generating employee wellbeing benefits. For educational institutions, it provides both sustainability advancements and valuable research opportunities. For municipalities, the platform offers citizen engagement in urban mobility policies through positive incentives rather than restrictions.

The timing of this approach is particularly significant given evolving regulatory frameworks concerning sustainability reporting. The European Commission's *Corporate Sustainability Reporting Directive (CSRD)*, effective January 2024 (European Commission 2023b), requires large companies and listed SMEs to produce standardised reports detailing their environmental, social, and governance impacts. Within this context, employee mobility emissions fall under "Scope 3 emissions"—greenhouse gases arising from an organisation's value chain but outside its direct operational control.

These Scope 3 emissions typically constitute the majority of a company's total carbon footprint, yet are notoriously challenging to quantify and mitigate due to their distributed nature across workforces, customers, and suppliers. By providing the behavioural tools to reduce these emissions and the analytical capabilities to measure them accurately, MUV addresses a critical gap in corporate sustainability strategies.

The B2B model thus creates a self-reinforcing mechanism between behavioural change and institutional commitment: organisations subscribe to MUV to meet regulatory requirements and sustainability goals, building communities of users engaged in gamified sustainability activities, generating measurable environmental impacts and rich mobility datasets that further inform organisational strategies. This cycle demonstrates how the theoretical principles of gamification and behavioural design discussed throughout this chapter can be successfully translated into sustainable business models that scale beyond individual interventions.

3.3 The MUV platform: technology and design

While the previous sections have explored the theoretical underpinnings of behavioural change and the gamification elements that drive MUV's approach to sustainable mobility, this section examines the technological architecture that transforms these concepts into a scalable, effective digital service.

The technological infrastructure comprises three interconnected components: a sophisticated backend infrastructure, a user-facing mobile application, and an analytics web dashboard. Each element plays a distinct role in the behavioural transformation process. The backend ensures system integrity through trip validation algorithms and scientifically certified impact measurement. The mobile application translates theoretical principles into engaging user experiences that motivate sustainable choices. The dashboard links individual actions and collective outcomes, providing evidence-based insights for organisational and urban planning decisions.

Initially developed during the Horizon 2020 research project, the MUV platform has progressively evolved to meet commercial goals and incorporate advances in cloud computing, geospatial analysis, and mobile technologies. This evolution has been driven by the principle that every technological choice must underpin psychological mechanisms critical to sustainable behaviour change. As described in Section 3.3.1, real-time validation algorithms implement positive reinforcement by delivering immediate feedback on sustainable travel. Likewise, the progressive disclosure interface (Section 3.3.2) minimises cognitive load while preserving user autonomy, both essential to sustained behavioural engagement.

All technology underpinning MUV has been developed internally, representing the research and commercial endeavour's primary intellectual asset and competitive advantage. The following subsections provide an in-depth analysis of the platform's three core components, highlighting how design principles, technical implementations, and behavioural objectives align to create a comprehensive system for sustainable mobility transformation.

3.3.1 Backend architecture and algorithms: the infrastructure foundations

MUV's backend infrastructure serves as the technological foundation that enables the behavioural change strategies outlined in Sections 3.1 and 3.2, addressing three fundamental challenges in large-scale gamified mobility interventions:

1. **Ensuring scalable performance** across diverse user populations.
2. **Validating sustainable travel** without invasive monitoring.
3. **Translating behavioural data** into credible environmental impact measurements.

The design prioritises behavioural effectiveness over technical complexity, implementing features that directly support SDT's psychological mechanisms. Real-time feedback system

reinforces sustainable choices, privacy-preserving validation maintains user autonomy, and flexible data processing personalises the experience to users' mobility habits and motivations.

Three core innovations set MUV apart from traditional mobility tracking platforms. First, the adaptive validation framework authenticates trips across multiple modes while maintaining transparency and user trust. Second, the point calculation system is aligned with verified environmental outcomes rather than generic engagement. Third, the ISO 14064-2 certified CO₂ methodology enables robust impact attribution at both individual and community levels.

The architecture balances real-time processing capabilities, crucial for behavioural reinforcement, with the precision required for scientific measurement and policy relevance. This dual requirement shapes all design decisions, from cloud-native microservices to validation algorithms adaptable across urban contexts.

Built as a layered system, the platform combines scalable infrastructure, behaviour-aligned algorithms, and interoperable APIs, forming a cohesive and robust technical foundation. The following sections detail each component, beginning with cloud infrastructure and progressing to the algorithms that form the computational core of MUV's behavioural change strategy.

3.3.1.1 Infrastructure and scalability principles

MUV's backend employs a cloud-native microservices architecture designed to support the variable engagement patterns typical of gamified behavioural interventions. This modular setup enables flexible management of multiple independent service components and dynamic resource allocation, essential to accommodate activity spikes during competition periods and seasonal changes, unlike the steadier patterns of conventional mobility platforms.

Each service runs in a containerised environment, allowing rapid scaling based on user activity. This is especially important during high-intensity phases, which may demand up to 4–5 x the normal processing load.

The technology stack is optimised for both responsiveness and technical efficiency. Developed entirely in Python, it uses Django REST Framework for business logic implementation and API exposure, Django Channels for real-time WebSocket communication essential for mobility tracking, and Celery for asynchronous task execution supporting time-sensitive behavioural reinforcement (Django Software Foundation 2024; Celery Project 2025).

Geospatial processing, crucial for trip validation, is handled by PostgreSQL with PostGIS extensions, while Redis ensures fast in-memory caching for a smooth user experience during peak usage periods (Redis.io 2025).

All these architectural choices are intentionally aligned with behavioural goals. Table 3.9 shows how each backend component contributes to mechanisms fostering sustainable mobility adoption.

3.3. The MUV platform: technology and design

Table 3.9: Key technologies in MUV’s backend infrastructure and their functional roles.¹

Technology	Primary function	Behavioural support role
Django & Django REST Framework	Implementation of business logic and REST API endpoints	Enables structured game mechanics and secure user authentication
Django Channels	Management of real-time WebSocket communications	Facilitates real-time feedback crucial for reinforcement and engagement
Celery	Asynchronous task processing and scheduling	Powers time-sensitive operations like challenge updates and notifications
GeoDjango	Geospatial data processing	Enables trip validation and location-based features
PostgreSQL with PostGIS	Persistent storage with geospatial capabilities	Supports geographical analysis for trip verification
Redis	In-memory NoSQL data storage and caching	Improves game dynamics, responsiveness, and leaderboard updates

Energy efficiency and sustainability alignment

The infrastructure design reflects MUV’s environmental mission through systematic energy optimisation strategies. Dynamic resource allocation ensures computational resources are utilised only when needed, eliminating idle energy consumption during low-activity periods. The platform prioritises cloud providers adhering to ISO 14001 - Environmental Management Systems and ISO 50001 - Energy Management Systems standards, leveraging facilities that consume up to 80 % less energy than traditional on-premise infrastructures (International Organization for Standardization 2015; International Organization for Standardization 2018).

Selected providers participate in the Climate Neutral Data Centre Pact, utilising renewable energy sources and implementing AI-driven power management systems that further reduce carbon footprints. This focus on green computing principles creates consistency between the service’s sustainability mission and its technical implementation, demonstrating how digital services can minimise environmental impact while delivering significant behavioural benefits.

Scalability for behavioural intervention patterns

The architecture addresses unique scaling challenges inherent in gamified behavioural interventions. Corporate implementations typically engage 15-25% of eligible employees with concentrated activity during working hours, while educational deployments may involve thousands of students with synchronised activity patterns around academic calendars.

The microservices design enables independent scaling of components based on specific usage patterns: trip validation services scale during commuting hours, competition man-

agement systems scale during tournament periods, and analytics processing scales during reporting cycles. This granular approach optimises both performance and energy consumption while maintaining responsive user experiences essential for behavioural reinforcement.

Container orchestration enables automated scaling responses to engagement spikes, ensuring that behavioural feedback remains immediate even during peak competitive periods. This technological responsiveness directly supports the variable ratio reinforcement schedules, which have proven effective in maintaining long-term user engagement.

3.3.1.2 Microservices architecture and component integration

MUV's backend architecture consists of several interconnected microservices, each designed to support specific aspects of the behavioural change ecosystem while maintaining system modularity and scalability.

The architecture implements six core service categories that collectively enable gamified mobility interventions:

- **Authentication and game mechanics services** handle user authentication and core gamification logic, including points calculation, challenge participation, and reward distribution, providing the foundational behavioural reinforcement systems.
- **Real-time communication services** manage GPS tracking and activity recognition through WebSocket connections, collecting location data essential for the trip validation algorithms that ensure system integrity and user trust.
- **Asynchronous processing services** handle scheduled operations such as leaderboard updates, challenge progression, and notification delivery, supporting the time-sensitive feedback loops crucial for behavioural reinforcement.
- **Data management services** maintain user profiles, travel records, and geographical information through relational and geospatial databases, providing the foundation for personalised experiences and impact measurement.
- **Performance optimisation services** ensure responsive user experiences through caching and task queues, particularly during peak engagement periods when immediate feedback becomes critical for sustained motivation.
- **Infrastructure orchestration services** manage deployment, scaling, and monitoring, ensuring the system handles varying loads during different phases of tournaments and challenges without compromising the behavioural intervention effectiveness.

Figure 3.5 illustrates how these components integrate to form the backend architecture supporting MUV's approach.

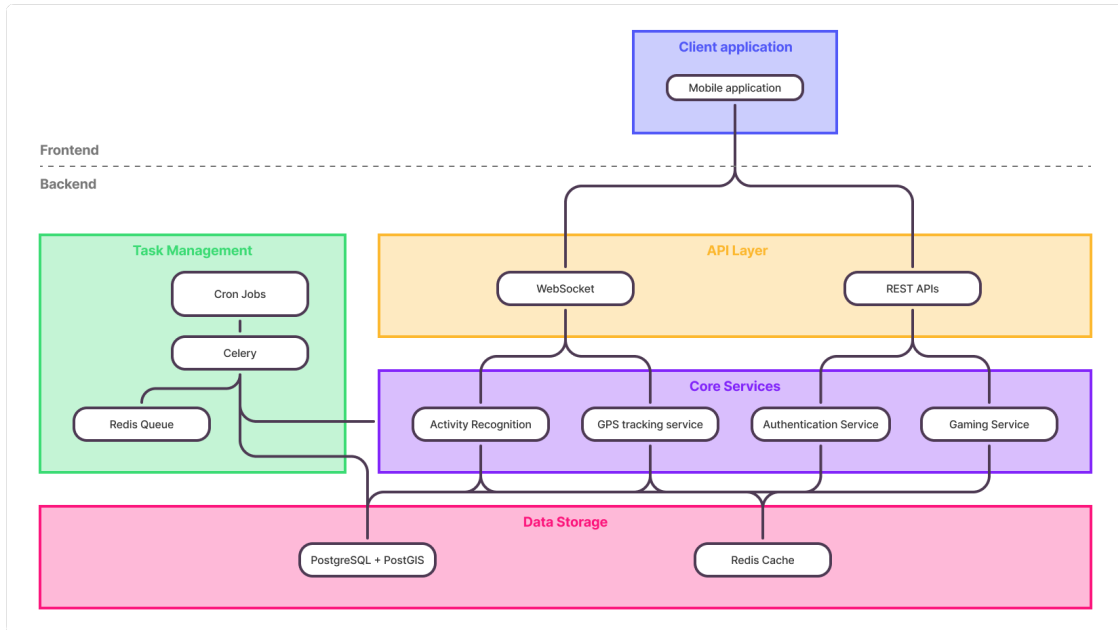


Figure 3.5: MUV’s backend cloud architecture, illustrating the interconnection of microservices and how they collectively support the gamification and behavioural change mechanisms.

3.3.1.3 Data processing and privacy

Efficient data management is fundamental to MUV’s behavioural change effectiveness, ensuring continuous information flow from data acquisition through structured storage to real-time processing and automated operations. The data pipeline supports behavioural objectives by facilitating immediate user feedback, accurate measurement of sustainable travel, and personalised gamification experiences while maintaining strict privacy compliance.

Privacy by design architecture

Privacy considerations are fundamental to MUV’s data architecture, particularly given the sensitive nature of location tracking under GDPR protections. The platform adopts a multi-layered approach that balances analytical needs with user rights protection.

Data minimisation is applied from registration, which requires only essential identifiers, while demographic fields remain optional. The application identifies users by usernames and avatars, decoupling public identity from personal data. Location tracking is subject to explicit consent, with clear distinctions between required and optional permissions.

Trip data used for analysis is anonymised and aggregated to preserve privacy while retaining value for mobility planning. Features involving third-party data sharing operate on informed consent basis, with granular controls that users can modify at any time.

Account deletion respects GDPR revocability, with personal information permanently erased after a 30-day recovery window, while statistical data is retained in anonymised form, enabling ongoing impact analysis.

This privacy model fosters trust by ensuring transparency, maintaining user control, and aligning with key data protection principles.

Data processing and automation

User data originates from two main channels in the mobile application: real-time tracking via WebSocket connections and structured API requests for gamification features and profile updates. Django Channels manages low-latency bidirectional communication for accurate movement monitoring, while Django REST Framework provides secure endpoints for game logic and user management.

Once collected, data is stored and processed to preserve integrity and support real-time decisions. PostgreSQL with PostGIS enables advanced geospatial analysis for trip validation and impact measurement, with cloud hosting ensuring autoscaling for fluctuating workloads. Redis enhances responsiveness by caching frequently accessed data and handling background processes, reducing query execution times, especially during peak competition periods.

Automated workflows powered by Celery manage asynchronous tasks such as competition updates, scoring, and data synchronisation. Scheduled cron jobs perform routine operations—daily score validation, database maintenance, and CO₂ calculations—maintaining data consistency with minimal manual effort.

This integrated system of real-time processing, structured storage, and automation ensures that MUV remains scalable, resilient, and responsive, meeting the demands of dynamic user engagement while sustaining behavioural engagement through immediate feedback loops.

3.3.1.4 Core algorithms

Algorithms play a central role in delivering MUV's service by ensuring the technical integrity of the system while supporting the behavioural intervention principles discussed in Section 3.1. The platform implements three interconnected algorithmic innovations that bridge technological capability with scientific rigour: trip validation, point calculation, and environmental impact measurement.

These algorithms serve a dual purpose beyond technical functionality: they preserve user trust through transparent and fair validation processes while implementing the behavioural psychology principles of immediate feedback, appropriate rewards, and meaningful impact metrics that sustain long-term engagement. Together, these elements form a composite framework validating genuine sustainable travel, translating behaviour into game mechanics, and quantifying environmental outcomes using internationally certified methodologies.

The algorithmic design addresses fundamental challenges in mobility gamification: ensuring authentic, sustainable behaviour without invasive monitoring, creating fair competition across diverse user contexts, and providing scientifically credible impact measurement that supports individual motivation and organisational sustainability reporting.

Trip validation algorithm

Validating sustainable travel represents a critical innovation that distinguishes MUV from comparable services that rely solely on user declarations without verification controls. The platform requires robust mechanisms to verify that users' declared transport modes align with actual travel patterns while maintaining privacy and user trust.

Methodological innovation and data sources

MUV employs a validation framework that combines multiple data streams to achieve accuracy without compromising user privacy. The primary data sources include location data provided by GPS systems (position, altitude, time), enabling speed and acceleration calculations, and activity recognition data from built-in mobile services that use sensor readings (accelerometer, gyroscope) combined with machine learning algorithms to classify user movements.

This multi-source approach enables the platform to detect activities such as walking, cycling, and being in a vehicle while optimising battery consumption through efficient sensor management. The validation methodology adapts to the inherent characteristics of different transport modes rather than applying universal detection rules, ensuring high accuracy across diverse mobility options.

Mode-specific validation strategies

The validation system implements tailored approaches for different transport categories, recognising that each mode presents unique detection challenges and opportunities.

For active mobility modes (walking, cycling, e-bikes, e-scooters), the algorithm employs a two-phase validation structure. During real-time tracking, GPS and activity recognition data are transmitted via WebSocket connections, with GPS points filtered to eliminate noise and ensure reliability. The system analyses trip segments defined by consecutive points, validating each segment through mode-specific speed and acceleration thresholds. Post-trip verification includes supplementary analysis of detected activities that must align with declared modes, plus overall assessment based on final average speed and the ratio of valid and total segments. This dual-phase approach supports immediate feedback during trips and summative reinforcement after completion, implementing the multi-layered reinforcement principles discussed in Section 3.1.2.2.

For public transport (buses, metros, trains), validation strategies differ based on infrastructure characteristics. Urban and intercity bus verification employs similar segment analysis during tracking to distinguish bus travel from private vehicle use, followed by post-trip validation that queries external travel planning services (Google Maps) to confirm route and duration alignment with existing mapped itineraries. Caching and pre-calculation strategies minimise computational costs while maintaining accuracy for repetitive trips. Rail transport validation (metro and train) focuses on infrastructure alignment rather than speed analysis, given the high variability in rail travel patterns. The system verifies that departure and arrival points are proximate to stations and that routes align with railway tracks using

OpenStreetMap data. OpenStreetMap data is distributed under the Open Database License, allowing integration with routing and mapping algorithms (OpenStreetMap Foundation 2023). For underground metro trips where GPS functionality is compromised, validation relies on station proximity and travel time consistency with estimated durations, with surface-level alerts reminding users to activate tracking when possible.

Electric vehicle verification employs a distinct approach that eliminates real-time monitoring in favour of post-trip confirmation. Users capture photographic images of license plates, processed through *Optical Character Recognition* (OCR) using the *Tesseract OCR engine*, an open-source system widely adopted for real-time text extraction from images (Smith 2007). The system cross-references plate information with public vehicle databases to confirm electric propulsion, implementing automated verification that balances security with user convenience. For frequent electric vehicle users, the application's "Garage" feature enables pre-registration of vehicles, including license plates and confirmation photographs, reducing friction through sporadic spot-checking rather than per-trip requirements. This approach balances behavioural verification with user convenience, implementing minimal intervention principles while maintaining system integrity.

Carpooling verification focuses on confirming shared travel rather than individual vehicle characteristics. The validation process involves pairing two to five users and comparing GPS coordinates and velocities to verify co-location throughout trips. When the first user concludes tracking, notifications prompt others to end shared journeys, enabling algorithmic verification of carpooling authenticity.

Validation performance and continuous improvement

The validation algorithms demonstrate robust performance, evidenced by a 57 % average weekly reduction in user-reported invalid trips after implementing the latest algorithmic iteration for individual and public transport modes. This improvement reflects ongoing refinement based on real-world deployment data and user feedback.

The system acknowledges that some valid trips may be classified as invalid due to device power-saving modes, poor connectivity, or GPS interference. In such cases, users can request manual evaluation through dedicated feedback mechanisms, with errors corrected through human oversight that maintains system learning capabilities.

Table 3.10 summarises the validation methodologies across different mobility modes, highlighting the adaptive approach that accommodates diverse transport characteristics while maintaining consistent accuracy standards.

Table 3.10: Summary of real-time and post-trip validation techniques for different mobility modes in the MUV platform.

Mobility mode	Real-time validation	Post-trip validation
Walking, cycling, e-bike and e-scooter	Analysis of average speeds and accelerations on segments with mode-related thresholds	Analysis of detected activities and final check on overall average speed and ratio of valid segments to totals
City and intercity buses	Analysis of average speeds and accelerations on segments with mode-specific thresholds	Path and travel time comparison with external travel planning services (e.g., Google Maps)
Metro and train	–	Analysis of railways, stations, and stops from OpenStreetMap, including travel duration verification
Electric vehicles	–	Vehicle plate photo analysis via OCR and public databases to confirm electric power supply
Carpooling	Comparison of paths and average speeds of users to confirm shared travel	–

Future development and research directions

Current research explores incorporating *Bluetooth Low Energy* technology for public transport validation, analysing proximate device quantities to verify user presence on vehicles. This approach could eliminate GPS dependency while providing more efficient validation through proximity-based detection, representing the next evolution in privacy-preserving mobility verification. Bluetooth Low Energy has already shown strong potential in other proximity-based mobility systems due to its low energy consumption and efficient broadcasting capabilities (Gomez et al. 2012).

The validation framework continues evolving through machine learning approaches that adapt to local infrastructure variations and user behaviour patterns, maintaining high accuracy while reducing computational requirements and improving user experience across diverse urban contexts.

Point calculation algorithm

The point calculation system is the core of the MUV game architecture, converting validated sustainable travel into meaningful game mechanics. It ensures that rewards reflect actual environmental impact rather than arbitrary engagement metrics. This algorithm operationalises the behavioural design principles outlined in Section 3.1.2.2, offering immediate, proportionate, and contextually appropriate reinforcement for sustainable mobility choices.

Theoretical foundation and design principles

The scoring methodology addresses key challenges in behavioural intervention design: ensuring fair competition across varied user contexts, preventing system exploitation via excessive travel, and maintaining engagement through evidence-based reward structures. It applies variable ratio reinforcement, proven effective in behavioural psychology, and incorporates equity mechanisms that account for diverse urban settings and mobility constraints.

The point system serves a dual purpose: it educates users about the relative environmental impact of different transport choices through transparent scoring hierarchies and enables fair competition among participants with varying mobility patterns and infrastructure access. The point system serves a dual purpose: it educates users on the environmental impact of different transport modes through transparent scoring, and it ensures fair competition among participants with diverse mobility habits and infrastructure access. By turning abstract sustainability concepts into clear, actionable feedback, it fosters habit formation and long-term behavioural change.

Core algorithm structure and innovation

The calculation framework operates on two parameters balancing behavioural psychology and environmental science:

- **Mobility coefficients (M)** vary by transport mode, reflecting actual environmental impact and effort required. Walking and cycling receive the highest values (1.0 and 0.5) due to zero emissions and health benefits, while other modes receive progressively lower coefficients reflecting their environmental footprint. The complete coefficient system and rationale are detailed in Appendix A.4.
- **Daily travel threshold (T)** defines an 8-kilometre equivalent mobility budget that decreases with each validated trip. This encourage sustainable urban travel while preventing excessively long-distance trips that contradict sustainability objectives. The threshold implements loss aversion principles from behavioural economics, making users conscious of their daily mobility choices.

Both parameters were calibrated using data from over 5 000 MUV2020 participants, ensuring reliability across diverse urban contexts. The algorithm computes daily cumulative distance (D_{day}) as the sum of validated trip distances weighted by mobility coefficients:

$$D_{day} = \sum_{i=1}^n D_i \cdot M_i \quad (3.1)$$

where D_i represents the trip distances and M_i its corresponding mobility coefficients.

The total distance, including the current trip, is represented as D_{tot} :

$$D_{tot} = D_{day} + (D_c \cdot M_c) \quad (3.2)$$

where D_c is the current trip distance and M_c its mobility coefficient.

Behavioural integration and threshold mechanism

The point allocation system implements a sophisticated threshold mechanism that reflects behavioural science insights about motivation and habit formation. When cumulative distance remains below the threshold ($D_{tot} < T$), points follow a linear calculation:

$$\text{Points} = K \cdot D_c \cdot M_c \quad (3.3)$$

where $K = 245$ is an empirically derived constant, D_c the current trip distance, and M_c its mobility coefficient.

Once the threshold is exceeded ($D_{tot} \geq T$), the algorithm applies a cubic function that progressively reduces point allocation for additional travel:

$$\text{Points} = \frac{D_{tot}^3}{K'} \quad (3.4)$$

where $K' = 1,200$ is derived from the threshold and linear constant.

This structure serves multiple behavioural functions: it encourages regular moderate activity over sporadic intensive use, implements diminishing returns that reflect real-world sustainability principles, and maintains engagement while preventing system abuse.

Figure 3.6 illustrates the relationship between cumulative distance and point allocation.

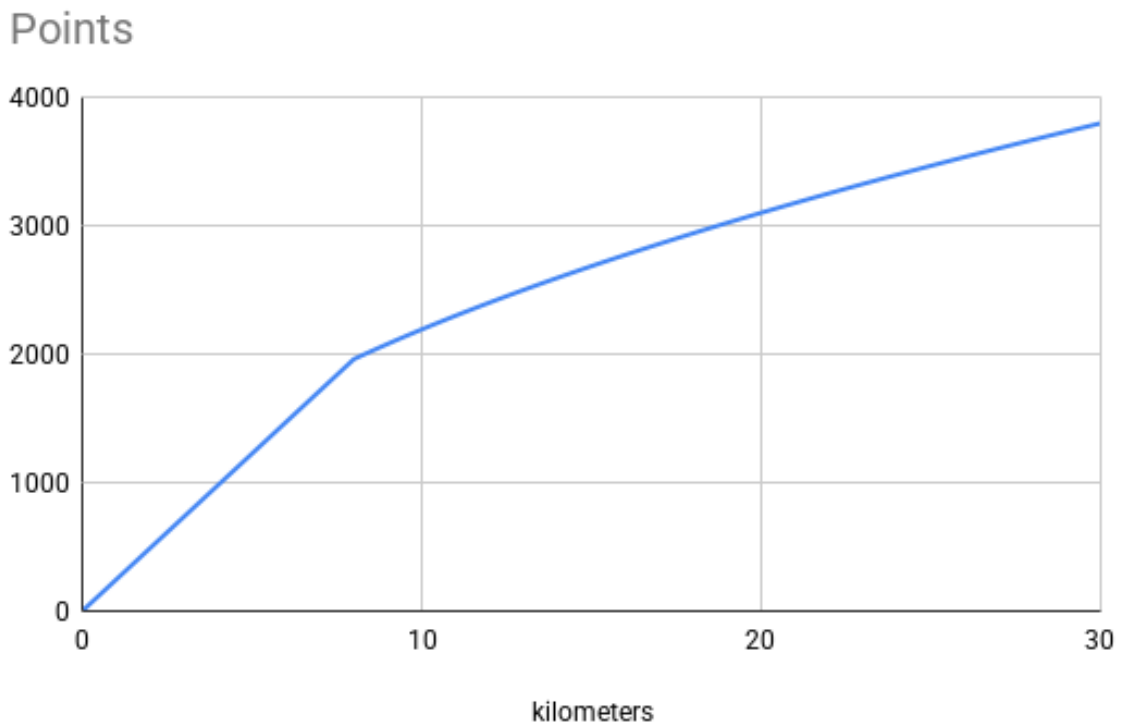


Figure 3.6: Points allocation based on cumulative equivalent distance travelled, showing the progressive reduction in rewards after exceeding the 8 km daily threshold.

By dynamically calibrating the parameters, the system remains adaptable to diverse user behaviours and evolving mobility patterns, preserving fairness and consistency.

Empirical validation and behavioural impact

The point calculation system has demonstrated effectiveness in promoting sustained engagement and behavioural change across diverse implementation contexts. Cross-case analysis reveals that the algorithm successfully balances fairness with motivation, as evidenced by consistent participation rates and positive user feedback regarding perceived equity and transparency.

The threshold mechanism proves particularly effective in encouraging urban-focused sustainable mobility while preventing gaming behaviours. Data analysis shows that 89 % of users remain within daily threshold limits, with point allocation patterns correlating positively with genuine sustainable mobility adoption rather than system exploitation.

The algorithm demonstrates how sophisticated behavioural science principles can translate into practical solutions that achieve engagement and environmental objectives. By combining immediate feedback with meaningful long-term progression, the system creates sustainable motivation for continued participation in urban mobility transformation.

CO₂ savings measurement: ISO 14064-2 certified methodology

MUV's environmental impact calculation represents a significant methodological innovation in gamified mobility interventions: an accredited framework for quantifying greenhouse gas emission reductions in behavioural change applications.

Methodological innovation and certification

The algorithm accurately attributes emission reductions to specific behavioural changes through personalised mobility baselines rather than generic assumptions. MUV's original methodology, developed internally and certified by RINA, an Italian classification and certification body with international recognition (RINA 2025), in accordance with ISO 14064-2 standards, enables precise quantification of CO₂ equivalent savings through personalised baseline establishment and differential analysis. This certification guarantees scientific validity and supports organisational sustainability reporting requirements under frameworks such as the European *Corporate Sustainability Reporting Directive* (CSRD).

Personal baseline definition

The first step involves defining a personalised *mobility baseline*, which serves as a counterfactual scenario representing the user's typical mobility emissions in the absence of MUV. This baseline estimates the relative carbon footprint associated with urban mobility and is established via an in-app survey. It consists of two interconnected profiles that reflect the complexity of individual mobility behaviours:

- **Generic profile:** capturing the user's overall travel patterns, including modal split distribution and average weekly distance across all trip types.
- **Frequent trip profile:** it focuses on the most recurring trip (e.g., home-to-work), detailing origin, destination, weekly frequency, and modal split.

This dual-profile approach enables accurate impact attribution by distinguishing between general mobility behaviour and routine travel patterns that often represent the largest intervention opportunities (complete baseline structure detailed in Appendix A.5.1).

Algorithm architecture and calculation logic

Weekly CO₂ equivalent savings are calculated through differential analysis comparing tracked sustainable travel against established baselines using certified emission coefficients from European Environment Agency standards 2020. The system accounts for both tracked distances (where behavioural change is directly measured) and untracked distances (where baseline modal split assumptions are applied), with dynamic baseline adjustment preventing overestimation while maintaining accuracy across diverse user profiles (complete algorithm specifications in Appendix A.5.3). Users who already practice sustainable mobility receive appropriate credit without artificially inflating system-wide impact metrics.

Key algorithmic features include personalised mobility habit calculation, separation between generic and frequent trip profiles, and optional integration of individual vehicle specifications for accurate emission estimation. Conservative estimation principles ensure impact claims reflect genuine behavioural change rather than rewarding existing sustainable behaviours, maintaining ISO 14064-2 certification requirements (emission coefficients and calculation parameters detailed in Appendix A.5.2).

Empirical validation and impact demonstration

The methodology's effectiveness is demonstrated through consistent impact measurement across diverse implementation contexts. Case study analysis reveals average emission reductions of 33.82 % among active users, with behavioural change penetration rates of 31.29 % across participant populations.

For example, a typical Italian commuter transitioning from car-based travel to carpooling and sustainable modes can achieve up to 6.1 kg CO₂ savings weekly (317 kg annually), representing roughly 5 % of average Italian per-capita emissions (complete calculation example in Appendix A.5.4).

Integration with the behavioural framework

The CO₂ calculation serves dual purposes within MUV's behavioural architecture: providing scientifically valid impact measurement for organisational reporting and delivering meaningful user feedback that reinforces sustainable choices through concrete environmental outcome awareness. While the methodology relies on user-declared data, which may introduce errors, it offers a more personalised and context-specific approach compared to methods based solely on national average statistical data on distances travelled, modal split, and average vehicle emissions.

This methodology demonstrates how rigorous scientific measurement enhances gamification effectiveness by providing credible environmental feedback that builds user trust while maintaining engagement through transparent impact quantification.

3.3.2 Mobile application: user interface and experience design

The MUV mobile application serves as the primary touchpoint through which users interact with the service, implementing the behavioural change principles and gamification elements discussed in Sections 3.1 and 3.2. Available for both *Android* and *iOS* operating systems, the application provides a digital environment where users can track sustainable movements, engage with game dynamics, and receive real-time feedback on rewards earned and environmental impact generated.

The interface design represents a critical bridge between theoretical concepts and practical implementation. Every view, button, and notification has been designed considering accessibility, usability, and behavioural impact, ensuring that the application is both easy to use and effective at motivating sustainable choices. This section examines how technological architecture, user experience design, and accessibility principles collectively enable effective behavioural intervention through digital interfaces.

3.3.2.1 Technical architecture and design principles

The design and development of the MUV mobile application required strategic technological decisions aligned with the primary objective of facilitating and reinforcing sustainable mobility behaviours. These decisions encompassed framework selection, processing distribution, and communication systems to support the real-time feedback and social reinforcement mechanisms essential for behavioural change.

Cross-platform development strategy

MUV employs *React Native*, an open-source framework developed by *Meta* that enables mobile application development across multiple platforms using a single JavaScript-based codebase (Meta Platforms Inc. 2024). This hybrid cross-platform approach balances performance with development efficiency while maintaining access to native functionalities essential for tracking mobility behaviours.

Hybrid frameworks have gained significant traction in recent years, with hybrid applications accounting for about one-third of all applications published on the *Apple App Store* and *Google Play* in 2023 (Statista 2023). *React Native* stands out as one of the most prevalent cross-platform frameworks in mobile development, utilised to build 43 % of hybrid applications, followed by *Flutter* (38 %), *Ionic* (12 %), and all others (8 %), such as *Xamarin* and *Cordova*. Numerous prominent applications, including *Instagram*, *Airbnb*, *Uber Eats*, and *Bloomberg*, are *React*-based, with *React Native* employed in approximately 14 % of all applications, whether native or hybrid (Stack Overflow 2023).

Key strategic advantages include reduced development time and costs through unified codebases, simplified platform maintenance and updates, integration with native device capabilities (GPS, camera, push notifications), and extensive community support for robust troubleshooting. This widespread adoption provides confidence in long-term viability and developer ecosystem support essential for sustained platform development.

Processing architecture and performance optimisation

The application adopts a processing model that strategically offloads computational tasks to the backend infrastructure, optimising performance and responsiveness. Frontend processing is minimised to approximately 10 % of the total workload, with calculations limited to those necessary for immediate user feedback.

This architecture necessitates increased communication between front and backend but leverages server computing power to reduce application workload, improve loading speeds, and optimise battery consumption—important considerations for users tracking daily mobility patterns. The primary trade-off involves stronger dependency on network connectivity, addressed through intelligent caching and offline capability where appropriate.

Real-time communication and engagement systems

Push notifications serve as fundamental engagement drivers, enabling real-time communication that supports multiple behavioural change principles discussed in Section 3.1. The system implements cross-platform *Software Development Kit* (SDK), interfacing with Android and iOS notification management centres, providing unified delivery of timely feedback.

The notification strategy encompasses real-time tracking feedback (movement alerts, mode compatibility warnings), competition and social updates (challenge notifications, team results, friend and community interactions), achievement recognition (rewards, badges, milestone achievements), and administrative communications (service updates, surveys). This comprehensive framework transforms MUV into an interactive service that actively engages users through multiple touchpoints while maintaining balanced frequency to avoid notification fatigue.

Integrating these technological components creates a responsive, scalable platform that delivers consistent behavioural interventions across diverse user segments and engagement contexts.

3.3.2.2 User experience framework

The MUV mobile interface implements behavioural design principles through carefully crafted user experience components that support sustained engagement and habit formation. The interface design follows the “progressive disclosure” principle, prioritising frequently used functions while maintaining access to all features within an intuitive navigation structure.

Core interface architecture

The application employs a five-component navigation system designed to balance functional accessibility with motivational engagement. These components comprise the navigation bar, home screen, context menu, user profile, and tracking screen. Figure 3.7 illustrates the hierarchical structure and interconnections among key application components.

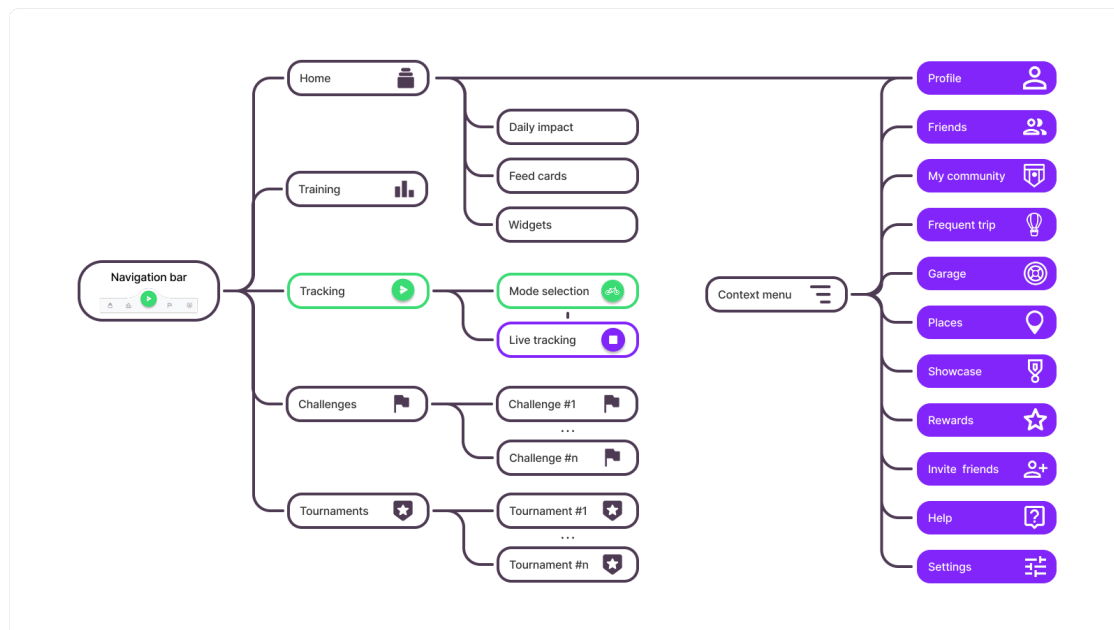


Figure 3.7: Hierarchical structure and interconnections among MUV mobile application components, showing the relationship between key sections and user flows.

The central navigation bar represents the primary wayfinding system of the application, giving users quick access to key features with minimal effort. It plays a dual role: activating sustainable travel tracking and guiding users through various game elements.

It features five strategically placed buttons. The central button emphasises travel tracking through its prominent positioning and visual hierarchy, reflecting the friction-reduction principles discussed in Section 3.1.2.3. The surrounding buttons offer streamlined access to various game features—training, challenges, and tournaments—bridging practical functions with motivational components.

Motivational hub design

The home screen acts as the main motivational interface, structured into three functional areas that present essential information such as achievements, progress, and environmental impact in a clear, accessible format while summarising recent user activity. The header displays weekly points and global ranking beside the user's avatar, applying social comparison principles (Section 3.1.3). Daily impact metrics such as CO₂ savings and steps offer instant feedback on environmental and health benefits, supporting goal-setting and self-monitoring (Section 3.1.2.1). Below, competition widgets adjust dynamically, showing ranking positions, live matches, and remaining time. This maintains engagement without cluttering the interface during non-competition periods; when no competitions are active, the widgets are hidden to maintain clarity. The lower screen area hosts a chronological activity feed highlighting completed actions and achievements, offering continuous reinforcement and documenting progress, thereby extending user interaction beyond tracking alone. Complete feed card specifications provided in Appendix B.2.2.

Tracking experience design

The live tracking interface is the central behavioural intervention mechanism, designed for simplicity and engagement through voluntary participation. Users initiate tracking via a prominent central button that intuitively changes state (*Play* → *Switch* → *Stop*) as the journey progresses,, as illustrated in Figure 3.8.

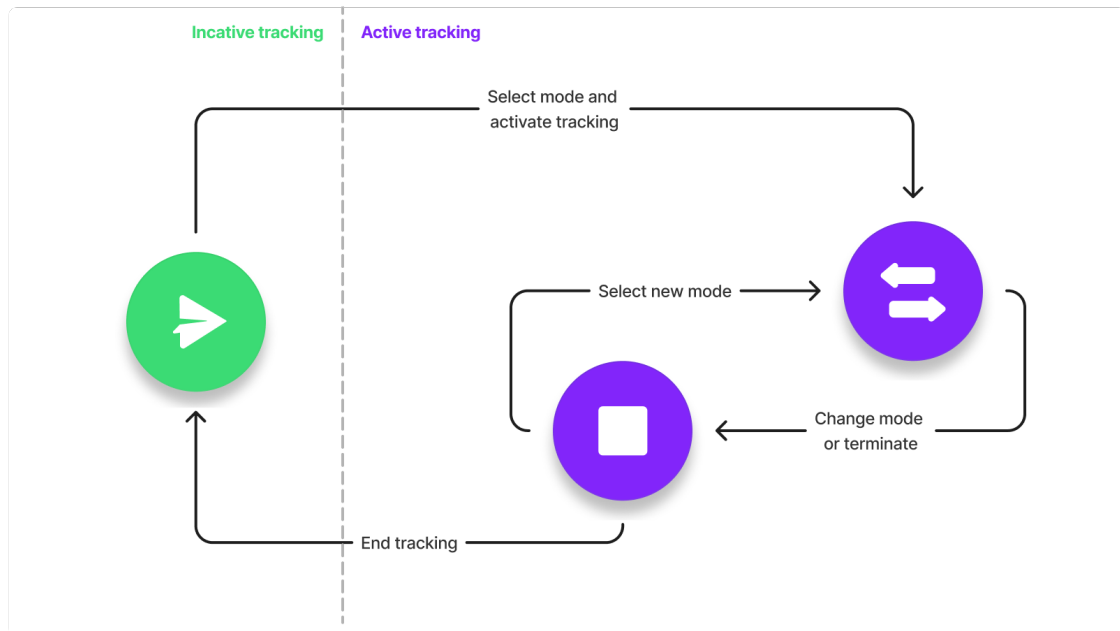


Figure 3.8: State transitions of the tracking button in the MUV application, showing the flow from Play to Switch to Stop states.

During tracking, users receive real-time feedback on distance, duration, speed, and earned points, implementing immediate reinforcement principles discussed in Section 3.1.2.2. Active multipliers (e.g., weather, peak hours, frequency) are displayed to highlight bonus opportunities and sustain engagement in diverse conditions.

The visual design employs consistent colour coding across transport modes: green for muscular mobility (walking, cycling), pink for electric vehicles, yellow for public transport, and blue for shared mobility. This systematic approach reinforces mode categorisation while supporting rapid visual recognition during daily usage (complete visual specifications and interaction flows detailed in Appendix B.2.1).

User profile and social engagement

The user profile provides a holistic overview across three key dimensions: performance metrics (rankings, points, trophies), mobility patterns (trips, distances, modal split), and environmental impact (CO₂ savings). This multi-dimensional feedback enhances user competence, as highlighted in Self-Determination Theory, while creating tangible evidence of the user's progress.

Social features strengthen individual motivation by introducing peer dynamics. Friend

connections and community participation promote accountability through shared leaderboards and visible achievements. These components activate normative influence pathways that support sustained behaviour modification beyond individual motivation alone.

Together, these components transform everyday travel into a motivating and socially enriched experience, combining feedback, recognition, and participation to foster sustainable habits (detailed specifications in Appendix B.2.1, B.2.2, and B.2.3).

3.3.2.3 User-centred design, accessibility, and inclusiveness

The development of the MUV service followed *user-centred design* methodology, placing users' needs, preferences, and limitations at the forefront of the design process. This approach, pioneered by Norman 1988, emphasises creating products and services with people rather than for them; a distinction that significantly impacts adoption and sustained use, particularly for behavioural change interventions.

MUV's user-centred design journey began during the MUV2020 research project, involving over 5 000 European citizens in a participatory design process (Di Dio, Lissandrello, et al. 2019). This strategy focused on co-creation established the foundation for the service's requirements, functionalities, and game dynamics, ensuring alignment with actual user requirements and motivations. Following the spinoff's establishment, this participatory approach evolved into an iterative development process, continuously incorporating user feedback and behavioural data to refine existing features and introduce new ones.

Multilingual and cross-cultural accessibility

Language accessibility is essential for any global service aiming to achieve widespread adoption. MUV was initially released in Italian and English, subsequently expanding to include French, Spanish, and Portuguese. This linguistic portfolio collectively covers approximately 90 % of the European population and 50 % globally, significantly lowering adoption barriers.

To go beyond simple translation, MUV adopted a crowdsourced refinement process, allowing users to suggest improvements in accuracy, cultural relevance, and terminology. This shared approach to language localisation ensures natural language use, enhancing comprehension and engagement while fostering a sense of ownership and community involvement.

Recognising that language is not merely a communication channel but a cultural lens, MUV ensures that mobility nudges and game elements are interpreted in ways that resonate meaningfully across different linguistic contexts.

Inclusive design principles

Designing truly inclusive digital services presents significant challenges, particularly in mobility contexts where user experiences are influenced by urban infrastructure and socio-cultural factors (University of Cambridge 2024). MUV adopted three fundamental principles guiding its development process:

1. **Inclusion by design:** Creating inherently accessible experiences rather than retrofitting inclusivity features, implementing a universal design approach.
2. **Continuous improvement through user feedback:** Regularly soliciting and incorporating suggestions to identify and address unconscious biases.
3. **A growth mindset:** Acknowledging limitations and implementing corrective measures promptly when inclusivity gaps are identified.

These principles reflect established guidelines for inclusive digital interface design (Schillaci 2022), focusing on gender inclusivity, and are implemented across multiple application design aspects. Sex selection balances measurement needs with respect for gender diversity by providing inclusive options, including "male", "female", "intersex", and "prefer not to say" for accurate calorie expenditure calculations. Gender-neutral language throughout the application avoids gendered pronouns and terminology, ensuring communications resonate equally with users across the gender spectrum. The inclusive visual identity intentionally represents diverse individuals and avoids gendered stereotypes in colours, clothing, or activity depictions, aiming to represent an active and diverse community where every user feels represented.

Accessibility for diverse mobility capabilities

While MUV cannot directly influence urban infrastructure or transport accessibility, it has taken steps to ensure that users with mobility impairments can engage in sustainable mobility tracking and related game dynamics. In early 2025, a dedicated research initiative was launched in collaboration with Paul Valéry University, Montpellier, involving a focus group of students with physical disabilities to develop wheelchair tracking functionality and identify accessibility barriers.

This work marks an initial move towards greater inclusivity, recognising that sustainable mobility must encompass diverse physical capabilities. By integrating wheelchair tracking, MUV aims to acknowledge the environmental value of self-propelled mobility in all forms, create more inclusive community experiences that enable broader participation, and raise awareness about mobility inequality in urban environments through user-generated data.

These features support MUV's behavioural objectives by fostering trust through transparent data practices and offering control mechanisms that enhance perceived autonomy, demonstrating that truly effective interventions must be both inclusive and accessible to deliver meaningful impact (detailed implementation specifications provided in Appendix B.2.4).

3.3.3 Web dashboard: decision support and analytics

The MUV web dashboard completes the platform's technological ecosystem, serving as a strategic analytics interface that transforms individual mobility data into organisational insights and actionable intelligence. While the mobile application engages individual users through gamification and behavioural interventions, the dashboard addresses institutional stakeholders by enabling evidence-based decision-making for corporate mobility management, municipal planning, and urban policy development.

This component bridges the critical gap between individual behavioural change and systemic transformation by providing real-time analytics supporting operational program management and strategic institutional planning. The dashboard enables organisations to move beyond simple participation metrics toward precise understanding of mobility patterns, behavioural change effectiveness, and environmental impact at scale. Through sophisticated data aggregation and visualisation, it transforms the collective actions of individual users into institutional knowledge that can inform everything from corporate sustainability reporting to urban infrastructure investments.

3.3.3.1 Strategic role and dual-purpose design

The dashboard architecture implements a dual-value framework that serves external organisational clients and internal platform optimisation through distinct but complementary analytical pathways. For external stakeholders—including corporations, educational institutions, and municipal administrations—the dashboard functions as a comprehensive mobility management tool that provides systematic evidence of program effectiveness, behavioural change outcomes, and environmental benefits to justify investments, meet regulatory requirements, and optimise intervention strategies.

Internally, the MUV team leverages the same analytical infrastructure to monitor platform-wide performance, identify successful implementation patterns, and optimise service delivery across diverse contexts. This dual-purpose design creates a self-reinforcing improvement cycle where better organisational insights lead to enhanced service delivery, which in turn generates more robust data for strategic decision making (detailed dashboard architecture and component specifications provided in Appendix C).

The strategic value proposition extends beyond traditional participation metrics by transforming individual mobility data into institutional intelligence. The dashboard enables organisations to understand how gamified interventions translate into measurable outcomes while positioning mobility data as a strategic asset for corporate policy development and urban planning decisions. This holistic approach is exemplified through applications like the Cagliari SUMP case study (described in Chapter 4), where individual behavioural data directly supported municipal transportation planning, demonstrating value that extends from immediate program management to broader urban transformation strategies.

3.3.3.2 Data visualisation framework

The dashboard employs a lightweight technical architecture focused on efficient data presentation and secure access, enabling rapid deployment with minimal configuration beyond authentication setup and data scope definition. The system utilises responsive web technologies (HTML5, JavaScript, Chart.js) with OAuth2 authentication protocols, ensuring scalable access control while maintaining consistent performance across diverse organisational environments (Chart.js 2024; Hardt 2012).

Privacy-by-design principles govern all data visualisation, with individual user information systematically aggregated and anonymised before presentation to client organisations. The only individual-level data shared are user nicknames, which maintains privacy while enabling tracking of participation. This approach ensures organisations receive actionable insights about collective mobility patterns and program effectiveness without accessing personally identifiable information, addressing both regulatory compliance requirements and ethical data stewardship expectations.

The visualisation framework organises information across four strategic dimensions: user engagement analytics (participation rates, activity patterns, demographic distribution), mobility behaviour assessment (modal split changes, distance patterns, sustainability adoption), environmental impact measurement (CO₂ reduction calculations, behavioural change penetration rates), and competition effectiveness evaluation (tournament vs. challenge performance, retention metrics). This structured approach enables organisations to evaluate both immediate program outcomes and long-term strategic sustainability objectives.

Multi-language support facilitates international scalability, while integrated chart export capabilities allow seamless integration with existing organisational reporting workflows and corporate sustainability frameworks. This rapid deployment approach supports MUV's scalability goals by enabling prompt community onboarding while ensuring consistent performance and security across diverse implementation contexts (complete technical specifications, interface screenshots, and implementation details provided in Appendix C).

Additionally, the dashboard provides internal analytics capabilities that enable continuous platform optimisation through systematic analysis of cross-organisational engagement patterns and retention metrics. It also incorporates an alert system that signals anomalous variations in key parameters at both platform-wide and community-specific levels, enabling timely intervention to address technical issues or engagement fluctuations before they significantly impact user experience.

Chapter 4

Assessing MUV's Effectiveness: Case Studies and Cross-Case Analysis

This chapter assesses MUV's effectiveness through systematic analysis of four case studies spanning corporate, educational, international, and municipal contexts with 4 872 participants. Cross-case analysis demonstrates robust capacity to drive sustainable mobility behaviour change, achieving 27.12 % average CO₂ emission reductions across diverse demographic and institutional settings. Key findings reveal tournament competitions generate 77% higher behavioural intensity than challenges, corporate implementations achieve remarkable cross-cultural consistency (15.7 % penetration rates), and intensive implementations (5–10) deliver 4:1 higher weekly efficiency than extended approaches. The research contributes a Context-Mechanism-Outcome framework demonstrating that optimal mechanisms vary by institutional embedding, temporal architecture, and motivational structure, establishing evidence-based guidance for scaling gamified mobility interventions across diverse urban environments.

4.1 Research approach

The empirical validation of MUV's behavioural change framework, established in Chapter 3, requires rigorous assessment in diverse real-world contexts. Since the founding of MUV Srl SB in 2020, the spinoff has systematically employed a scientific methodology to evaluate intervention efficacy across multiple dimensions: user engagement, behavioural modification, and environmental impact. The overarching goal of this research was to demonstrate how MUV could effectively influence and sustain individuals' mobility behaviour over time, generating measurable environmental, social, and economic benefits. This approach is grounded in the theoretical understanding that successful habit transformation requires both disruption of existing patterns and consistent reinforcement of new behaviours over time (Verplanken and Wood 2006).

The research design follows a multiple case study methodology, selected for its capacity to examine contemporary phenomena within their real-life contexts, particularly appropriate when investigating complex behavioural interventions where boundaries between phenomenon and context are not clearly evident.

This case-based research approach aligns with established principles for empirical investigation, allowing for replication logic and analytic generalisation that extends beyond the specific contexts studied (Yin 2014). The methodology supports both literal replication (predicting similar results across cases) and theoretical replication (predicting contrasting results for anticipatable reasons), enhancing the external validity of findings.

Case selection followed purposive sampling principles based on three primary criteria:

- **Scale and reach:** Initiatives with substantial participant numbers (100+ active users), ensuring adequate statistical power for analysis.
- **Temporal dimension:** Projects spanning varied durations (from five weeks to one year), enabling assessment of immediate and medium-term behavioural effects.
- **Data completeness:** Cases with comprehensive datasets covering user demographics, engagement metrics, mobility patterns, and environmental impacts.

The resulting portfolio of four case studies encompasses diverse implementation contexts—corporate, research, educational, and municipal—providing a robust foundation for evaluating MUV’s effectiveness across different user segments and organisational settings. The subsequent sections present the four principal findings that emerged from cross-case analysis, illustrating both the platform’s versatility and the differential effects of various gamification approaches on sustainable mobility adoption.

4.1.1 The importance of communication in bringing users on board

Across all case studies, a consistent pattern emerged regarding the critical role of strategic communication in driving initial platform adoption. The success in activating diverse communities, from corporate environments to educational institutions and open citizen initiatives, demonstrated a strong correlation with the quality and intensity of supporting communication activities. Indeed, the number of users engaged is contingent upon the capacity to reach them through clear and targeted messages that effectively elucidate the initiative and its purpose. This finding aligns with Rogers’s diffusion of innovation theory, which posits that adoption rates are significantly influenced by how effectively an innovation’s attributes and benefits are communicated to potential adopters (Rogers 2003).

Quantitative analysis revealed that organisations implementing structured communication campaigns achieved approximately 100 % higher engagement rates compared to implementations without such strategies. The most effective campaigns incorporated multiple channels and touchpoints, including digital communications (emails, newsletters, intranet announcements), physical materials (posters, banners in communal areas), and in-person promotion (launch events, information sessions). These multi-modal approaches ensured message penetration across different user segments and engagement preferences.

In response to this evidence, MUV has systematically developed thorough communication packages for all community implementations. These tailored “welcome kits” include

branded promotional materials, presentation templates, social media assets, and suggested communication timelines. This standardised yet customisable approach enables client organisations to effectively introduce the platform within their specific cultural and organisational contexts, addressing a critical success factor in behavioural intervention implementation.

4.1.2 Carbon footprint reduction benchmarked against other interventions

The environmental impact assessment methodology detailed in Section 3.3.1.4 enables precise quantification of mobility-related emission reductions across different implementation contexts. This approach—constructing individualised mobility baselines and comparing them with tracked sustainable travel data—provides a robust measurement framework that accounts for pre-existing travel patterns and contextual variations.

Longitudinal data collected between 2022-2024 from all community implementations (2 856 active users) demonstrated that participants reduced their mobility-related carbon footprint by an average of 33.82 % compared to their personal baselines. This substantial reduction reflects the capacity of behavioural interventions to drive meaningful environmental change without requiring policy restrictions or infrastructure modifications.

This impact is particularly noteworthy when benchmarked against established urban mobility interventions. Comparative analysis with restrictive measures like *Limited Traffic Zones* (LTZs) in Milan (AMAT 2023) and London's *Ultra Low Emission Zone* (ULEZ) (Greater London Authority 2025) indicates that MUV's voluntary, incentive-based approach achieves comparable or, in some contexts, superior emission reductions per participant. While regulatory approaches affect larger populations through mandatory compliance, the MUV model demonstrates how game design principles and positive incentives can drive considerable behavioural shifts through voluntary participation, potentially offering complementary strategies to traditional policy instruments.

Similar smartphone-based interventions in university contexts have demonstrated comparable effectiveness, showing significant potential for voluntary behavioural change and CO₂ emission reductions (Di Dio, Massa, et al. 2020; Cirrincione et al. 2022). These studies consistently demonstrate that gamified approaches can effectively complement traditional urban policies, achieving substantial engagement levels through positive reinforcement rather than restrictive measures. The findings support the broader applicability of voluntary, incentive-based mobility interventions across diverse institutional contexts, from corporate environments to educational institutions.

4.1.3 Game dynamics and their role in sustained engagement

Analysis of user engagement metrics across different game formats revealed significant variations in both participation rates and activity intensity. The design of structured, variable, and contextually relevant game dynamics emerged as a critical factor in driving and

sustaining behavioural change. Combining collaborative and competitive aspects helps leverage community spirit and team identity, creating strong social cohesion. Team-based tournaments consistently generated the highest engagement levels, with 43.69 % of registered users actively participating compared to 37.67 % for challenges. Moreover, users tracked an average of 11.56 weekly trips during tournaments versus 6.09 during challenges—nearly double the activity intensity.

This differential effectiveness appears linked to the social reinforcement mechanisms inherent in team competitions. By creating interdependent success structures where individual actions contribute to collective outcomes, tournaments activate stronger personal achievement motivations and social responsibility drivers. The scheduled match format with weekly head-to-head competitions also establishes clear temporal anchors that structure participation and create anticipation, elements known to reinforce habit formation (Duhigg 2012).

However, user responses to different game dynamics demonstrated significant variation based on demographic profiles and community characteristics. While tournaments generally outperformed challenges, the magnitude of this difference varied considerably across implementation contexts, suggesting the importance of tailoring approaches to specific communities. This finding aligns with contemporary gamification research that emphasises matching game elements to user motivational profiles and behavioural patterns (Morschheuser et al. 2018; Hamari et al. 2014), as well as Self-Determination Theory’s emphasis on balancing intrinsic and extrinsic motivational drivers (Ryan and Deci 2007).

4.1.4 Long-term behavioural retention: beyond competitions

Perhaps the most remarkable finding for sustainable behaviour change is the evidence of continued platform usage beyond structured competition periods. Post-implementation monitoring revealed a *Daily Active Users to Monthly Active Users* (DAU/MAU) ratio of 14.9 %—significantly exceeding the 10 % threshold widely considered indicative of strong user retention in mobile applications. This retention level is particularly notable given industry statistics showing that typical mobile applications lose over 80 % of users within three days of installation (A. Chen 2015).

The emergence of self-organised user communities represents a particularly promising pathway to behavioural sustainability. In multiple implementation contexts, core groups of engaged users continued platform usage well beyond formal initiatives, often developing their own supplementary game modes or competition structures. An exemplary case emerged in Cagliari, where participants, after competing in a one-shot challenge promoted by their municipality (further detailed in Section 4.5), continued to use the application through “FantaMUV”, the annual open tournament dedicated to Serie A football team enthusiasts (Fantacalcio.it 2025). These participants joined to represent the Cagliari team and even established a dedicated Facebook page for result sharing and social reinforcement. This self-organising community activity, while not formally studied in academic literature,

represents a compelling instance of user-led gamification that extends the intended platform usage beyond its designed parameters.

These organic community formations demonstrate the potential for digital interventions to catalyse social dynamics that sustain behaviour change beyond initial programmatic support. The phenomenon aligns with research on community-driven environmental interventions, which identifies peer support and social identity as critical factors in maintaining pro-environmental behaviours over time (Osbaldeston and Schott 2012). It also echoes findings from studies of serious games and exergames, which suggest that sustained engagement often stems from identity formation, narrative involvement, and community connection rather than purely extrinsic rewards (Watson et al. 2022; McGonigal 2011).

The following sections present a detailed analysis of the four most significant case studies, delineating their primary characteristics and the specific rationale for their selection. For each case, the implementation methodology and measured outcomes are systematically described, followed by a critical discussion of the limitations and potential areas for future improvement. This structured approach enables both granular assessment of individual implementations and identification of cross-cutting patterns that inform future applications of gamified mobility interventions.

4.2 Fostering workplace sustainability: insights from INAIL's nationwide initiative

The first case study examines a comprehensive workplace sustainability initiative implemented by *INAIL* (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro), Italy's national workers' compensation agency operating under the Ministry of Labour and Social Policies. With approximately 10 000 employees distributed across 14 territorial offices nationwide, INAIL launched "Giochiamoci il futuro" (Let's play our future), an internal mobility transformation project designed to promote sustainable commuting practices through gamified competition among regional locations.

This eleven-month initiative (September 2022–July 2023) encompassed seven distinct competitions, strategically structured across four phases, targeting offices in Rome, Southern Italy, and Northern Italy. The project represents a pioneering application of gamification applied to sustainability within Italy's public sector, demonstrating how large institutional organisations can leverage competitive dynamics to drive employee engagement in sustainability initiatives. By integrating multiple game formats, from introductory challenges to multi-week tournaments, the initiative provided a comprehensive testing ground for examining the differential effectiveness of various game approaches in corporate environments.

The strategic importance of this case extends beyond its scale to encompass its institutional context: as a management-mandated initiative within a traditional bureaucratic entity, it offers critical insights into top-down implementation of voluntary behavioural interventions and the role of organisational culture in determining engagement outcomes.



Figure 4.1: Promotional graphic for the INAIL Italy Tournament, the final phase of the "Giochiamoci il futuro" initiative. The tournament represented the culmination of eleven months of gamified sustainability engagement across INAIL's territorial offices.

4.2.1 Distinctive characteristics of case study and rationale for selection

This case study was selected based on three methodological criteria establishing its significance for understanding gamified interventions in large organisational contexts. First, as the inaugural MUV deployment within a major public institution, it provides baseline insights into adoption patterns and implementation challenges specific to bureaucratic environments. Second, the extensive geographical coverage across Italy's territorial divisions enables systematic analysis of regional variations in engagement and participation. Third, the substantial employee participation rate (15.75 % of the eligible workforce) combined with direct senior management endorsement demonstrates the potential for voluntary behavioural interventions within traditionally hierarchical governmental structures.

The implementation's natural experimental framework emerges from INAIL's distributed organisational structure, where 14 territorially distinct offices operate under unified corporate policies yet within different urban contexts and regional cultures. As shown in Table 4.1, participation rates varied markedly across macro-regions, with Northern offices achieving 25.93 % participation compared to 9.84 % in Rome and 15.95 % in Southern regions. This geographical gradient suggests systematic factors influencing adoption beyond individual preferences, potentially including urban mobility infrastructure, commuting patterns, or regional cultural attitudes toward innovation adoption.

Table 4.1: INAIL implementation overview by macro-region and participation metrics.

Macro-region	Offices	Cities	Total employees	Participants	Participation rate	Range (min-max)
Rome	4	Rome	1 230	121	9.84 %	3.25 %– 22.46 %
South	5	Bari, Catanzaro, Cagliari, Naples, Palermo	840	134	15.95 %	7.03 %– 44.25 %
North	5	Bologna, Florence, Genoa, Milan, Turin	698	181	25.93 %	16.79 %– 32.35 %
Total	14	11 cities	2 768	436	15.75 %	3.25 %– 44.25 %

The competition architecture comprised seven distinct engagements—three preliminary challenges and four progressive tournaments—designed to test different game dynamics across varying temporal scales and competitive structures. This multi-phase approach enabled comparative analysis of user engagement patterns between individual challenges (one-week duration) and team-based tournaments (six to eight weeks), providing empirical evidence for the behavioural mechanisms discussed in Section 4.1.3. The structured progression from regional competitions to a national finale also created opportunities to examine how competitive intensity and stakes influence sustained participation over extended periods.

The institutional context of management-driven implementation offers particular analytical value for understanding how executive endorsement affects employee uptake of voluntary initiatives. Unlike grassroots or externally mandated programs, this top-down approach enables assessment of how leadership communication and corporate cultural factors mediate the relationship between game design and behavioural outcomes in workplace settings (SuperAble INAIL 2022).

4.2.2 Implementation methodology and measured outcomes

4.2.2.1 Competition design and structure

The INAIL initiative employed a progressive four-phase tournament structure designed to test escalating levels of competitive intensity and team cohesion. The design followed gamification principles established in Section 3.2.3, incorporating both individual challenges and team-based tournaments to assess differential engagement patterns across various competitive formats.

Table 4.2: INAIL competition structure and progression across four phases.

Phase	Competition name	Dates	Duration (weeks)	Format	Teams
1	Rome Special Challenge	Sep 2022	1	Challenge	4
	Rome Tournament	Oct–Dec 2022	8	Tournament	4
2	Southern Special Challenge	Dec 2022	1	Challenge	6
	Southern Tournament	Jan–Mar 2023	8	Tournament	6
3	Northern Special Challenge	Mar 2023	1	Challenge	6
	Northern Tournament	Apr–Jun 2023	8	Tournament	6
4	Tournament of Italy	Jun–Jul 2023	6	Tournament	6

The tournament architecture incorporated a sophisticated progression mechanism to ensure competitive balance and escalating engagement. A specific formula was employed to maintain even team numbers, mandatory for scheduling head-to-head matches between pairs of teams. According to this progression structure, the victorious team from the *Rome Tournament* advanced to compete in the *Southern Tournament*, while the winner of the Southern Tournament proceeded to the *Northern Tournament*. Ultimately, both finalist teams from the three regional tournaments qualified for the *Tournament of Italy*, representing the culmination of the initiative.

Each phase integrated preliminary challenges (one-week competitive events aimed at stimulating player engagement within participating teams) with extended tournaments structured over eight-week periods. The tournament format began with a free-ranking phase, followed by weekly head-to-head matches that determined semifinal pairings and, ultimately, knockout finals conducted as one-on-one elimination rounds. The final Italy Tournament was condensed to six weeks due to temporal constraints, excluding the initial ranking phase and limiting group matches to four rounds instead of five, thereby preventing teams from competing against others within the same geographical origin group.

The incentive structure balanced intrinsic and extrinsic motivational drivers through a comprehensive reward system. Each tournament awarded prizes to the top three players from victorious teams, consisting of vouchers valued at € 120, € 100, and € 80, redeemable for sports equipment or books. Additionally, winning teams received commemorative trophies or engraved plaques and a € 200 donation to a charity of their choice, implementing the collaborative reward mechanisms discussed in Section 3.2.3.2.

This multi-layered structure enabled systematic comparison between short-term activation strategies and sustained engagement mechanisms, providing empirical validation for the tournament effectiveness patterns identified in Section 4.1.3.

4.2.2.2 Communication strategy and organisational support

Implementation success was significantly enhanced by full institutional support and strategic communication campaigns. Senior management endorsement was operationalised through multiple channels: official announcements via internal communication systems, customised promotional materials distributed across all territorial offices aimed not only at presenting *Giochiamoci il futuro* but also at chronicling the progression of the competitions over time, and live award ceremonies following each tournament phase. This multi-modal approach exemplified the communication strategies identified as critical success factors in Section 4.1.1.

The communication strategy incorporated both digital channels (internal newsletters, intranet announcements) and physical presence (posters, banners in office common areas), ensuring message penetration across diverse employee segments and technological preferences. This approach reflects the crucial role of internal communication in driving employee engagement, particularly when aligned with corporate sustainability goals (Mishra et al. 2014). A well-designed internal communication strategy can increase employee trust and awareness, boosting participation and commitment to sustainability initiatives.

Notably, the standardised communication approach across all offices enabled assessment of implementation consistency while accounting for regional cultural variations in adoption patterns.

4.2.2.3 Participation patterns and engagement dynamics

The initiative achieved substantial organisational penetration, with 436 employees (15.75 % of the eligible workforce) registering for the community and 365 users (83.7 % of registrants) completing at least one validated sustainable trip. This conversion rate significantly exceeds typical mobile application engagement benchmarks, suggesting effective alignment between gamification design and user motivations. These active users are included in all impact calculations and distance metrics, as they represent employees who, albeit to varying extents, actively contributed to the behavioural transformation objectives of the case study.

Participation rates varied significantly by location, ranging from 3 % to 44 %, despite uniform communication campaigns across all territorial offices. This variation likely reflects the presence of localised user bases in certain cities that embraced the initiative, promoting it internally through peer networks and engaging substantial portions of office staff, demonstrating the influence of social contagion mechanisms in organisational adoption patterns.

In examining user participation dynamics, the analysis concentrated on tournaments due to their extended duration compared to brief one-week challenges. The primary metric evaluated was the number of active users (AU), defined as those registering at least one valid trip, measured weekly against total users (TU) who joined the INAIL community. This temporal analysis was cross-referenced with tournament schedules to identify engagement correlations, as illustrated in Figure 4.2.

Active users vs Total users per week

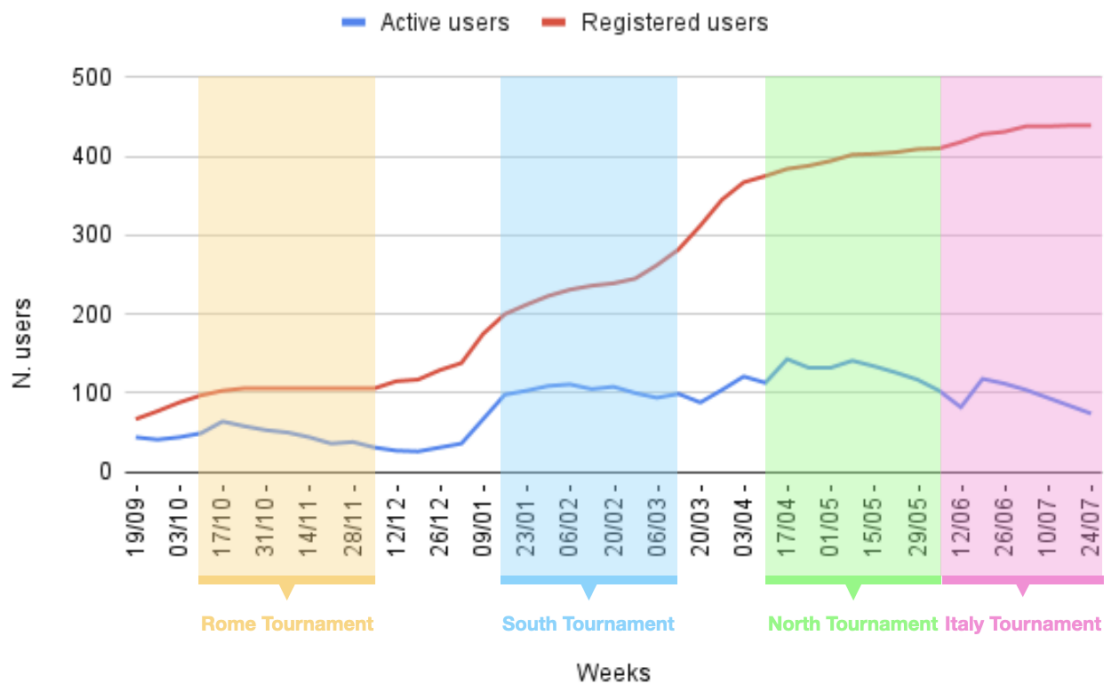


Figure 4.2: Weekly active user patterns throughout the INAIL initiative, showing correlation between tournament periods and engagement levels. Tournaments are highlighted to demonstrate the link between structured competition and sustained participation.

The correlation between tournament occurrence and user involvement becomes more pronounced when analysing valid trips recorded over time, as depicted in Figure 4.3.

When assessing tournament-specific engagement, each competition involved only a subset of the fourteen office teams (four teams in the Rome phase, six in subsequent regional tournaments). Consequently, impact evaluation required measuring active users against involved users (those potentially participating in each tournament) rather than the entire community, ensuring accurate assessment of competition-specific engagement rates.

Table 4.3: User engagement patterns across INAIL tournament phases.

Competition	RU	IU	Avg AU per week	AU/IU	Trips/AU	Trips/AU per week
Rome Tournament	106	103	44.25	42.96 %	100.74	12.59
South Tournament	262	150	90.00	60.00 %	124.64	15.58
North Tournament	410	213	114.63	53.82 %	119.04	14.88
Italy Tournament	436	262	83.71	31.95 %	105.95	15.14

RU = Registered Users, IU = Involved Users, AU = Active Users

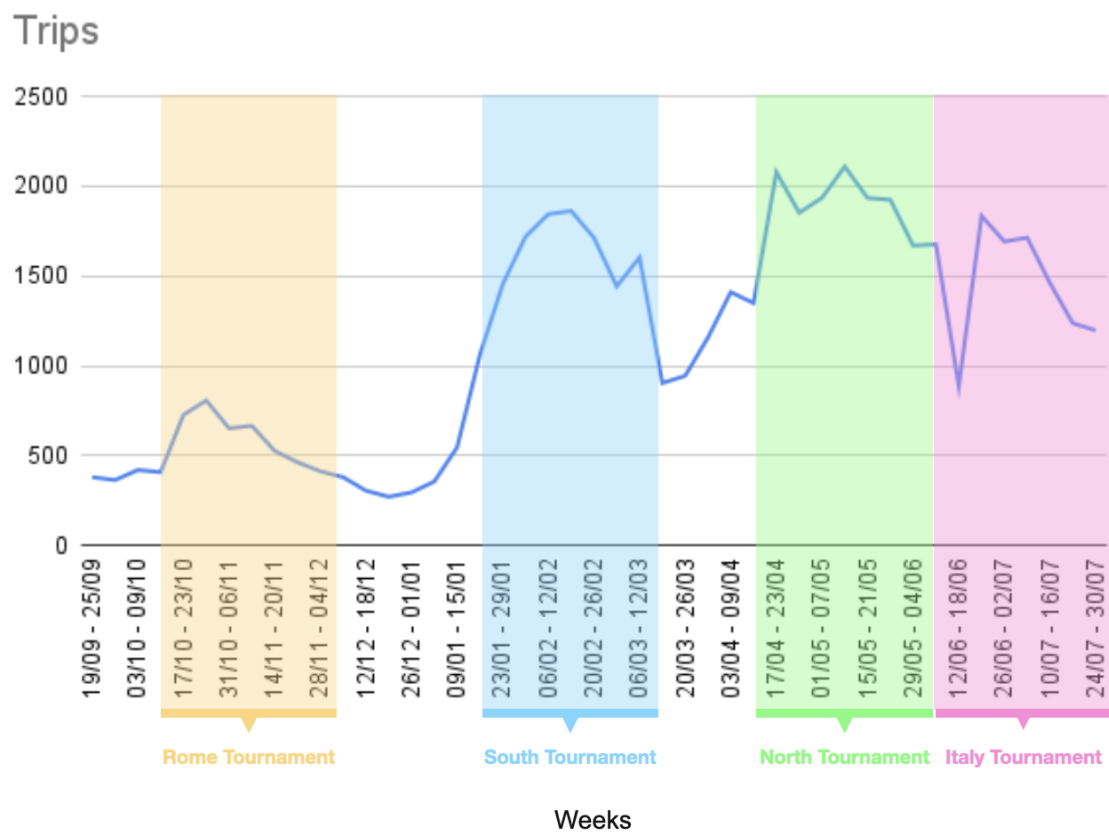


Figure 4.3: Weekly trip registration patterns during the INAIL initiative, demonstrating heightened activity during tournament periods and the relationship between competitive structure and behavioural engagement intensity.

The metrics indicate that the four tournaments yielded remarkably consistent results concerning both active user engagement and trip recording intensity. The average number of trips per active user varied between 100.74 and 124.64, while weekly trip frequency ranged from 12.59 to 15.58 trips per active user. The ratio of active users to involved users remained approximately 43 %, 60 %, and 54 % in the first three tournaments, declining to 32 % in the final tournament. This reduction is partially attributed to seasonal factors—the June-July timing when many employees were on vacation, rather than diminished engagement with the gamification mechanics. The average participation rate across all tournaments was 45.69 %, substantially exceeding typical corporate engagement benchmarks for voluntary initiatives.

These participation patterns validate the tournament effectiveness identified in cross-case analysis Section 4.1.3 while revealing the importance of temporal factors and organisational context in determining engagement outcomes. The consistency of engagement intensity among active participants across all phases suggests that the gamification design successfully maintained motivation despite varying external conditions.

4.2.2.4 Environmental and behavioural outcomes

Participants recorded 51 638 validated trips covering 933 873 sustainable kilometres, averaging 2 558 km per active user over the eleven-month period. Modal split analysis revealed a strong preference for public transportation (82 % of trips), with rail transport dominating (43 %), followed by bus (24 %), metro (12 %) and suburban bus (3 %). Active mobility modes (walking and cycling) each contributed 7 % of total trips, while electric vehicles and carpooling represented 2 % each.

The calculated CO₂ emission reduction of 3.39 t (9.29 kg per user) represents an average 15.28 % decrease in mobility-related emissions per participant. While this reduction falls below MUV's typical 33.82 % average, the difference primarily reflects the modal composition of INAIL participants, who predominantly utilised existing public transportation rather than shifting from private vehicle usage. This pattern suggests that game dynamics effectiveness varies based on baseline mobility patterns and available infrastructure alternatives—a finding with important implications for targeting behavioural interventions in different urban contexts.

4.2.3 Limitations, lessons learned and future applications

4.2.3.1 Methodological limitations and constraints

Several methodological limitations constrain the generalisability and depth of findings from the INAIL case study. The primary temporal constraint was the predetermined one-year project duration, which precluded assessment of long-term behavioural retention beyond the formal intervention period. This limitation is particularly significant given that sustainable habit formation typically requires extended reinforcement cycles, as established

in Section 3.1.3.1.

The geographical distribution of participation rates (3 %–44 %) suggests potential selection bias effects that were not systematically controlled. While uniform communication strategies were implemented across all offices, unmeasured confounding variables, including local transportation infrastructure quality, urban density, and regional cultural attitudes toward innovation adoption, may have influenced engagement patterns. The absence of randomised assignment to intervention conditions limits causal inferences about gamification effectiveness.

Additionally, the seasonal timing of the final Italy Tournament (June–July) coincided with vacation periods, introducing temporal confounds that affected participation metrics. The observed 32 % engagement rate during this phase may reflect calendar effects rather than diminished gamification effectiveness, highlighting the importance of temporal considerations in corporate intervention design.

Finally, the reliance on self-reported baseline mobility data introduces potential recall bias and social desirability effects in CO₂ calculations. While the ISO 14064-2 certified methodology provides robust impact quantification, the accuracy depends on participants' honest and accurate reporting of pre-intervention travel patterns.

4.2.3.2 Key insights and lessons learned

The INAIL implementation generated several critical insights that extend theoretical understanding of gamified behavioural interventions in organisational contexts. Most significantly, the differential effectiveness between tournament and challenge formats provided empirical validation for the social reinforcement mechanisms identified in Section 4.1.3. Tournament structures consistently generated higher engagement intensity (12.59–15.58 trips per active user per week) than individual challenges, confirming the behavioural value of interdependent success structures and scheduled competitive anchors.

Data collected during the tournaments indicated that this format was particularly effective in engaging users. Interviews conducted with a sample of employees at the conclusion of the initiative revealed that this effectiveness was primarily attributed to the competition among different offices. This finding confirms evidence from the literature on game-based learning, which shows that competition-based formats can significantly enhance participant motivation and performance, especially in structured organisational contexts (Burguillo 2010).

The nearly twofold variation in engagement rates achieved through structured communication campaigns demonstrates the critical importance of systematic change management in corporate sustainability projects. This finding aligns with Rogers's diffusion of innovation theory and reinforces the communication strategies identified as success factors in Section 4.1.1. Integrating ceremonial elements, including live award presentations and executive recognition, proved particularly effective in legitimising sustainable mobility choices within the institutional hierarchy.

Geographical participation patterns revealed the influence of social contagion mechanisms in organisational adoption. Offices with localised "champion" users who embraced the initiative internally achieved substantially higher engagement rates, suggesting that peer influence networks operate as powerful amplifiers of institutional change initiatives. This finding has important implications for implementation strategies, indicating that identifying and activating internal advocates may be more effective than relying solely on top-down communication approaches.

The modal composition of INAIL participants (82 % public transportation usage) yielded lower CO₂ reduction percentages (15.28 %) compared to MUV's typical 33.82 % average, highlighting the importance of baseline mobility patterns in determining intervention impact. This insight suggests that gamification effectiveness varies systematically based on available infrastructure alternatives and existing travel habits, a crucial consideration for targeting behavioural interventions across different urban contexts.

4.2.3.3 Implications for future implementations

The INAIL case study yields several strategic recommendations for scaling gamified mobility interventions in large organisational contexts. For temporal design, implementation periods should extend beyond twelve months to enable assessment of post-intervention behavioural retention, with particular attention to seasonal variation effects. Multi-year implementations could incorporate cyclical tournament structures that maintain engagement while allowing for natural participation fluctuations.

Regarding communication strategy, companies should prioritise the identification and activation of internal champions across different geographical or departmental units rather than relying exclusively on centralised communication approaches. Developing peer-to-peer promotion mechanisms could amplify institutional messaging through trusted social networks, potentially achieving more sustainable engagement than top-down approaches alone.

For competitive structure design, the tournament format should be prioritised over individual challenges for sustained engagement, with particular emphasis on weekly head-to-head matches that create consistent competitive dynamics. However, preliminary challenges remain valuable for onboarding and skills development, suggesting an optimal progression from individual activation to team-based competition.

Context-specific adaptations should account for baseline mobility patterns and available infrastructure. Organisations in car-dependent contexts may achieve higher emission reduction percentages but potentially lower absolute participation rates, while public-transit-oriented environments may demonstrate inverse patterns. Implementation strategies should be tailored accordingly, with different engagement targets and success metrics based on contextual mobility characteristics.

Finally, the integration of mobility data collection with corporate mobility management planning represents a valuable secondary benefit that enhances intervention value beyond

behavioural change outcomes. The mobility data related to home-work commutes collected during the project were provided to the mobility manager in an anonymous and aggregated format, enriched with qualitative information from employee surveys on propensity to change. This comprehensive dataset, compiled into fourteen reports for all involved offices, enabled evidence-based mobility management plans for each territorial office. The use of anonymised, aggregate data to inform localised planning strategies aligns with best practices in mobility management, which increasingly rely on data-driven approaches to support decision-making in the context of shared and sustainable transport systems (Shaheen and Cohen 2020). This integrated approach aligns with contemporary corporate sustainability reporting requirements and positions mobility gamification as a strategic organisational capability rather than merely an employee engagement initiative.

4.3 Driving change: encouraging sustainable commuting at LIST in Luxembourg

The second case study examines MUV's inaugural international deployment, implemented at the *Luxembourg Institute of Science and Technology* (LIST), a leading research and technology organisation situated at the Belval Innovation Campus in Esch-sur-Alzette. This implementation represents a critical milestone in understanding the cross-cultural transferability of gamified behavioural interventions, providing insights into how digital sustainability solutions perform across different national contexts, policy environments, and mobility infrastructures.

LIST's partnership with MUV emerged within a unique policy landscape where Luxembourg had become the first country globally to introduce free public transport in 2020, yet car dependency remained persistently high among the 600-employee workforce, particularly among cross-border commuters. Recent analyses show that this policy has not produced the expected behavioural shift, and a significant number of residents and workers still rely on private vehicles for daily mobility (RTL Today 2023). According to Inrix's 2024 Global Traffic Scorecard, Luxembourg City ranks as the 87th most traffic-congested city globally, while Esch-sur-Alzette, the location of LIST, is ranked 283rd, with drivers losing an average of 36 hours annually in traffic (Inrix 2024). This contextual paradox, where comprehensive policy innovation coexisted with persistent behavioural inertia, created an ideal natural experiment examining how gamification mechanisms perform when traditional policy incentives prove insufficient to drive modal shift.

The twelve-month initiative (throughout 2022) was structured around four distinct competition formats within a controlled organisational environment. This case study builds upon previous analysis of the LIST implementation (Schillaci, Tinnirello, et al. 2025), extending the original findings with comprehensive longitudinal data and cross-case comparative insights. Unlike the geographically distributed INAIL implementation, LIST provided a concentrated setting where uniform conditions could be maintained while testing multiple competitive

structures sequentially, ranging from individual challenges to team tournaments. As the first comprehensive multi-format experiment within a single organisation, this case yields crucial empirical evidence for the differential impact of various game dynamics on sustained behavioural change in corporate sustainability initiatives.



Figure 4.4: Promotional graphic for LIST's first tournament implementation. The visual communication strategy reflected LIST's technology-oriented culture.

4.3.1 Distinctive characteristics of case study and rationale for selection

This case study was selected based on four methodological criteria establishing its unique value for understanding service effectiveness across different contexts. First, as MUV's inaugural international implementation, it provides critical insights into the cross-cultural transferability of behavioural interventions beyond the Italian context. Second, the concentrated single-site deployment enabled controlled experimental conditions that were impossible to achieve in geographically distributed implementations like INAIL. Third, the sequential testing of four distinct game formats within the same organisational environment allows for precise comparative analysis of differential engagement patterns. Fourth, the implementation occurred within a unique policy environment where traditional incentives (free public transport) struggled to modify behaviour, creating an ideal testing ground for alternative intervention mechanisms.

The experimental framework emerges from LIST's characteristics as a mid-sized research institution with a relatively homogeneous, highly educated workforce. Unlike INAIL's diverse geographical and cultural contexts, LIST provided uniform conditions across participants in terms of urban environment, mobility infrastructure access, and organisational culture. This homogeneity eliminates many confounding variables present in multi-site studies, enabling more precise attribution of engagement differences to specific gamification mechanics rather than contextual factors.

The sequential competition structure implemented at LIST represents a methodological innovation compared to the parallel tournament approach used in INAIL. As shown in Table 4.4, the four competitions were deliberately structured to test different engagement

mechanisms: competitive individual challenges, collaborative community challenges, and two distinct tournament formats with varying team structures and durations.

Table 4.4: LIST competition structure and sequential implementation across 2022.

Phase	Competition name	Dates	Duration (weeks)	Format	Teams
1	Competitive Challenge	Feb 2022	4	Challenge	–
2	Collaborative Challenge	Mar–Apr 2022	4	Challenge	–
3	Tournament #1	Jun–Jul 2022	8	Tournament	5
4	Tournament #2	Oct–Dec 2022	6	Tournament	4

The Luxembourg policy context provides particular analytical value for understanding intervention effectiveness in environments where traditional policy tools have proven insufficient. The persistence of car dependency despite comprehensive public transport subsidisation creates a natural control condition, enabling assessment of whether gamification mechanisms can succeed where economic incentives have failed. This context is particularly relevant for policymakers seeking alternative approaches to behavioural change in mobility-resistant populations.

4.3.2 Implementation methodology and results achieved

4.3.2.1 Competition design and structure

The LIST implementation operationalised four distinct competitions—a competitive challenge, a collaborative challenge, and two team tournaments—to test distinct engagement mechanisms within the same organisational environment, enabling precise comparative analysis of game dynamics effectiveness.

The incentive structure demonstrated strategic variation across competition formats. The competitive challenge offered € 30 gift cards from an organic product store to the top five performers, implementing individual achievement recognition. The collaborative challenge incorporated collective environmental impact through donations to a reforestation project in Guatemala upon achieving predetermined community thresholds, testing cooperative motivation mechanisms. Both tournaments operated without material rewards, relying exclusively on intrinsic motivational drivers and social recognition, enabling assessment of sustained engagement without extrinsic incentives.

Tournament team formation employed random allocation rather than pre-existing organisational structures, ensuring equitable distribution of registered participants across five teams in Tournament #1 and four teams in Tournament #2. This randomisation approach eliminated potential bias effects from established social networks or departmental hierarchies, providing controlled experimental conditions that enhanced comparative validity.

A significant procedural evolution occurred mid-implementation regarding competition registration requirements. Initially, MUV required manual individual registration for all dedicated competitions, creating participation barriers. This approach was subsequently modified to implement automatic enrollment for all community members, simplifying access and reducing friction. This methodological adjustment proved critical for understanding how administrative barriers affect user adoption patterns in corporate environments.

4.3.2.2 Communication strategy and organisational support

Implementation commenced through an online launch event to introduce MUV's functionality and establish initial user engagement. This digital-first approach reflected LIST's research-oriented culture and distributed work arrangements, particularly relevant during the 2022 implementation period.

The communication strategy centred on sustained internal campaigns incorporating customised graphic materials disseminated through corporate email channels. Unlike INAIL's multi-modal approach combining digital and physical promotional materials, LIST's streamlined digital strategy leveraged the organisation's communication infrastructure and technology-comfortable workforce. This concentrated approach enabled assessment of digital communication effectiveness in isolation from physical promotional elements.

Organisational support was integrated through alignment with LIST's broader sustainability initiatives and corporate environmental reporting frameworks. Management endorsement provided institutional legitimacy while positioning the mobility intervention within established corporate social responsibility structures, facilitating employee participation without creating additional administrative burden.

4.3.2.3 Participation patterns and engagement dynamics

The initiative achieved 93 employee participants, representing 15.5 % of LIST's 600-person workforce, closely paralleling INAIL's 15.75 % engagement rate despite vastly different organisational structures and national contexts. This consistency suggests robust cross-cultural transferability of gamified mobility interventions in corporate environments.

Temporal analysis revealed a strong correlation between competition scheduling and platform activity, demonstrating clear activation spikes corresponding to tournament periods. Weekly active user analysis, employing methodology consistent with the INAIL case study, confirmed that engagement patterns closely tracked competition timing, with tournaments generating particularly pronounced effects. Figure 4.5 illustrates the progression of active, registered, and deleted users throughout the twelve-month implementation, highlighting substantial activation during competitive phases compared to baseline periods.

The correlation between structured competitions and user behaviour intensified when examining trip registration patterns, as demonstrated in Figure 4.6. Weekly trip data revealed dramatic spikes during tournament periods, validating the behavioural anchoring effects of competitive temporal structures identified in cross-case analysis Section 4.1.3.

Active users vs Total users per week

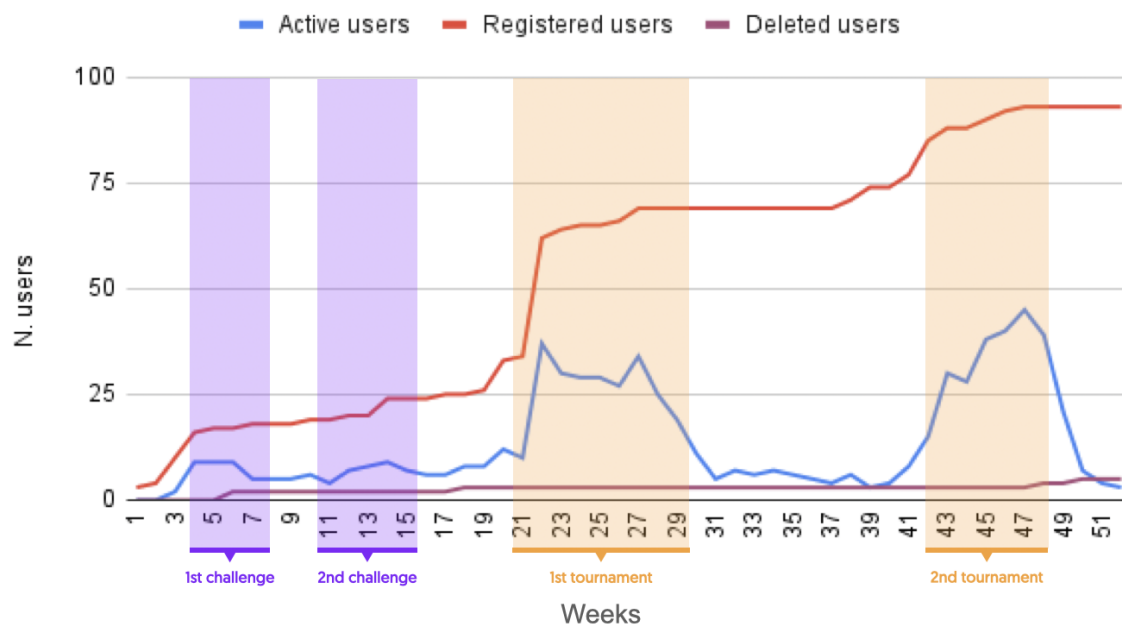


Figure 4.5: LIST user engagement patterns throughout 2022, showing correlation between competition periods and active user participation. The timeline highlights substantial activation spikes during tournament phases compared to baseline activity levels.

Trips

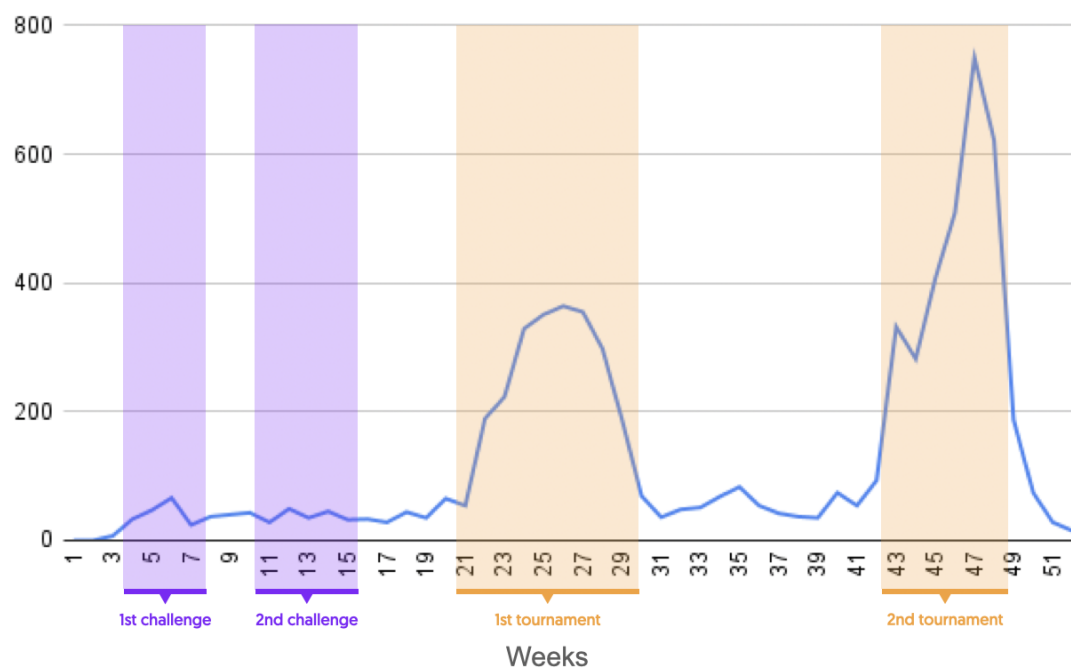


Figure 4.6: Weekly trip registration patterns at LIST during 2022, demonstrating pronounced correlation between tournament scheduling and user activity intensity. Tournament periods generated higher trip recording compared to challenge and non-competition phases.

4.3. Driving change: encouraging sustainable commuting at LIST in Luxembourg

Competition-specific engagement metrics demonstrated significant variation across game formats, as detailed in Table 4.5.

Table 4.5: LIST competition trends showing engagement metrics across different game formats

Competition	TU	RU	Avg AU per week	AU/RU	Trips/AU	Trips/AU per week
Competitive Challenge	17	9	6.00	66.67 %	24.86	6.21
Collaborative Challenge	20	19	7.75	40.79 %	20.77	5.19
Tournament #1	64	48	28.75	59.90 %	79.90	9.99
Tournament #2	88	53	36.67	69.19 %	79.17	13.20

TU = Total Users, RU = Registered Users, AU = Active Users

The proportion of active users among total community subscribers remained consistent across competitions (35–45 %), indicating stable baseline engagement regardless of format variation. However, conversion rates among competition registrants reached 69.19 % during Tournament #2, demonstrating improved efficiency over time and validating the learning curve effects in gamification adoption.

Most significantly, trip recording intensity varied dramatically between challenges (average 22.8 trips per active user) and tournaments (average 79.5 trips per active user), with tournaments generating nearly quadruple the activity levels. Weekly trip frequency analysis confirmed this pattern, with tournaments achieving 9.99–13.20 trips per active user weekly compared to 5.19–6.21 trips for challenges.

Temporal aggregation across competition categories revealed systematic engagement differentials, as presented in Table 4.6.

Table 4.6: LIST competition ranges comparing engagement patterns across different competition types and non-competition periods

Range considered	Duration (weeks)	Avg AU per week	AU/TU	Trips per week	Trips/AU per week
Sum of challenges	8	6.88	37.67 %	41.88	6.09
Sum of tournaments	14	32.14	43.69 %	371.43	11.56
Sum of weeks with no competitions	30	6.60	13.37 %	48.63	7.37
Entire initiative	52	13.60	26.61 %	134.50	9.89

TU = Total Users, AU = Active Users

These aggregated metrics validate tournament superiority identified in Section 4.1.3, with tournament periods generating 43.69 % active user ratios compared to 37.67 % for challenges and 13.37 % during non-competition periods. Critical evidence emerges from weekly trip intensity: tournaments achieved 11.56 trips per active user weekly, nearly doubling challenge performance (6.09) and significantly exceeding baseline activity (7.37).

This pattern confirms that tournament formats activate stronger engagement mechanisms through social reinforcement and temporal anchoring effects.

4.3.2.4 Environmental and behavioural outcomes

The environmental impact assessment was not available for the LIST case study due to the absence of CO₂ emission calculation capabilities during the implementation period. Analysis was therefore limited to behavioural engagement patterns, as detailed in the preceding sections. The methodological implications of this constraint are addressed comprehensively in Section 4.3.3.1.

4.3.3 Limitations, lessons learned and future applications

4.3.3.1 Methodological limitations and constraints

Several methodological limitations constrain the generalisability and comprehensiveness of findings from the LIST case study. The primary constraint was the inability to assess the reduction in the community's carbon footprint, preventing a full assessment of MUV's environmental impact beyond behavioural engagement metrics. The LIST implementation preceded the development of MUV's standardised CO₂ emission calculation algorithm, limiting analysis to participation patterns rather than environmental outcomes. This measurement gap represents a critical limitation for evaluating the ultimate sustainability objectives of gamified mobility interventions.

The procedural evolution regarding competition registration requirements introduced potential confounding effects in comparative analysis. The transition from manual individual registration to automatic enrollment mid-implementation may have artificially inflated participation rates in later competitions, complicating direct comparisons between early challenges and subsequent tournaments. This methodological inconsistency limits the precision of causal inferences about differential game format effectiveness.

The concentrated single-site deployment, while enabling controlled experimental conditions, constrains external validity regarding scalability across different organisational contexts. LIST's characteristics as a research-oriented institution with a highly educated, technology-comfortable workforce may not represent broader corporate environments, particularly those with diverse skill levels or varying technological adoption patterns.

Additionally, the unique Luxembourg policy context, featuring free public transport since 2020, creates complex baseline conditions that may influence both participation patterns and potential emission reduction calculations. The persistence of car dependency despite policy incentives suggests systematic behavioural resistance that may not generalise to contexts with different mobility infrastructure or policy environments.

4.3.3.2 Key insights and lessons learned

The LIST implementation generated several critical insights that advance theoretical understanding of gamified behavioural interventions in corporate contexts. Most significantly, the data presented indicate that team tournaments unequivocally constitute the most promising game dynamic for user activation and frequency of application usage in tracking sustainable trips. Tournament formats achieved nearly quadruple the trip recording intensity compared to challenges (average 79.5 vs 22.8 trips per active user), with weekly engagement rates reaching 9.99–13.20 tripsperactiveuser compared to 5.19–6.21 trips for challenges.

This differential effectiveness appears attributable to the inherent structural characteristics of tournaments versus challenges. Tournaments featuring weekly head-to-head matches stimulate consistent engagement, particularly in matches with uncertain outcomes, creating sustained behavioural anchoring effects throughout extended competition periods. Conversely, competitive and collaborative challenges, despite performing adequately for active users, proved less effective in fostering sustained participation. Challenges with defined start and end points resulted in diminished intensity of use over time, especially with fewer participants and more predictable outcomes.

The cross-cultural transferability demonstrated by LIST's 15.5 % engagement rate, closely paralleling INAIL's 15.75 % despite vastly different organisational and national contexts, suggests robust applicability of gamification mechanisms across diverse corporate environments. This consistency indicates that fundamental engagement drivers transcend specific cultural or institutional characteristics, supporting broader scalability potential.

The effectiveness of streamlined digital communication strategies, in contrast to INAIL's multi-modal approach, provides evidence for context-appropriate implementation methodologies. LIST's technology-oriented workforce responded effectively to email-based campaigns, suggesting that communication strategies should align with organisational culture and employee technological preferences rather than applying universal approaches.

The random team allocation methodology successfully eliminated bias effects from pre-existing social networks while maintaining high engagement levels, demonstrating that artificially constructed team structures can effectively activate social reinforcement mechanisms without relying on established organisational hierarchies.

4.3.3.3 Implications for future implementations

The LIST case study yields several strategic recommendations for enhancing gamified mobility interventions in corporate contexts. Regarding competitive structure design, tournament formats should be prioritised for sustained engagement, with particular emphasis on weekly head-to-head scheduling that creates consistent temporal anchors for participation. However, the observation that different game dynamics serve distinct engagement purposes suggests the need for custom tournament formats tailored to specific community characteristics. Testing different structures in varied communities could help determine which configurations are most effective in fostering engagement, or whether flexible, community-tailored

tournament models may prove most effective in fostering participation.

The procedural lessons regarding registration requirements indicate that automatic enrollment should be implemented from project launch to ensure consistent measurement conditions and reduce participation barriers. The mid-implementation transition observed at LIST created analytical complications that could be avoided through careful initial system design.

For communication strategy development, organisations should conduct preliminary assessments of workforce technological preferences and communication patterns to optimise engagement approaches. The effectiveness of LIST's streamlined digital strategy suggests that well-designed single-channel approaches may outperform multi-modal campaigns in appropriate contexts, potentially reducing implementation complexity while maintaining effectiveness.

Finally, context-specific adaptations should account for unique policy environments and mobility infrastructure characteristics. The Luxembourg free public transport context demonstrates that gamification effectiveness may vary based on existing policy incentives, suggesting that intervention design should incorporate local mobility policies, infrastructure availability, and existing behavioural patterns in strategic planning.

4.4 Gamifying student mobility: the MOB Tournament experience

The third case study examines the most extensive gamified mobility intervention undertaken by MUV to date, implemented through a strategic partnership with *Fondazione Unipolis* between 2022 and 2024. *Fondazione Unipolis* serves as the non-profit enterprise foundation of the *Unipol Group*, a prominent Italian insurance conglomerate, dedicated to implementing social responsibility initiatives and fostering cultural and civic development among individuals and communities.

The two-year initiative, titled "*MOB — Movimento in Rivoluzione*" (Movement in Revolution), was strategically designed to engage *Generation Z* with sustainable mobility through active participation and civic engagement. Unlike the corporate implementations examined in previous case studies, the MOB project targeted young people across Italy, focusing on high school students, university participants, and members of sports, cultural, and religious organisations. This demographic focus represents a critical departure from workplace-oriented interventions, enabling assessment of gamification effectiveness across different age cohorts and institutional contexts.

The tournament component, conducted from 20 March to 29 May 2023 as one of the most relevant phases within the two-year project, achieved unprecedented participation with 2 560 registered individuals across 154 teams, representing the largest gamified mobility intervention in MUV's operational history. The MOB tournament's institutional framework provided unique analytical opportunities for understanding gamification effectiveness in

educational contexts. The integration of learning components, bonus mechanisms, and social media engagement created a multi-layered intervention that extended beyond traditional competition formats.

The temporal structure of the initiative, spanning from registration in September 2022 through competition conclusion in May 2023, provided extended observation periods for behavioural analysis. The preliminary "athletic preparation" phase, featuring five preparatory challenges over six months, offered insights into sustained engagement mechanisms prior to formal competition commencement. This extended timeline enables examination of both immediate competitive effects and medium-term behavioural retention patterns among young participants.



Figure 4.7: Visual identity and branding of the MOB Tournament, designed to appeal to Generation Z participants. The branding strategy reflected the initiative's focus on youth engagement and digital-native communication approaches.

4.4.1 Distinctive characteristics of case study and rationale for selection

This case study was selected based on five methodological criteria establishing its critical value for understanding gamification effectiveness across demographic and institutional contexts. First, as MUV's largest implementation by participant volume (2 560 individuals), it provides robust statistical power for engagement analysis and enables identification of patterns that may not be detectable in smaller corporate implementations. Second, the exclusive focus on Generation Z participants (16–25 years) enables precise assessment of age-specific responsiveness to gamification mechanisms, addressing a critical gap in existing corporate-focused mobility research.

Third, the nationwide geographic distribution across all Italian regions eliminates the regional limitations present in previous case studies, enabling assessment of cultural and infrastructural variations in engagement patterns. The representation spans diverse urban densities, mobility infrastructure qualities, and regional economic conditions, providing adequate coverage of Italian demographic diversity. Fourth, the educational institutional context represents a fundamental departure from workplace implementations, enabling evaluation

of gamification transferability across organisational types and authority structures.

Fifth, the integration of learning components, social media engagement, and multimedia content creation establishes a multi-dimensional intervention model that extends beyond pure competition mechanics. This complexity enables assessment of how supplementary engagement mechanisms interact with core game elements to influence sustained participation and behavioural change outcomes.

The demographic composition provides particular analytical value for understanding generational differences in sustainability engagement, focusing on digital natives with high technological comfort levels and established social media usage patterns.

4.4.2 Implementation methodology and results achieved

4.4.2.1 Competition design and structure

The MOB tournament implemented an innovative three-phase competitive structure spanning ten weeks, designed to accommodate the largest participant volume in MUV's deployment history while maintaining competitive intensity throughout extended duration. Unlike traditional tournaments with predetermined team numbers, the MOB format employed dynamic team formation based on registration demand, ultimately accommodating 154 teams across diverse institutional contexts.

The methodological innovation emerged from the tournament's adaptive team formation system, which required sophisticated geographic and institutional matching algorithms. A specific procedure was devised to prevent multiple students from the same association, school, or class from forming redundant teams or creating teams with insufficient participants. This system required individuals to select their province and municipality of residence, followed by their school and class or organisation, thereby establishing a unique link between each team and its respective institution. The mechanism encouraged participants to join existing teams associated with their organisation before creating new ones, optimising team distribution and institutional representation.

Once a team was established, its creator was allocated 48 hours to invite at least five additional participants; failure to meet this requirement resulted in automatic team deletion. The integration of countdown timers and time-triggered notifications effectively prevented the formation of "ghost teams"—teams unable to compete due to insufficient membership. This mechanism necessitated comprehensive integration of all eligible schools and organisations across Italy, simplifying the team-building process while minimising registration errors.

The competitive architecture comprised three distinct phases designed to progressively filter teams while maintaining engagement intensity. The initial phase, lasting two weeks, functioned as a qualification round where all 154 teams competed within a unified ranking system. Upon phase conclusion, the top 128 teams advanced to the group stage, ensuring competitive merit determined progression while eliminating less engaged participants.

The second phase extended over three weeks and featured group-based competition, where the 128 qualifying teams were divided into 32 groups of four teams each. Each group conducted three weekly matches in head-to-head format, with the highest-ranked team from each group (32 teams total) advancing to the playoff stage. This structure maintained the weekly competitive anchoring identified as effective in previous case studies while adapting to larger participant volumes.

The final phase comprised five weekly knockout matches, progressing from round of 16 through semifinals to the championship final. This tournament-style elimination format created escalating competitive intensity while maintaining participant engagement even for eliminated teams through continued tracking opportunities.

Team scoring employed a hybrid individual-collective mechanism designed to balance personal contribution with team collaboration. Team points were calculated by summing the scores of the six highest-performing players and adding the average score of remaining team members. This approach prevented teams from gaining advantages through excessive membership while ensuring all participants could contribute meaningfully to team success.

The incentive structure represented the most substantial reward system in MUV's implementation portfolio, with total prizes exceeding € 20 000. Fondazione Unipolis provided both collective and individual incentives, with the top three teams receiving monetary prizes of € 7 000 for first place and € 4 000 each for second and third positions. Additionally, the best individual players from winning teams and overall tournament leaders received € 400 vouchers redeemable for events or international travel, creating both team-based and individual motivation mechanisms.

4.4.2.2 Communication strategy and organisational support

The MOB tournament's communication strategy employed a multi-channel approach specifically designed for Generation Z engagement, leveraging both traditional institutional channels and contemporary social media platforms. Implementation commenced with a launch event in Genoa on 16 September 2022, establishing initial visibility and generating media coverage that contributed to nationwide awareness among target demographics.

The campaign incorporated systematic institutional outreach through educational networks, youth organisations, and religious associations. Unlike the corporate-focused approaches used in INAIL and LIST implementations, the MOB strategy required coordination with diverse institutional types, each with distinct communication protocols. This complexity necessitated development of customised promotional materials adapted to different contexts while maintaining consistent branding and messaging.

Digital engagement formed the central component of the communication strategy, recognising Generation Z's digital-native characteristics and platform preferences. Rather than relying on traditional institutional channels, the campaign strategically targeted young audiences through direct partnerships with platforms highly frequented by students, including collaborations with *Skuola.net*, Italy's leading student forum, and engagement with young

influencers through *TikTok*. This approach enabled direct access to target demographics through their preferred digital environments.

The initiative included innovative social media-oriented engagement mechanisms, including the "MOB stories" component that encouraged participants to create and share videos demonstrating sustainable travel methods on their personal social media accounts. Participants tagged MUV and Fondazione Unipolis, included their MUV nickname, and used the hashtag #TorneoMOB, creating organic content amplification through peer networks. This user-generated content approach leveraged peer influence and social validation mechanisms particularly effective among young adult demographics, with over 50 videos posted throughout the competition period.

Organisational support was facilitated through Fondazione Unipolis's established networks and institutional credibility within Italian educational and youth sectors. The foundation's backing provided legitimacy and resources that enabled systematic outreach across regional and institutional boundaries, addressing the challenge of coordinating a nationwide initiative across diverse organisational types.

The extended promotional timeline, spanning from September 2022 registration through March 2023 competition commencement, enabled sustained awareness building and gradual engagement escalation. The "athletic preparation" phase, featuring five preparatory challenges over six months, served both as engagement maintenance and communication reinforcement, ensuring participant retention during the extended pre-competition period.

4.4.2.3 Participation patterns and engagement dynamics

The MOB tournament achieved exceptional scale with 2 560 total registrations across 154 teams, demonstrating substantial appeal among Generation Z participants. Geographic distribution reflected nationwide engagement, with 47 % of teams originating from southern regions and islands, 34 % from northern regions, and 19 % from central regions. This distribution indicates successful penetration across diverse regional contexts and varying mobility infrastructure conditions.

Institutional composition revealed broad appeal across educational and youth organisational types. Secondary schools contributed 89 teams (57.8 %), representing the largest participant category, followed by sports and cultural associations with 42 teams (27.3 %), universities with 14 teams (9.1 %), and religious organisations with 9 teams (5.8 %). This diversity enables systematic comparison of engagement patterns across different institutional contexts within the same demographic cohort.

Active participation analysis reveals significant engagement intensity throughout the ten-week competition period. Of the 2 560 total registrants, 852 individuals (33.28 %) actively participated in the tournament, substantially exceeding engagement rates observed in corporate implementations. The average weekly active user count reached 454 participants, representing 17.8 % of total registrants, indicating sustained engagement despite extended competition duration.

4.4. Gamifying student mobility: the MOB Tournament experience

Phase-specific engagement patterns demonstrated interesting variations correlating with competitive intensity and team numbers, as detailed in Table 4.7.

Table 4.7: MOB tournament phase trends showing engagement and trip metrics across different competitive phases

(a) Participation metrics

Tournament phase	Duration (weeks)	Teams	RU	IU	Avg AU per week	AU/IU
Free ranking	2	154	2 314	1 948	512.50	26.32 %
Group phase	3	128	2 367	1 846	307.00	16.63 %
Playoffs	5	32	2 538	1 088	254.60	23.40 %
Overall Tournament	10	154	2 560	1 487	321.90	21.64 %

(b) Trip intensity metrics

Tournament phase	Duration (weeks)	Teams	AU/team per week	Trips/AU	Trips/AU per week
Free ranking	2	154	3.33	21.91	10.95
Group phase	3	128	2.40	25.69	8.56
Playoffs	5	32	7.96	61.95	12.39
Overall Tournament	10	154	3.42	109.55	10.95

RU = Registered Users, IU = Involved Users, AU = Active Users

The data reveal several noteworthy engagement patterns across tournament phases. Active user participation remained relatively stable throughout the competition (16.63–26.32 %), with the group phase showing the lowest engagement rate. However, trip recording intensity demonstrated significant variation, with playoff participants achieving 61.95 trips per active user compared to 21.91–25.69 in earlier phases. Weekly trip frequency analysis confirms escalating engagement intensity, reaching 12.39 trips per active user weekly during playoffs compared to 8.56–10.95 in preliminary phases.

Similarly, an analysis of the average number of active players per team reveals a deviation from 3.33 in the first phase to 2.40 in the second and 7.96 in the playoffs. This suggests a significant increase in player participation during the final phase compared to the initial two phases. A similar trend is observed in the data concerning the average number of trips travelled per week per user, which shows a deviation from 10.95 trips in the first phase to 8.56 in the second phase and then to 12.39 in the playoffs.

The progressive filtering mechanism successfully maintained competitive engagement while accommodating the large initial participant volume. The reduction from 154 to 32 teams across phases created escalating competitive intensity without losing overall participant engagement, as evidenced by sustained weekly active user counts and increasing individual trip intensity among remaining participants. The success of the MOB Tournament also received national visibility, with widespread media coverage highlighting the

engagement of thousands of young participants and the final awarding of prizes (ESG News 2023).

4.4.2.4 Environmental and behavioural outcomes

The MOB tournament generated substantial sustainable mobility activity, with participants completing 36 221 validated trips covering 233 094 km over the ten-week competition period. This represents an average of 274 km and 42.5 trips per active participant, demonstrating significant individual engagement with sustainable transport modes.

Modal split analysis revealed patterns consistent with the target demographic's mobility characteristics. Public transport emerged as the predominant mode (81.7 % of trips), followed by walking (8.2 %), cycling (4.3 %), carpooling (3.7 %), and electric scooters (2.1 %). This distribution reflects the high school student majority whose primary travel involves home-school commuting, typically via public transportation systems.

Environmental impact calculations yielded 6.86 t CO₂ emission reductions, equivalent to 8.05 kg per active user. The average emission reduction of 28.10 % closely aligns with MUV's cross-implementation average of 33.82 %, indicating that behavioural change mechanisms operated effectively despite the different demographic and institutional context. This consistency suggests robust transferability of gamification approaches across age groups and organisational settings.

The alignment between MOB outcomes and overall MUV performance indicates that many car-based trips were successfully replaced by public transport alternatives, demonstrating the intervention's effectiveness in promoting modal shift among young adults. The substantial absolute numbers (36 221 trips, 233 094 km) validate the scalability potential of gamified mobility interventions when applied to large, motivated demographic cohorts.

4.4.3 Limitations, lessons learned and future applications

4.4.3.1 Methodological limitations and constraints

Several methodological limitations constrain the generalisability and long-term validity of findings from the MOB tournament case study. The primary temporal constraint was the limited ten-week competition duration, which precludes assessment of long-term behavioural changes or sustained effects on students' mobility choices beyond the immediate competitive period. This limitation is particularly significant for youth demographics, where habit formation and modal shift preferences may require extended observation periods to distinguish between temporary competition effects and genuine behavioural transformation.

The demographic focus on 16–25 year participants, while enabling targeted analysis of Generation Z engagement patterns, introduces age-specific constraints that limit generalisability across broader population segments. The concentration on students and young adults creates potential bias effects, as this demographic typically demonstrates higher technological adoption rates and environmental awareness compared to general population

samples. Consequently, engagement metrics and behavioural change outcomes may not transfer directly to older demographics or non-student populations.

The voluntary participation model, while ethically appropriate and practically necessary for youth engagement, introduces self-selection bias that affects result interpretation. Participants represent individuals already predisposed toward sustainable mobility or competitive gaming, potentially inflating engagement rates and environmental impact measurements compared to mandatory or population-representative interventions.

The geographical concentration in Italy, despite nationwide coverage, limits cross-cultural transferability assessment. While the initiative demonstrated effectiveness across Italian regional variations, cultural, infrastructural, and policy contexts in other European or international settings may yield different engagement patterns and behavioural outcomes. The integration with Italian educational systems and youth organisations creates institutional dependencies that may not exist in alternative national contexts.

Additionally, the substantial financial reward structure (€ 15 000 in prizes plus individual vouchers) represents a resource requirement that may not be replicable in contexts with limited funding availability. The relationship between incentive magnitude and sustained engagement remains unclear, potentially creating scalability constraints for future implementations with reduced economic resources.

4.4.3.2 Key insights and lessons learned

The MOB tournament generated significant insights advancing understanding of gamified behavioural interventions in youth demographics and large-scale competitive implementations. Most importantly, the initiative demonstrated exceptional scalability potential, with 2 560 participants across 154 teams representing the largest successful gamified mobility deployment in MUV's operational history. The 33.28 % active participation rate substantially exceeded corporate implementation benchmarks, indicating that youth demographics respond particularly favourably to competitive sustainability interventions.

The progressive filtering tournament structure proved highly effective in maintaining engagement intensity while accommodating large initial participant volumes. The three-phase architecture (qualification → group stage → playoffs) successfully balanced inclusivity with competitive intensity, as evidenced by escalating trip recording rates during playoff phases (61.95 trips per active user compared to 21.91–25.69 in earlier phases). This structure enables accommodation of diverse participation levels while rewarding sustained engagement through advancement mechanisms.

The integration of supplementary engagement mechanisms represents a critical innovation in gamification design for youth demographics. Three distinct supplementary activities were successfully implemented for the first time: online training webinars addressing gamification and mobility management topics, bonus question features with timed multiple-choice responses, and the "MOB stories" social media component encouraging user-generated content creation. These activities proved beneficial and well-integrated with core game

mechanics, illustrating how supplementary elements can enhance primary competitive dynamics while increasing variety and enjoyment.

The webinar component, delivered via three online sessions covering gamification in mobility, mobility management plans, and data analysis, achieved dual educational and engagement objectives. Participants received 200 bonus points for attendance, and sessions were recognised as complementary academic credits by participating schools. This integration of learning and gameplay aligns with research highlighting how digital games can support cognitive engagement and informal learning processes among younger audiences (Gee 2003).

The bonus question feature demonstrated effective real-time engagement mechanisms, with periodic notifications prompting spontaneous responses to multiple-choice questions within 30-second time limits. Correct answers yielded 100 bonus points, maintaining consistent platform interaction beyond primary trip tracking activities. Questions aligned with webinar content, reinforcing educational components while providing immediate gratification through point acquisition.

The "MOB stories" social media initiative achieved remarkable organic content generation, with over 50 videos posted demonstrating sustainable travel methods. Participants tagged MUV and Fondazione Unipolis, included MUV nicknames, and used the hashtag #TorneoMOB, creating substantial user-generated promotional content that amplified initiative visibility through peer networks. This component received 100 bonus points per video, effectively incentivising content creation while leveraging Generation Z's social media engagement preferences.

The adaptive team formation system successfully prevented "ghost team" formation through sophisticated geographic and institutional matching algorithms, demonstrating that technological solutions can address common participation barriers in large-scale competitive implementations. The 48-hour invitation requirement combined with countdown notifications proved effective in ensuring viable team composition without affecting registration accessibility.

4.4.3.3 Implications for future implementations

The MOB tournament success establishes a comprehensive framework for large-scale gamified mobility interventions targeting youth demographics. The demonstrated effectiveness across participants validates scalability potential for national and international implementations, providing evidence that competitive sustainability interventions can achieve substantial reach while maintaining engagement quality.

The progressive filtering tournament structure should be prioritised for large-scale implementations, with particular emphasis on three-phase architectures that balance inclusivity with competitive intensity. Future implementations should incorporate qualification phases to accommodate diverse participation levels, group stages to maintain engagement, and playoff structures to reward consistent performers. The optimal duration appears to

be ten weeks, enabling sufficient competitive development without excessive temporal commitment.

The integration of supplementary engagement mechanisms represents essential design components for youth-focused implementations. Future deployments should incorporate educational webinars aligned with curriculum requirements, enabling academic credit recognition that enhances institutional support. Bonus question features provide effective real-time engagement maintenance, while social media content creation leverages natural youth communication preferences. The 100–200 point reward structure for supplementary activities proved effective and should be maintained in future implementations.

Communication strategies should prioritise digital-first approaches targeting Generation Z platform preferences. The successful partnerships with Skuola.net and TikTok influencers demonstrate the effectiveness of direct demographic targeting through preferred digital environments. Future implementations should identify equivalent platforms in target regions and develop localised influencer partnerships to achieve similar penetration rates.

The substantial financial incentive structure, while effective, requires careful adaptation to available resources. The € 15 000 prize pool combined with individual € 400 vouchers created significant motivation, but alternative incentives could include educational scholarships, internship opportunities, or technology prizes that align with youth preferences while maintaining cost efficiency.

Given the success in terms of engagement, learning outcomes, and environmental impact, this format presents strong potential for replication across European contexts. Future iterations could adapt tournament structures to secondary schools, universities, or youth organisations internationally, tailoring game dynamics and learning modules to local educational systems, mobility policies, and cultural preferences. The framework provides sufficient flexibility for contextual adaptation while maintaining core competitive and educational components that drive engagement and behavioural change.

4.5 Engaging citizens through collaborative competitions: the Cagliari's SUMP Challenge

The final case study examines a municipal-scale gamified mobility intervention implemented in the metropolitan area of Cagliari in 2024, representing MUV's first deployment within a *Sustainable Urban Mobility Plan* (SUMP, or PUMS in Italian) development framework. The *PUMS Cagliari Challenge* was strategically designed as an integral component of the metropolitan city of Cagliari's campaign to introduce and promote citizen engagement with the newly developed SUMP, demonstrating how gamification mechanisms can support urban policy implementation and community participation in transportation planning processes.

The initiative represents a fundamental departure from the workplace and educational contexts examined in previous case studies, focusing instead on open citizen engagement across diverse demographic segments within a defined metropolitan territory. This urban-

scale implementation enables assessment of gamification effectiveness in heterogeneous population contexts without the institutional structure present in corporate or educational settings.

The collaborative challenge employed a fundamentally different competitive structure compared to previous case studies, creating community-wide cooperation rather than competitive dynamics. This collaborative approach reflects emerging trends in civic engagement gamification and provides critical insights into alternative motivational frameworks for large-scale behavioural interventions.

The institutional framework provided unique analytical opportunities for understanding gamification integration within urban policy development processes. This integration enables assessment of how gamified interventions can serve dual objectives: immediate behavioural change among participants and broader community awareness of sustainable mobility policies.



Figure 4.8: Visual identity and promotional graphic of the PUMS Cagliari Challenge. The municipal branding strategy emphasised institutional legitimacy and community-wide collaboration in support of SUMP development.

4.5.1 Distinctive characteristics of case study and rationale for selection

This case study was selected based on four methodological criteria establishing its critical value for understanding gamification effectiveness in urban governance and open citizen engagement contexts. First, as MUV's inaugural municipal-scale implementation targeting general population demographics, it provides essential insights into scalability beyond institutional boundaries and effectiveness across diverse citizen segments without pre-existing organisational structures or motivational frameworks.

Second, the collaborative-competitive structure marks a key methodological innovation compared to individual and team-based approaches examined in previous case studies. By pursuing shared point thresholds rather than direct competition, this collective goal mechanism allows for assessing cooperative versus competitive motivation in large-scale behavioural interventions. This structure also addresses research gaps related to social cohesion and community engagement in gamified sustainability initiatives.

Third, the integration with urban policy development processes provides unique analytical value for understanding gamification applications beyond pure behavioural change toward civic engagement and policy communication. The explicit linkage between individual participation and SUMP development creates opportunities to assess how gamified interventions can support participatory governance and enhance citizen awareness of municipal sustainability initiatives.

Fourth, the short-term intensive implementation format (35 days) combined with open population targeting enables assessment of rapid engagement mechanisms and immediate behavioural response patterns across diverse demographic segments. Unlike the extended implementations in corporate and educational contexts, this compressed timeline provides insights into activation strategies for time-limited policy engagement campaigns.

The metropolitan territorial scope encompasses diverse urban densities, mobility infrastructure qualities, and socioeconomic conditions across 17 municipalities, providing comprehensive coverage of suburban and urban contexts within a single administrative framework. This territorial diversity enables systematic comparison of engagement patterns across different municipal contexts while maintaining unified policy and communication frameworks.

The demographic composition represents the most heterogeneous participant pool across all MUV implementations, spanning multiple age groups, professional backgrounds, and mobility patterns without institutional filtering mechanisms. This diversity provides particular analytical value for understanding gamification transferability across general population segments and identifying demographic factors that influence engagement with sustainability-focused competitive interventions.

The institutional support framework, provided directly by metropolitan and municipal administrations, represents the highest level of governmental endorsement across all case studies. This official backing enabled systematic promotional campaigns across territorial boundaries and integration with formal policy development processes, providing insights into the role of institutional legitimacy in driving citizen participation in gamified civic engagement initiatives.

The reward structure implemented tangible incentives directly relevant to sustainable mobility, including bicycles, electric scooters, and public transport subscriptions, creating alignment between competitive participation and practical sustainable mobility adoption. This approach enables assessment of how reward relevance influences engagement and potential behavioural continuation beyond formal competition periods.

The communication strategy employed traditional municipal channels including billboard campaigns across multiple municipalities, representing a departure from digital-first approaches used in previous case studies. This multi-modal municipal communication framework provides insights into the effectiveness of institutional promotional mechanisms and their impact on citizen awareness and participation in gamified policy engagement initiatives.

4.5.2 Implementation methodology and results achieved

4.5.2.1 Competition design and structure

The PUMS Cagliari Challenge structure comprised three progressive collective targets designed to maintain engagement intensity throughout the 35-day implementation period. Participants collectively aimed to reach predefined point thresholds set at 20 000, 300 000, and 1 000 000 points, creating escalating difficulty levels that required sustained community participation to achieve. All three targets were successfully surpassed, with participants collectively accumulating over 5.8 million points throughout the challenge period.

The point accumulation system employed MUV's standard scoring mechanisms, with all points contributing to collective community totals instead of individual team rankings, eliminating competitive pressure.

The temporal framework spanned five weeks from 2 April to 6 May 2024, strategically positioned to precede formal SUMP presentation and adoption processes. This timing created natural linkages between individual participation and policy development, enabling citizens to experience sustainable mobility tracking prior to formal policy implementation. The compressed timeframe enabled intensive engagement assessment while minimising participant fatigue and maintaining focus on immediate behavioural activation.

All sustainable mobility modes were accepted for point accumulation, with the sole requirement being travel within the metropolitan boundary encompassing Cagliari and 16 surrounding municipalities. This inclusive approach enabled assessment of gamification effectiveness across diverse urban densities, infrastructure qualities, and mobility options without mode-specific restrictions. The geographical constraint ensured relevance to local SUMP development while accommodating diverse mobility patterns across the metropolitan territory.

4.5.2.2 Communication strategy and organisational support

The communication strategy employed a multi-channel approach combining traditional institutional promotion with strategic media engagement. The campaign incorporated billboard deployment across the metropolitan territory, representing a departure from the digital-first approaches employed in previous case studies. This traditional promotional methodology enabled systematic reach across diverse demographic segments and geographical areas, particularly targeting citizens who may not engage with social media or digital platforms.

Municipal endorsement was operationalised through direct administrative support from the metropolitan city of Cagliari, providing official backing and institutional legitimacy for citizen participation. The initiative leveraged established municipal communication channels to ensure systematic message penetration across the territorial scope, creating formal governmental endorsement that distinguished the challenge from commercial or private sector initiatives.

A critical component of the communication strategy involved comprehensive media engagement coordinated by the municipal press office. This systematic media relations approach generated substantial coverage across major Sardinian news platforms and local media outlets before, during, and after the challenge implementation. The sustained media attention provided ongoing public awareness and reinforced the initiative's legitimacy through third-party validation from established regional media sources.

The communication timeline was strategically structured to maximise both immediate participation and long-term policy connection. Initial promotional activities preceded the challenge launch to build awareness and enable registration, while sustained media coverage maintained visibility throughout the implementation period. Most significantly, the award ceremony was scheduled during the formal SUMP presentation event, creating direct linkages between individual citizen participation and broader municipal transportation planning processes.

This integrated approach enabled the challenge to serve dual communication objectives: immediate citizen engagement in sustainable mobility and broader community awareness of upcoming SUMP implementation. The connection between individual participation recognition and formal policy presentation demonstrated how gamified interventions can support municipal communication strategies beyond isolated behavioural change initiatives.

4.5.2.3 Participation patterns and engagement dynamics

The PUMS Cagliari Challenge achieved substantial citizen engagement with 856 total registrations across the metropolitan territory, demonstrating significant appeal among general population demographics. The demographic distribution revealed 56 % male, 42 % female, and 2 % intersex participants, indicating broad gender representation across the citizen participant pool.

Active participation analysis reveals strong engagement intensity throughout the implementation period. Of the 856 total registrants, 547 individuals (64 %) actively participated by completing at least one valid trip during the challenge period. This conversion rate substantially exceeds typical mobile application engagement benchmarks and demonstrates effective activation mechanisms for open citizen participation contexts.

Weekly engagement patterns maintained consistent participation levels throughout the challenge duration. The average number of active users reached 329.8 participants per week, representing 38 % of total registrants. This sustained engagement rate indicates successful maintenance of citizen interest across the compressed timeframe despite the absence of competitive pressure or elimination mechanisms.

The evolution of active user participation throughout the five-week implementation period is illustrated in Figure 4.9, which demonstrates the consistency of citizen engagement across the challenge duration.

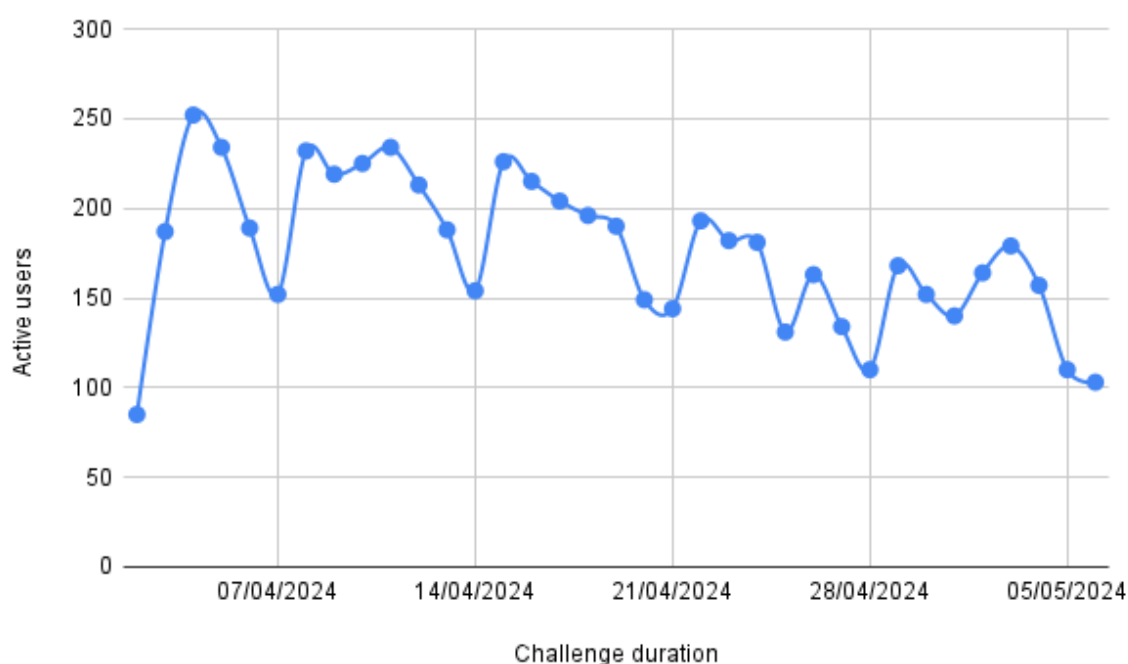


Figure 4.9: Weekly active user patterns during the PUMS Cagliari Challenge, showing citizen engagement throughout the implementation period. The graph illustrates characteristic tracking cycles with noticeable weekend declines compared to weekday activity levels.

Individual usage intensity demonstrated significant commitment among active participants. On average, active participants completed 55 trips during the five-week competition period, equating to 11 trips per week and 1.57 trips per day. This frequency indicates consistent daily application usage and systematic integration of sustainable mobility tracking into participants' routine travel patterns.

Temporal analysis revealed characteristic patterns reflecting typical urban mobility cycles. Participation trends showed noticeable declines during weekends compared to weekday activity levels, consistent with commuting-focused travel patterns among urban populations. This pattern validates the authenticity of reported travel behaviour and suggests successful integration with genuine mobility needs rather than artificial trip generation for competitive purposes.

4.5.2.4 Environmental and behavioural outcomes

The challenge generated substantial sustainable mobility activity, with participants completing 18 130 validated trips covering 81 966 kilometres. This represents an average of 150 kilometres and 33.1 trips per active participant, demonstrating significant individual engagement with sustainable transport modes within the compressed timeframe.

Modal split analysis revealed patterns reflecting the metropolitan area's transportation infrastructure and citizen preferences. Public transport emerged as the predominant mode, accounting for 51 % of total trips, comprising 26 % bus usage, 13 % train, and 12 % suburban bus services. Active mobility modes represented substantial portions, with walking con-

tributing 20 % and cycling 12 % of trips. Alternative sustainable modes included carpooling (8 %) and electric vehicles (8 %), indicating diverse sustainable mobility adoption across the participant population.

Despite the compressed timeframe, the environmental impact assessment produced notable results. Among the 547 active participants, 105 (19.20 %) showed measurable reductions in mobility-related emissions, averaging a 33.50 % decrease in their carbon footprint. This aligns closely with MUV's overall average of 33.82 %, confirming consistent behavioural change effectiveness across diverse contexts.

Total emission reductions amounted to 1.644 t CO₂, equivalent to 3.01 kg per active participant. While the absolute impact reflects the compressed timeframe and limited participant volume compared to extended implementations, the per-participant reduction rate validates the effectiveness of collaborative motivation mechanisms in driving immediate behavioural change among general population segments.

The alignment between Cagliari outcomes and overall MUV performance indicators suggests robust transferability of gamification approaches across different competitive structures and institutional contexts. The achievement of comparable emission reduction percentages through collaborative instead of competitive mechanisms provides evidence for alternative motivation frameworks in civic engagement applications.

4.5.3 Limitations, lessons learned and future applications

4.5.3.1 Methodological limitations and constraints

Several methodological limitations constrain the generalisability and long-term validity of findings from the PUMS Cagliari Challenge case study. The primary temporal constraint was the compressed 35-day implementation period, which precludes assessment of long-term behavioural changes or sustained effects on citizens' mobility choices beyond the immediate challenge period. This limitation is particularly significant for evaluating genuine habit formation versus temporary participation in a time-limited civic engagement activity.

The voluntary participation model introduces self-selection bias, as participants likely represent individuals already interested in sustainable mobility or civic participation, potentially inflating engagement rates compared to population-representative interventions. The geographical limitation to metropolitan Cagliari constrains transferability assessment to other urban contexts with different mobility infrastructure, population density, or administrative structures.

The collaborative competition structure, while innovative, provides limited comparative data for assessing alternative motivation mechanisms. The exclusive focus on collective goals prevents systematic evaluation of which motivational frameworks prove most effective for different citizen segments. Additionally, the reliance on municipal communication channels creates dependency on governmental support that may not be available in contexts with limited administrative resources or political commitment to citizen engagement initiatives.

4.5.3.2 Key insights and lessons learned

The PUMS Cagliari Challenge generated several critical insights advancing understanding of gamified interventions in civic engagement contexts. The initiative demonstrated exceptional effectiveness of collaborative motivation frameworks, with all three collective point thresholds successfully surpassed and total community accumulation exceeding 5.8 million points, indicating strong citizen response to cooperation-based engagement mechanisms.

The engagement metrics achieved substantially exceed typical mobile application benchmarks, with a 64 % conversion rate from registration to active participation and a sustained weekly engagement rate of 38 % throughout the compressed timeframe. These rates demonstrate successful public interest despite the absence of competitive pressure or elimination mechanisms, validating the effectiveness of collaborative frameworks in open participation contexts.

The strategic integration with formal policy development processes proved highly effective. Most significantly, the award ceremony was scheduled during the SUMP presentation event, creating direct linkages between individual citizen participation and municipal transportation planning. This approach gave the competition a formal and solemn awarding moment and established a strong connection between the challenge and the city's draft sustainable mobility plan. The success of this integration gained international recognition, as the SUMP Challenge was featured by Interreg Europe as an example of citizen engagement in sustainable mobility planning (Interreg Europe 2024).

The effectiveness of traditional communication approaches, particularly the poster-based billboard campaign, effectively engaged participants from all involved municipalities and provided evidence for multi-modal engagement strategies that extend beyond digital-first approaches. The substantial media coverage generated through municipal press office coordination reinforced institutional legitimacy and encouraged broader community participation.

Environmental impact outcomes validate the effectiveness of collaborative frameworks in driving immediate behavioural change. The 33.50 % average emission reduction among participating citizens closely aligns with MUV's cross-implementation average of 33.82 %, indicating consistent behavioural change effectiveness across different motivation structures and institutional contexts. This alignment suggests robust transferability of gamification approaches beyond competitive tournament formats.

Post-challenge retention patterns provide particularly promising evidence for sustained engagement potential. Despite the limited timeframe, notable interest extended beyond the immediate challenge, with a community of Cagliari users emerging and self-organising to support the Cagliari team in the FantaMUV tournament. Six months following challenge conclusion, 15 active users remained engaged with the MUV platform in the Cagliari area, representing 10.5 % of final-week participants. Research by the startup Quettra suggests that mobile applications typically lose 77 % of daily active users within three days of installation, 90 % after 30 days, and over 95 % after 90 days (A. Chen 2015). The retention data observed by MUV in this context is particularly promising, substantially exceeding industry benchmarks.

4.5.3.3 Implications for future implementations

The Cagliari model establishes a framework for municipal-scale gamified interventions supporting policy development and citizen engagement objectives. The demonstrated effectiveness of collaborative motivation mechanisms provides evidence that cooperation-based frameworks can achieve substantial participation while maintaining environmental impact effectiveness comparable to competitive approaches.

Future municipal implementations should prioritise integration with formal policy development processes, coordinating challenge timing with policy presentation schedules to maximise both immediate participation and long-term awareness outcomes. The strategic timing of recognition events during policy activities creates valuable linkages between individual engagement and broader planning initiatives.

Communication strategies should incorporate traditional municipal channels alongside digital approaches to ensure comprehensive citizen reach. The effectiveness of billboard campaigns and press office coordination demonstrates the continued value of established institutional communication mechanisms, particularly when adapted to local contexts.

The compressed timeframe approach proves effective for intensive citizen engagement while minimising participation fatigue. This duration enables systematic assessment of rapid engagement mechanisms and provides sufficient time for meaningful impact measurement. The collaborative goal structure provides an alternative to competitive tournaments that may be more appropriate for civic engagement contexts where community cooperation aligns better with municipal values.

Given the success in citizen engagement, environmental impact, and policy integration, the Cagliari model presents strong potential for replication across diverse municipal contexts. Future iterations should adapt the collaborative framework and communication approaches to local governance structures while maintaining the core integration between individual participation and broader municipal planning processes.

4.6 Cross-case analysis: insights and trends

The comprehensive examination of four selected case studies—INAIL’s corporate nationwide implementation, LIST’s controlled international deployment, the MOB Tournament’s youth-focused initiative, and Cagliari’s municipal civic engagement challenge—provides an unprecedented empirical foundation for advancing gamification theory in sustainable mobility interventions. These implementations, while exhibiting significant variation in temporal frameworks (5–52 weeks), demographic targeting (corporate employees to metropolitan citizens), institutional contexts (hierarchical to open communities), and competitive architectures (individual challenges to collaborative frameworks), collectively enable systematic theory-building through analytic generalisation rather than statistical generalisation.

This cross-case analysis addresses three fundamental theoretical gaps in the gamification literature:

Research Question 1: How do engagement patterns vary across institutional contexts and demographic segments, and what theoretical principles explain these variations?

Research Question 2: Which game dynamics generate superior behavioural intensity and environmental impact, and through what psychological mechanisms do they operate?

Research Question 3: What contextual factors moderate gamification effectiveness, and how can these insights inform predictive frameworks for implementation design?

The analytical approach employed here extends Yin's Yin (2014) replication logic through both literal replication (predicting similar results under similar conditions) and theoretical replication (predicting contrasting results for theoretically meaningful reasons). This methodology enables the development of middle-range theory connecting abstract gamification principles with observable behavioural outcomes across diverse real-world contexts.

The analysis reveals a novel *Context-Mechanism-Outcome* (CMO) framework (Pawson and Tilley 1997)—a heuristic for explaining generative causation in complex, context-dependent interventions—that challenges universal gamification approaches by demonstrating that optimal engagement mechanisms vary systematically based on institutional embedding, temporal architecture, and motivational structure. This finding necessitates a paradigm shift from universal gamification design principles toward contextually adaptive frameworks that match mechanism types to implementation characteristics.

Beyond theoretical advancement, this cross-case analysis provides evidence-based guidance for practitioners implementing gamified interventions across diverse organisational and civic contexts. The identification of consistent patterns (approximately one-sixth corporate penetration rates) alongside context-specific variations (substantial tournament superiority) enables both confident replication and strategic adaptation based on implementation constraints and objectives.

4.6.1 Theoretical framework for cross-case comparison

4.6.1.1 Methodological foundation: from description to theory-building

The comparative analysis framework addresses the fundamental methodological challenge of theoretical generalisation from diverse contexts while maintaining analytical rigour. Following Eisenhardt (1989) theory-building methodology, cases are systematically analysed through pattern recognition, replication logic, and theoretical sampling principles to identify both universal mechanisms and boundary conditions of gamification effectiveness.

The four case studies represent distinct implementation archetypes that enable a comprehensive assessment of gamification effectiveness across institutional and demographic contexts. This diversity creates natural experimental conditions for testing key theoretical propositions about gamified behaviour change interventions. The framework employs dimensionalisation of implementation characteristics to enable systematic comparison despite surface-level heterogeneity, with three critical dimensions emerging from preliminary analysis.

Institutional embedding: The first dimension tests *Legitimate Authority Theory* (French and Raven 1959) predictions about institutional endorsement effects on voluntary behaviour adoption, distinguishing between:

- *Closed Communities* (INAIL, LIST): Predetermined user pools with formal authority structures where institutional endorsement, management support, and formal communication channels create legitimacy frameworks that may enhance participation through authority-based motivation.
- *Open Communities* (MOB, Cagliari): Voluntary participation from undefined populations where gamification appeal must operate beyond institutional boundaries, testing whether competitive dynamics and collaborative frameworks can generate engagement without formal authority structures.

Temporal architecture: The second dimension examines *Habit Formation Theory* (Verplanken and Wood 2006) predictions about optimal temporal frameworks for technology-mediated behaviour change, categorised into:

- *Intensive Implementations* (5-10 weeks): Compressed high-intensity engagement exemplified by Cagliari's 35-day challenge and MOB's 10-week tournament, testing whether focused competitive dynamics can compensate for limited duration.
- *Extended Implementations* (45+ weeks): Sustained moderate-intensity engagement demonstrated by LIST's 52-week observation and INAIL's 45-week initiative, enabling assessment of long-term habit formation and seasonal variation effects.

Motivational Structure: The third dimension tests *Self-Determination Theory* (Deci and Ryan 2000) propositions on intrinsic versus extrinsic motivation in sustained engagement, discriminating between:

- *Competitive Frameworks*: Individual/team-based competition with rankings employed in INAIL, LIST, and MOB tournaments, creating explicit performance comparison and elimination mechanisms that may activate extrinsic achievement motivations.
- *Collaborative Frameworks*: Collective goal achievement without interpersonal competition demonstrated in Cagliari's challenge, potentially preserving intrinsic motivation through community cooperation while avoiding demotivating competitive comparison effects.

This dimensional framework enables systematic assessment of gamification transferability across varying institutional contexts, demographic profiles, and motivational structures, providing critical evidence for scalability potential beyond specific organisational or demographic boundaries.

4.6.1.2 Measurement framework: standardised metrics for theory testing

To enable meaningful comparison across diverse implementation contexts, standardised metrics are employed that account for structural differences while preserving analytical validity. The measurement framework addresses the challenge of comparing interventions that vary dramatically in scale (93 to 2 560 participants), duration (5 to 52 weeks), and institutional context, requiring metrics that isolate intervention effectiveness from contextual factors.

Primary engagement metrics include registration rates where total addressable populations are measurable, active user conversion rates capturing the transition from registration to meaningful participation, and weekly participation intensity that accounts for temporal variations. Trip recording frequency per active user provides insight into behavioural integration depth, distinguishing between broad adoption and intensive usage patterns.

Environmental impact assessment employs consistent CO₂ calculation methodologies across implementations where baseline data permits measurement. Impact metrics include total emission reductions, per-user savings enabling size-independent comparison, temporal efficiency measured as savings per week, and behavioural change success rates indicating the percentage of participants achieving measurable reductions. This latter metric proves particularly important for distinguishing between platform engagement and actual mobility pattern changes.

Engagement intensity standardisation addresses temporal challenges through weekly active user rates relative to registered populations, enabling comparison of sustained participation patterns despite varying durations. The framework prioritises effect size calculations and confidence interval estimation over traditional hypothesis testing, aligning with realistic evaluation methodology that emphasises mechanism identification and practical significance appropriate for small-N comparative design and exploratory research contexts.

4.6.2 Engagement patterns across contexts

Systematic analysis of engagement patterns reveals consistent trends across implementation contexts while highlighting the influence of demographic, institutional, and structural factors on participation outcomes. The patterns provide empirical validation for theoretical predictions about authority legitimacy, demographic responsiveness, and temporal optimisation in gamified behavioural interventions.

4.6.2.1 Registration and activation rates in closed communities

Closed community implementations demonstrate remarkably consistent penetration rates despite substantial differences in organisational contexts and national settings. This consistency provides strong evidence for cross-cultural transferability of gamification appeal in workplace environments, validating theoretical predictions about universal engagement drivers that transcend specific organisational cultures.

Table 4.8 illustrates engagement metrics for INAIL and LIST implementations, enabling direct comparison of corporate and research institutional contexts.

Table 4.8: Engagement metrics for INAIL and LIST implementations, enabling direct comparison of corporate and research institutional contexts.

Case study	Duration (weeks)	TU	RU	RU/TU	Average AU per week	AU/RU
INAIL	45	2 768	436	15.75 %	82.98	32.38 %
LIST	52	600	93	15.50 %	13.60	26.61 %

TU = Total Users, RU = Registered Users, AU = Active Users

The registration rates (RU/TU) demonstrate remarkable consistency at $15.7 \% \pm 0.25 \%$, suggesting robust cross-cultural transferability of gamification appeal among employee populations. This consistency aligns with Rogers (2003) Diffusion of Innovation Theory, indicating that approximately one-sixth of organisational populations represent early adopters willing to engage with voluntary sustainability innovations regardless of national context or organisational structure.

However, sustained engagement patterns (AU/RU) reveal institutional context effects, with INAIL achieving 32.38 % weekly active user rates compared to LIST's 26.61 %. This differential may reflect organisational scale effects, competitive intensity variations, or cultural factors influencing sustained participation. The higher engagement at INAIL suggests that larger organisations with multiple competitive units may generate stronger social dynamics and peer pressure mechanisms that sustain participation beyond initial adoption.

4.6.2.2 Competition-specific engagement dynamics

Analysis focusing exclusively on competition periods reveals enhanced engagement patterns and provides insights into optimal activation mechanisms. During active competition phases, both implementations demonstrate elevated participation rates, with temporal distribution of competitive activities significantly influencing overall engagement sustainability.

Table 4.9 presents engagement metrics across all implementations during active competition periods, enabling assessment of competitive effectiveness across different contexts and structures.

Table 4.9: User engagement patterns across all implementations during active competition periods.

Case study	Duration (weeks)	RU	Average AU per week	AU engagement rate*
INAIL (during competitions)	31	436	92.42	32.33 %
LIST (during competitions)	22	93	13.60	43.28 %
MOB Tournament	10	2 560	336.7	21.64 %
PUMS Cagliari Challenge	5	856	329.80	42.31 %

RU = Registered Users, IU = Involved Users, AU = Active Users

* Calculated against relevant user base (RU for closed communities, IU for competitions)

Competition period engagement rates peak at 43.28 % (LIST) and 42.31 % (Cagliari), compared to 21.64 % (MOB) and 32.33 % (INAIL). These variations suggest that compressed timeframes and focused competitive structures generate higher participation intensity, while extended implementations require sustained motivation mechanisms to maintain comparable engagement levels.

4.6.2.3 Demographic and institutional context effects

Cross-case comparison reveals systematic variations in engagement patterns that reflect underlying demographic and institutional characteristics. Generation Z participants (MOB) demonstrate exceptional absolute scale capacity but moderate relative engagement intensity, while corporate employees show consistent penetration rates across cultural contexts. Municipal citizens (Cagliari) achieve high engagement intensity within compressed timeframes, suggesting that civic identity activation can effectively substitute for institutional authority in driving participation.

The temporal distribution patterns indicate that sustained competitive scheduling maintains higher baseline engagement. INAIL's tournaments comprised 68.89 % of total implementation time (31 weeks of 45), while LIST's competitions occupied 42.31 % (22 weeks of 52). This suggests that "competitive density" rather than absolute duration determines engagement sustainability, with implications for resource allocation and scheduling optimisation.

These engagement patterns validate key propositions from Bandura (2001) *Social Cognitive Theory* regarding the interplay between environmental factors (institutional support), personal factors (demographic characteristics), and behavioural outcomes. The consistency of corporate penetration rates across contexts supports universal engagement drivers, while variation in sustained participation confirms context-dependent maintenance mechanisms, contributing to gamification theory by demonstrating that adoption and retention operate through distinct psychological processes.

4.6.3 Game dynamics effectiveness analysis

Systematic comparison of different game dynamics reveals significant variations in user engagement and behavioural intensity across competitive structures, providing evidence for optimal mechanism selection based on implementation objectives and target demographics. The analysis enables identification of causal mechanisms underlying engagement differentials and contributes to theoretical understanding of motivation frameworks in gamified behavioural interventions.

4.6.3.1 Challenge versus tournament performance

Challenges represent individual or collaborative goal-oriented activities with defined end-points, while tournaments employ sustained competitive structures with elimination mechanisms and progressive advancement. This structural distinction activates fundamentally different psychological mechanisms with measurable behavioural consequences.

Table 4.10 presents aggregated performance metrics for challenge implementations across INAIL, LIST, and Cagliari case studies, enabling assessment of challenge effectiveness across different contexts.

Table 4.10: Performance overview of challenge implementations in the three pilot sites.

Competition	Duration (weeks)	Average AU/RU per week	Trips/AU per week
Rome Special Challenge	1	65.67 %	8.86
Southern Special Challenge	3	25.00 %	5.62
Northern Special Challenge	2	40.98 %	6.69
LIST Competitive Challenge	4	66.67 %	6.21
LIST Collaborative Challenge	4	40.79 %	5.19
PUMS Cagliari Challenge	5	42.31 %	11.00
Challenge average	3.17	45.47 %	7.35

RU = Registered Users, AU = Active Users

Challenge implementations demonstrate significant variation in engagement rates (25.00–66.67 %) and trip intensity (5.19–11.00 trips per week per active user), with an overall average of 45.47 % participation and 7.35 weekly trips per active user. Short-duration challenges (1–2 weeks) tend to generate higher participation rates but may lack sufficient duration for sustained behavioural integration.

While participation rates vary across INAIL, LIST, and MOB case studies, tournament formats consistently generate greater engagement intensity, as shown in Table 4.11.

Table 4.11: Performance overview of tournament implementations three pilot sites.

Competition	Duration (weeks)	Average AU/RU per week	Trips/AU per week
LIST Tournament #1	8	59.90 %	9.99
LIST Tournament #2	6	69.19 %	13.20
INAIL Rome Tournament	8	42.96 %	12.59
INAIL South Tournament	8	60.00 %	15.58
INAIL North Tournament	8	53.82 %	14.88
INAIL Italy Tournament	6	31.95 %	15.14
MOB Tournament	10	21.64 %	10.95
Tournament average	7.72	47.35 %	13.03

RU = Registered Users, AU = Active Users

Tournament implementations achieve an average participation rate of 47.35 % with 13.03 weekly trips per active user, representing a **77 % increase in trip intensity** compared to challenge formats. This differential effectiveness has been consistently validated in corporate environments (Schillaci, Tinnirello, et al. 2025), confirming that tournament structures activate stronger engagement mechanisms through social reinforcement and temporal anchoring effects across diverse organisational contexts.

4.6.3.2 Causal mechanisms underlying tournament superiority

Three primary mechanisms explain consistent tournament superiority across diverse contexts:

Social Reinforcement Amplification: Tournament structures create team interdependence and weekly competitive cycles that generate peer visibility and social accountability pressure. The weekly match format provides regular social reinforcement opportunities that sustain motivation through social comparison, activating Bandura (2001) *Social Cognitive Theory*'s reciprocal determinism.

Temporal Anchoring Effects: Scheduled matches create consistent implementation intentions and behavioural cues that structure engagement. Regular competitive deadlines function as temporal landmarks triggering planning behaviour, contrasting with challenges that lack structured temporal anchors beyond start/end dates.

Progressive Achievement Architecture: Elimination and advancement mechanisms create escalating stakes and investment effects. Progression possibilities activate *Achievement Goal Theory*'s (Hulleman et al. 2020) mastery orientation, while elimination pressure creates loss aversion effects (Tversky and Kahneman 1991), sustaining participation.

4.6.3.3 Collaborative versus competitive motivation frameworks

The Cagliari collaborative framework achieved 42.31 % engagement rates and 11.00 trips per active user per week, demonstrating effectiveness comparable to competitive tournaments while creating community cooperation. This validates Deci and Ryan (2000) Self-Determination Theory predictions about intrinsic motivation preservation through autonomy support and relatedness satisfaction.

The comparable effectiveness of collaborative and competitive frameworks (11.00 vs 13.03 trips per week) suggests that social connection, rather than competition type, drives engagement sustainability. Both activate social psychological mechanisms through different pathways: competitive frameworks through social comparison, and collaborative frameworks through community identity. This extends gamification theory by demonstrating multiple viable pathways to social motivation activation, with framework selection depending on implementation objectives and institutional contexts.

4.6.4 Environmental impact assessment

Cross-case environmental impact analysis enables assessment of emission reduction effectiveness across different intervention types, durations, and participant demographics, providing evidence for scalability and optimisation of gamified sustainability interventions. The analysis reveals consistent behavioural change patterns while highlighting efficiency variations based on implementation design choices.

4.6.4.1 Comparative CO₂ reduction outcomes

Environmental impact assessment across three case studies (LIST excluded due to missing baseline data) reveals consistent emission reduction effectiveness despite varying implementation contexts and competitive structures. Table 4.12 presents standardised impact metrics enabling direct comparison across different intervention scales and durations.

Table 4.12: Standardised CO₂ impact metrics across case studies enabling direct comparison across different intervention scales and durations.

Case study	Total CO ₂	Participants	CO ₂ /user	Duration (weeks)	Weekly CO ₂ /user
INAIL	3.39 t	365	9.29 kg	45	0.20 kg
MOB Tournament	6.86 t	852	8.05 kg	10	0.80 kg
PUMS Cagliari Challenge	1.64 t	547	3.01 kg	5	0.60 kg

The data reveal an inverse relationship between implementation duration and weekly emission reduction efficiency, with compressed timeframes generating higher per-week impact rates. This pattern reflects the intensity effect of focused interventions versus

the sustained engagement patterns required for extended implementations. The weekly efficiency ranges from 0.20 kg (extended INAIL implementation) to 0.80 kg (intensive MOB Tournament), representing a 4:1 efficiency differential.

Total emission reductions scale proportionally with participant volume, as expected, but per-user impacts vary significantly (3.01–9.29 kg), suggesting that implementation context, baseline mobility patterns, and available infrastructure alternatives influence individual behaviour change potential.

4.6.4.2 Behavioural change penetration rates

Environmental impact analysis reveals that not all participants achieve measurable emission reductions, consistent with behavioural intervention research emphasising the distinction between participation and actual behaviour change (Abrahamse et al. 2005). Table 4.13 examines both the proportion of participants achieving emission reductions and the magnitude of those changes.

Table 4.13: Proportion of participants achieving emission reductions and magnitude of behavioural changes across case studies.

Case study	Participants	Behavioural changers	Penetration rate (%)	Average reduction (%)
INAIL	365	143	39.18 %	15.28 %
MOB Tournament	852	304	35.68 %	28.10 %
PUMS Cagliari Challenge	547	105	19.20 %	33.50 %
Case study total	1 764	552	31.29 %	27.12 %

Behavioural change penetration rates vary substantially (19.20–39.18 %), with an overall average of 31.29 % of active participants achieving measurable emission reductions. Interestingly, penetration rates demonstrate an inverse relationship with reduction magnitude, suggesting that broader participation may involve more modest individual changes while focused engagement generates deeper behavioural transformation.

The combined average emission reduction of 27.12 % aligns with MUV's overall average of 33.82 %, indicating consistent effectiveness across diverse implementation contexts and validating the robustness of gamification approaches for sustainable mobility interventions.

4.6.4.3 Implementation efficiency patterns

The environmental impact patterns reveal strategic insights for intervention optimisation.

Intensive implementations (MOB, Cagliari) achieve higher weekly efficiency rates but may sacrifice total impact potential through limited duration.

Extended implementations (INAIL) enable deeper penetration and sustained habit formation but require engagement maintenance mechanisms to optimise efficiency.

The participation-impact trade-off suggests different optimisation strategies based on implementation objectives: broad awareness campaigns may prioritise high penetration rates with modest individual changes. In contrast, intensive behaviour change initiatives may focus on deep transformation among smaller participant cohorts. The 4:1 efficiency differential between intensive and extended implementations indicates substantial resource allocation implications for intervention design.

4.6.5 Strategic insights and implementation implications

Cross-case analysis reveals several strategic insights with significant implications for future gamified mobility interventions, organisational implementation strategies, and policy applications of behaviour change technologies. The patterns identified enable evidence-based guidance for practitioners while contributing to theoretical understanding of contextual factors that moderate gamification effectiveness.

4.6.5.1 Scalability patterns and context transferability

The remarkable consistency in corporate registration rates ($15.7\% \pm 0.25\%$) across diverse organisational contexts (INAIL, LIST) provides strong evidence for cross-cultural and cross-institutional transferability of gamification appeal. This consistency suggests that fundamental engagement drivers transcend specific organisational cultures, national contexts, and institutional structures, supporting robust scalability potential for corporate implementations across diverse settings.

However, sustained engagement patterns reveal context sensitivity, with institutional characteristics influencing long-term participation maintenance. Research-oriented environments (LIST: 26.61 % engagement) demonstrate different dynamics compared to large bureaucratic organisations (INAIL: 32.38 %), suggesting the need for context-specific adaptation strategies while maintaining core gamification mechanisms.

The successful scaling from corporate contexts (hundreds of participants) to large youth initiatives (2 560 participants in MOB) and open civic engagement (856 participants in Cagliari) demonstrates platform robustness across diverse demographic segments and implementation scales. Generation Z participants achieved exceptional absolute scale capacity (33.28 % active participation from open recruitment) while municipal citizens demonstrated rapid activation potential (42.31 % weekly engagement), indicating scalability beyond traditional institutional boundaries.

Cross-cultural validation emerges from the LIST Luxembourg implementation, where corporate penetration rates (15.50 %) closely matched Italian contexts despite different national mobility policies and organisational cultures. This consistency supports broader European applicability and potentially global transferability of game-based approaches in workplace sustainability initiatives.

4.6.5.2 Optimal game dynamics for different objectives

Tournament structures consistently outperform challenge formats, generating substantially higher behavioural intensity (13.03 vs 7.35 trips per week per active user). This substantial differential validates sustained competitive structures with progressive advancement mechanisms for applications requiring intensive behaviour change. The three causal mechanisms identified (detailed in Section 4.6.3.2) provide design principles for tournament optimisation.

However, collaborative frameworks demonstrated comparable effectiveness (11.00 trips per week in Cagliari) while creating community cooperation rather than individual competition. This finding suggests that motivation framework selection should align with broader implementation objectives: competitive tournaments for intensive individual behaviour change in corporate environments emphasizing performance, versus collaborative approaches for community building and civic engagement applications, where divisive competition could undermine policy objectives.

Temporal optimisation insights reveal that compressed implementations (5–10 weeks) generate higher weekly environmental impact (0.60–0.80 kg CO₂ per user per week) but may sacrifice sustained behaviour change potential, while extended implementations (45–52 weeks) enable deeper habit formation but require sophisticated engagement maintenance mechanisms. The optimal balance appears at 6–12 week durations, maximising intensity while providing sufficient time for behavioural integration.

Implementation efficiency trade-offs indicate that resource allocation decisions should consider the substantial efficiency differential between intensive and extended approaches. Organisations with limited resources may prioritise compressed high-impact interventions, while those seeking long-term culture change should invest in extended implementations with sustained engagement mechanisms.

4.6.5.3 Implementation strategy recommendations

Based on cross-case evidence, future implementations should employ differentiated strategies based on primary objectives and target contexts.

Corporate environments seeking employee engagement in sustainability initiatives should prioritise tournament-based approaches with 6–8 week durations, providing optimal balance between engagement intensity and practical implementation requirements. The 15.7 % penetration rate provides reliable planning metrics, while management endorsement proves essential for participation legitimacy. Multi-office organisations should leverage competitive dynamics between locations to enhance social reinforcement mechanisms.

Educational contexts benefit from extended tournament structures (10+ weeks) that accommodate academic calendars while maintaining competitive intensity through progressive filtering mechanisms. The MOB Tournament's three-phase architecture (qualification, group stage, and playoffs) provides a tested framework for large-scale youth engagement, with supplementary elements (webinars, social media content creation) enhancing educational value and platform stickiness.

Municipal and civic engagement applications should prioritise collaborative frameworks that align with community cooperation objectives while incorporating traditional communication channels (billboards, press engagement) alongside digital strategies. The Cagliari model demonstrates effective integration of gamification with policy development processes, with compressed timeframes (5 weeks) proving optimal for citizen activation without participation fatigue.

Environmental impact optimisation requires careful consideration of baseline mobility patterns and available infrastructure alternatives. Corporate contexts with high private vehicle dependency achieve larger absolute emission reductions (9.29 kg per user), while public transport-oriented environments generate more modest but significant behavioural change outcomes (3.01–8.05 kg per user). Implementation strategies should set realistic targets based on contextual mobility characteristics rather than universal benchmarks.

Demographic targeting should recognise that Generation Z demonstrates superior scale potential but requires distinct engagement mechanisms (social media integration, peer-to-peer promotion) compared to corporate employees who respond to institutional authority and formal communication channels. Mixed-age implementations should employ hybrid approaches accommodating technological comfort levels and motivational preferences.

The consistent alignment between case study results and overall MUV platform performance validates the representativeness of these implementations and supports confidence in broader application potential. The case study results demonstrate strong alignment with overall platform performance metrics, with both emission reduction magnitudes and behavioural change penetration rates closely matching broader MUV performance indicators from 2022 to 2024.

4.6.6 Theoretical contribution and framework development

The cross-case analysis contributes to gamification theory through the development of a novel Context-Mechanism-Outcome (CMO) framework that challenges prevailing universal design approaches and establishes contextual adaptation principles for behavioural change interventions.

4.6.6.1 The CMO framework and paradigm shift

The emergent CMO framework demonstrates that optimal engagement mechanisms vary systematically based on three contextual dimensions:

- **Institutional embedding** determines adoption pathways, with closed communities achieving consistent corporate penetration rates through formal endorsement while open communities require peer influence mechanisms.
- **Temporal architecture** balances intensity and sustainability, with compressed implementations generating 4:1 higher weekly efficiency but potentially sacrificing habit formation.

- **Motivational structure** affects outcomes, with competitive frameworks optimising individual intensity (77% superiority) while collaborative frameworks preserve community cohesion without substantial performance penalties.

This framework necessitates a paradigm shift from universal gamification principles toward contextually adaptive frameworks that match mechanism types to implementation characteristics, challenging one-size-fits-all approaches prevalent in gamification literature (Deterding et al. 2011; Hamari et al. 2014).

4.6.6.2 Specific theoretical contributions

The cross-case analysis generates four distinct theoretical contributions that extend existing knowledge in gamification and behavioural change intervention fields:

- **Temporal Optimisation Theory:** The inverse relationship between duration and weekly intensity (4:1 differential) establishes optimal 6–12 week timeframes that balance engagement with behavioural integration, contributing to Habit Formation Theory (Verplanken and Wood 2006).
- **Social Motivation Pathway Theory:** The comparable effectiveness of competitive and collaborative frameworks (13.03 vs 11.00 trips per week) demonstrates that social connection, more than competition type, drives sustainability, extending gamification theory beyond competitive assumptions.
- **Cross-Cultural Transferability Constants:** The consistency in corporate engagement patterns across contexts ($15.7\% \pm 0.25\%$) establishes universal drivers that transcend cultural boundaries, contributing to Rogers (2003) Diffusion of Innovation Theory.
- **Scale-Efficiency Trade-off Theory:** The demonstration that absolute scale capacity and relative intensity operate through different mechanisms (Generation Z: high scale, moderate intensity; Corporate: inverse pattern) establishes foundations for scale optimisation strategies.

The theoretical contributions advance gamification from descriptive application toward predictive framework development, enabling practitioners to select optimal mechanisms based on contextual assessment rather than trial-and-error approaches. The CMO framework provides both theoretical foundation for future research and practical guidance for evidence-based intervention design.

4.7 Lessons learned and future directions

Both individual and comparative analyses confirm the success of all initiatives in terms of engagement, participation, and environmental impact, despite their significant contextual differences spanning corporate, educational and municipal implementations. The cross-case validation demonstrates the robustness of game-based mobility interventions while revealing systematic patterns that inform both theoretical understanding and practical application.

4.7.1 Key success factors and limitations

Two fundamental success factors emerged consistently across implementations. Team-based dynamics with weekly competitive cycles proved essential for sustained engagement, generating 77 % higher behavioural intensity compared to individual challenge formats. The weekly match structure creates structured engagement patterns (as detailed in Section 4.6.3.2) and social accountability through peer visibility, validating social reinforcement mechanisms in voluntary behavioural change initiatives.

Strategic communication and narrative construction emerged as the second critical success factor, with the “sustainable mobility as a sport” narrative providing compelling framing across diverse audiences. Tailored communication campaigns, co-designed with client organisations, achieved remarkably consistent penetration rates (approximately one-sixth in corporate contexts) and enabled successful adaptation across cultural boundaries.

A key limitation emerged from the predominance of one-off event structures. Except for LIST’s extended observation period, all initiatives operated as discrete competitions, limiting evaluation of long-term engagement sustainability and genuine behavioural change persistence beyond competitive periods. Duration differences suggest that extended implementations (45+ weeks) effectively build organisational cohesion and employee engagement, while compressed implementations (5–10 weeks) maximise immediate outreach and weekly efficiency but potentially sacrifice long-term habit formation.

4.7.2 Future research priorities

Future research should prioritise longitudinal behavioural retention studies with 6–24 month post-intervention follow-up to distinguish between temporary competitive activation and sustained behavioural change. Personalisation research should explore how individual mobility patterns and gamification preferences affect outcomes, enabling adaptive game dynamics tailored to user profiles and community characteristics.

Integrating MUV into complex urban systems requires testing its effectiveness across varied mobility infrastructures and policy settings to validate transferability. Policy integration should explore MUV’s potential as a co-creation tool for sustainable mobility strategies, extending beyond individual behaviour change to foster community involvement in transport planning, as shown in the Cagliari SUMP model.

These research priorities position gamified mobility interventions not merely as digital services for individual behavioural change, but as comprehensive policy innovation tools supporting the transition toward sustainable urban mobility systems through evidence-based community engagement and systematic behavioural transformation at scale.

Chapter 5

Future Directions: AI-Enhanced Behavioural Mobility Systems

This chapter examines the strategic integration of Artificial Intelligence to enhance the adaptability and scalability of gamified mobility interventions. Building on empirical evidence from Chapter 4, it presents three interconnected developments: AI-driven personalisation frameworks that adapt game mechanics to individual behavioural profiles, automated mobility planning systems leveraging organisational data, and modular service architectures enabling third-party platform integration. The chapter introduces the behavioural infrastructure paradigm—a four-layer framework positioning digital platforms as enablers of evidence-based urban transformation. Technical contributions include synthetic data generation for privacy-preserving analysis and SDK deployment for seamless integration. These innovations evolve MUV from a gamification tool into comprehensive infrastructure for behaviour change, mobility management, and policy support.

5.1 The evolution towards intelligent behavioural mobility systems

Urban mobility is undergoing a fundamental shift that transcends traditional infrastructure optimisation to embrace intelligent behavioural intervention systems. The integration of *Artificial Intelligence* (AI) enables adaptive solutions that influence individual travel decisions while continuously learning from collective patterns (Nikitas et al. 2020).

5.1.1 From static to adaptive mobility systems

The transformation toward intelligent mobility systems manifests through pioneering deployments worldwide. Services such as *Waymo* in San Francisco and *Apollo Go* by Baidu already operate fleets of self-driving taxis, while European pilot initiatives—such as *Navya* in Lyon and the *Turin "ToMove" Living Lab* developed as part of the experimental project *MaaS for Italy* of the Italian Government—test automated shuttles in urban contexts. Car manufacturers increasingly equip vehicles with Advanced Driver Assistance Systems (ADAS), gradually advancing driving task automation (OECD 2019). As discussed in Chapter 2, ICTs

have introduced groundbreaking advancements through Mobility as a Service (MaaS), collaborative Intelligent Transport Systems (ITS), and data-driven urban planning. However, AI introduces a fundamentally new paradigm, enabling adaptive, predictive, and autonomous decision-making beyond infrastructure optimisation to encompass behavioural intervention systems.

Traditional mobility management operates through static rule-based systems with pre-determined responses. AI introduces adaptive capabilities that fundamentally alter this paradigm. Through continuous learning from real-time data streams, intelligent systems can identify patterns invisible to traditional approaches, predict behavioural responses to interventions, and dynamically adjust strategies based on measured outcomes. This evolution enables transition from reactive management to proactive influence systems that shape mobility patterns rather than merely responding to them (Agrahari et al. 2024).

5.1.2 AI technologies enabling behavioural transformation

AI-powered systems demonstrate broad transformation potential across mobility services, including real-time demand prediction for public transport (Ke et al. 2017), intelligent traffic signal control (Genders and Razavi 2016), and hyper-personalised multimodal journey planning (Urban Institute 2023). This transformation aligns with current smart mobility trends, integrating data-driven services into Mobility as a Service platforms (Octo Telematics 2023), while supporting strategic urban planning through policy simulation (Da et al. 2025).

The practical implementation of intelligent behavioural systems relies on convergent advances across multiple AI domains, each contributing distinct capabilities that collectively enable comprehensive transformation.

Large Language Models (LLMs) facilitate natural language interactions that can provide personalised mobility guidance and adapt communication styles to individual user preferences. Integrating LLMs enables sophisticated dialogue systems to understand context and provide culturally appropriate responses across diverse user populations (L. Chen et al. 2020).

Machine Learning recommendation systems analyse behavioural patterns to suggest optimal mobility choices based on individual preferences, environmental conditions, and collective intelligence by employing collaborative filtering and content-based matching (Zhao et al. 2019).

Predictive analytics leverage historical data and real-time inputs to anticipate user needs, infrastructure demands, and intervention opportunities. Advanced time-series analysis and deep learning models enable accurate forecasting of mobility patterns at individual and system levels (Ke et al. 2017).

Computer vision and sensor fusion provide real-time environmental awareness that can trigger contextual interventions. Integrating visual data, IoT sensors, and mobile device inputs creates situational awareness for adaptive response systems.

5.1.3 The behavioural infrastructure paradigm

The convergence of these AI capabilities with behavioural science principles establishes the foundation for behavioural infrastructure—integrated digital systems that simultaneously influence individual choices while generating collective intelligence for system optimisation. This paradigm extends beyond traditional gamification or information provision to create comprehensive environments where sustainable mobility becomes inherently rewarding and systematically supported.

Behavioural infrastructure operates through four interconnected layers:

- **Data collection and integration layer:** Combines explicit user inputs, passive behavioural tracking, environmental sensors, and external data sources to create complete contextual awareness. Privacy-preserving techniques ensure data utilisation while maintaining user trust and regulatory compliance.
- **Intelligence and adaptation layer:** Employs machine learning algorithms to identify patterns, predict behaviours, and optimise intervention strategies. This layer continuously refines understanding individual and collective mobility patterns while adapting approaches based on measured outcomes.
- **Intervention and engagement layer:** Delivers personalised experiences through adaptive interfaces, contextual recommendations, social dynamics, and gamified elements. The layer implements behavioural science principles through AI-mediated interactions that evolve with user engagement.
- **System integration and policy layer:** Connects individual behaviours to collective outcomes through data aggregation, policy support systems, and institutional integration. This enables personal choices to inform evidence-based planning while maintaining privacy and democratic governance principles.

5.1.4 MUV as a case study in behavioural infrastructure evolution

For digital services such as MUV, this shift represents an opportunity to move from descriptive analytics to prescriptive systems capable of recommending, personalising, and adapting interventions to users and organisations. The gamified mobility interventions analysed in Chapter 4 demonstrate consistent patterns across contexts, yet represent static implementations with predetermined rule sets. AI integration facilitates evolution towards adaptive systems that continuously adjust based on individual behavioural patterns, contextual factors, and longitudinal engagement data.

Current MUV implementations employ predetermined game mechanics, universal point calculations, and static competition structures that, while effective, cannot optimise for individual motivational profiles or adapt to changing behavioural patterns. The transition

toward AI-enhanced systems addresses these limitations through three strategic developments: intelligent personalisation through machine learning, automated planning through natural language processing, and modular integration through API architectures.

This evolution positions MUV as comprehensive behavioural infrastructure supporting diverse stakeholders: individuals seeking sustainable mobility support, organisations requiring evidence-based engagement tools, and institutions developing data-driven transportation policies. The following sections detail specific implementations of these principles, examining how theoretical frameworks translate into concrete technological solutions.

5.2 AI-driven personalisation in practice: MUV's intelligent systems

Building on the Context-Mechanism-Outcome framework established in Section 4.6 and the behavioural infrastructure paradigm outlined in Section 5.1, MUV has initiated the development of AI-enhanced systems that address key limitations in traditional gamification approaches. These implementations represent initial steps toward the adaptive, personalised behavioural intervention systems capable of supporting the four-layer infrastructure model previously described.

The transition from static rule-based systems to AI-enhanced personalisation addresses fundamental scalability constraints identified in Chapter 4's cross-case analysis, highlighting that universal design approaches require contextual adaptation that manual configuration cannot efficiently accommodate at scale. AI integration enables systematic personalisation that preserves proven engagement mechanisms while adapting to individual motivational profiles and organisational characteristics.

Artificial Intelligence constitutes a substantial asset in behavioural change, particularly in applications designed to influence decision-making in mobility. By acquiring comprehensive understanding of individual characteristics and habits, AI can facilitate the development of personalised interventions, thereby enhancing the effectiveness of behavioural change and its long-term sustainability (Zhu et al. 2021). Moreover, the capability to analyse mobility data in conjunction with behavioural patterns enables the automation of mobility management plan development for organisations and provides evidence-based policy support for governmental bodies.

This progression from individual engagement tools toward comprehensive planning infrastructure operationalises the systemic integration layer of the behavioural infrastructure model, demonstrating how personal behavioural change can aggregate to collective transformation. The following sections present three interconnected AI applications demonstrating this progression from static gamification to adaptive, personalised behavioural intervention systems: domain-specific consultation through natural language processing, automated planning through data integration and template generation, and intelligent gamification through machine learning-driven personalisation.

5.2.1 The MUV mobility manager assistant: domain-specific AI consultation

The inaugural AI application developed by MUV addresses the growing demand for expert consultation in corporate mobility management. With Italy's regulatory framework mandating mobility managers for organisations with 100+ employees (Infrastrutture e dei Trasporti 2021) and similar requirements emerging across European contexts, standardised expert guidance becomes crucial for implementation success.

The MUV Mobility Manager Assistant leverages *OpenAI's GPT-4* technology to provide tailored information regarding Italian regulations, assist mobility professionals in enhancing data collection and analysis of employee travel behaviours, and support the integration of innovative practices into sustainable mobility management plans, following the growing adoption of AI-based virtual assistants in public service delivery (Lindgren et al. 2024).

By merging MUV's accumulated expertise with generative AI capabilities, the assistant streamlines mobility plan development while ensuring regulatory compliance and practical applicability.

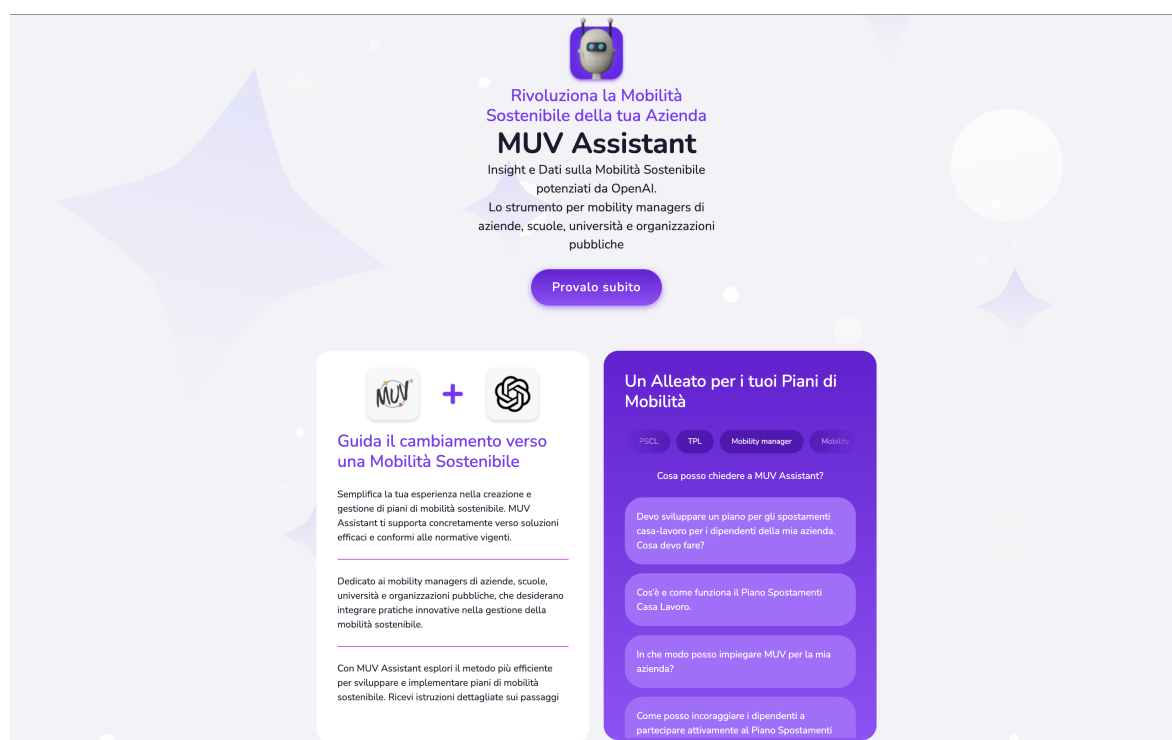


Figure 5.1: Landing page of the MUV Mobility Manager Assistant, providing key information and user-friendly access for specific AI consultation in corporate mobility management.

5.2.1.1 Technical architecture and domain expertise integration

The assistant operates through a sophisticated knowledge integration framework that combines regulatory accuracy with practical implementation guidance. The training corpus encompasses all mobility management plans developed by MUV for its clients, plus others publicly available from diverse organisational contexts, ranging from large corporations

with multi-site operations to educational institutions and public administrations, enabling recognition of sector-specific requirements and proven implementation strategies.

Knowledge base architecture employs document embedding techniques that preserve semantic relationships and structural hierarchies between regulations, guidelines, and practical implementations. The foundation draws from multiple institutional sources: ministerial guidelines from the Ministry of Infrastructure and Transport (MIT), technical specifications from regional mobility authorities, standardised templates from the Association of Mobility Managers, and MUV's proprietary database of successful implementations across 20+ corporate deployments. This multi-source training approach ensures comprehensive coverage while maintaining regulatory accuracy and practical applicability, following established principles for domain-specific AI system development (Devlin et al. 2019).

Document categorisation follows a structured taxonomy addressing four critical domains: regulatory compliance frameworks (national and regional requirements), technical methodologies (survey design and data analysis protocols), implementation strategies (employee engagement and incentive programs), and reporting standards (KPI frameworks and environmental impact measurement). This systematic organisation enables contextual retrieval where responses draw from relevant precedents while maintaining regulatory accuracy.

The system configuration process involved iterative refinement through extensive testing cycles, allowing for tool fine-tuning and error correction. Instructions were designed to shape behaviour, language tone, and response structure to align with professional mobility management contexts while ensuring accessibility for users with varying technical expertise levels.

5.2.1.2 Implementation capabilities and user engagement

Based on user requirements and specific inquiries, the assistant provides precise guidance on necessary documentation, regulatory procedures, and supplementary activities such as internal communication strategies for promoting employee surveys or designing incentive programs. The system excels at generating contextually appropriate recommendations that balance regulatory compliance with organisational feasibility constraints.

Current deployment through beta release enables systematic evaluation of effectiveness and user acceptance patterns. Registration requires email verification for access credentials, while post-interaction surveys capture feedback on utility, accuracy, and user experience quality. This controlled release approach facilitates systematic improvement through direct user input while maintaining service quality standards.

The assistant demonstrates particular strength in survey design and incentive program recommendations, with over 80 % of users rating these components as highly beneficial for plan formulation. The system effectively translates complex regulatory requirements into actionable implementation steps while providing sector-specific adaptations that reflect organisational context and constraints.

5.2.1.3 Current limitations and enhancement opportunities

Beta version deployment reveals systematic patterns in both capabilities and constraints that inform ongoing development priorities. The most frequent limitation involves handling organisation-specific contexts that deviate from standard frameworks, particularly companies with complex multi-regional operations or unique mobility constraints such as shift-based work patterns or security-restricted facility access.

While the system demonstrates strong performance in regulatory compliance and standard plan structures, it requires additional guidance for highly specialised sectors. User feedback indicates weaker performance in quantitative data analysis interpretation, particularly when organisations provide complex modal split data or atypical commuting patterns that fall outside training data distributions.

The most significant enhancement opportunity lies in developing dynamic learning capabilities that could incorporate feedback from implemented plans to refine recommendations. Currently operating on static knowledge, future iterations could analyse the effectiveness of generated plans to continuously improve guidance quality, creating feedback loops between recommendation and outcome that would enhance accuracy and practical relevance.

This systematic approach positions the MUV Assistant as a scalable solution for democratising mobility management expertise while maintaining professional standards, addressing the growing demand for accessible yet sophisticated consultation tools in the evolving landscape of corporate sustainability requirements.

5.2.2 Automated mobility planning: from data to strategy

Generative AI enables the automation of mobility management plans by leveraging data collected through the MUV service in corporate and educational settings. This advancement involves enhancing the MUV web dashboard with integrated survey tools and data analysis capabilities. The approach helps translate mobility tracking data into actionable corporate policies while lowering the expertise barrier for effective implementation.

The automated planning system encompasses six integrated phases that form a comprehensive workflow. This systematic approach leverages organisational mobility data to generate evidence-based intervention strategies, operationalising the adaptive intervention principles discussed in Section 5.1 within organisational contexts.

5.2.2.1 Intelligent survey design and deployment

Effective mobility plan formulation requires integrating both qualitative and quantitative data, specifically information regarding distance, time, frequency, and modes of daily employee commutes, as well as general mobility habits and potential for behavioural change. The automated survey generation addresses this requirement through systematic template-based approaches that capture the three critical mobility dimensions consistently identified across MUV implementations.

Survey customisation employs organisational profiling algorithms considering company size, geographical distribution, existing mobility infrastructure, and previous intervention history to generate contextually appropriate data collection instruments. The standardised framework addresses three core components derived from successful implementations: general mobility habits (frequency patterns, preferred transport modes, typical travel distances, and infrastructure utilisation), home-work commuting patterns (origin-destination pairs, current modal split, timing preferences, and seasonal variations), and change propensity assessment (perceived barriers to modal shift, incentive responsiveness, infrastructure improvement priorities, and organisational support requirements).

The AI agent facilitates mobility manager interaction within a dedicated dashboard section, gathering organisational information necessary to tailor employee mobility surveys. Template generation draws from MUV's database of successful survey implementations across diverse contexts, automatically adapting question sets, response scales, and demographic categories to organisational characteristics. The system creates surveys as online web forms embedded within dedicated landing pages, enabling seamless distribution via email or mobile application to all community members.

Data collection monitoring provides real-time response tracking and quality assessment. The system determines minimum response thresholds necessary for reliable plan development, automatically triggering reminder notifications when participation rates fall below statistical requirements. Integration with existing MUV tracking data enables cross-validation of survey responses against recorded sustainable trip patterns, enhancing data reliability and identifying potential inconsistencies requiring follow-up.

This approach addresses the limitations identified in traditional mobility surveys, which often employ generic questionnaires that fail to capture organisation-specific factors influencing mobility behaviour (Roby 2010).

5.2.2.2 AI-powered analysis and plan generation

Upon achieving sufficient data collection, the mobility manager receives automated notification enabling plan generation initiation. Plan generation utilises natural language processing pipelines that interpret survey responses and tracking data to assess employee willingness to change modal choices and identify intervention opportunities. The system analyses modal split patterns, distance distributions, and timing preferences to identify specific behavioural change leverage points while considering infrastructure constraints and organisational resources.

The AI system integrates MUV's existing data analytics capabilities, including community modal split analysis from dashboard visualisations, vehicle fleet composition from garage registrations, and home-work trip patterns from tracked sustainable travel. This integration enables comprehensive baseline establishment that combines self-reported survey data with verified behavioural tracking, providing robust foundations for intervention recommendations.

The document is generated by artificial intelligence using a predefined template consisting of a table of contents and various sections, consistent with the increasing use of AI in automating documentation processes within public sector organisations (Wirtz et al. 2019). Specific recommendations draw from proven strategies identified in successful MUV implementations, adapting challenge structures, tournament formats, and incentive mechanisms to organisational characteristics and employee preferences identified through data analysis.

Compliance verification ensures generated plans align with regulatory requirements and corporate reporting standards. The system incorporates knowledge from the MUV Assistant's regulatory database to verify plan components meet legal obligations while suggesting enhancements that support broader sustainability reporting frameworks such as the Corporate Sustainability Reporting Directive requirements.

5.2.2.3 Continuous optimisation and performance monitoring

The automated planning framework extends beyond initial document creation to encompass ongoing monitoring and iterative improvement capabilities. Implementation effectiveness tracking utilises MUV's existing tracking infrastructure to monitor adoption rates, modal shift patterns, and environmental impact achievement against plan projections.

Performance evaluation employs the platform's established metrics framework, including trip registration rates, modal distribution changes, and CO₂ emission reductions calculated through the ISO 14064-2 certified methodology. The system compares actual behavioural changes against plan predictions, identifying successful intervention components and areas requiring adjustment. Adaptive optimisation capabilities enable plan refinement based on implementation experience. The system can suggest modifications to incentive structures, communication strategies, or competition formats based on observed engagement patterns and behavioural response data. Long-term monitoring supports annual plan updates, incorporating lessons learned and evolving organisational contexts.

Future development priorities include integrating external data sources to enhance context awareness, such as local transportation infrastructure changes, seasonal mobility pattern variations, and regional policy developments that may affect employee travel options.

The workflow illustrated in Figure 5.2 demonstrates how AI integration transforms traditional mobility planning from manual, expertise-dependent processes into systematic, data-driven methodologies that can be deployed across diverse organisational contexts while maintaining compliance with regulatory requirements and corporate sustainability objectives.

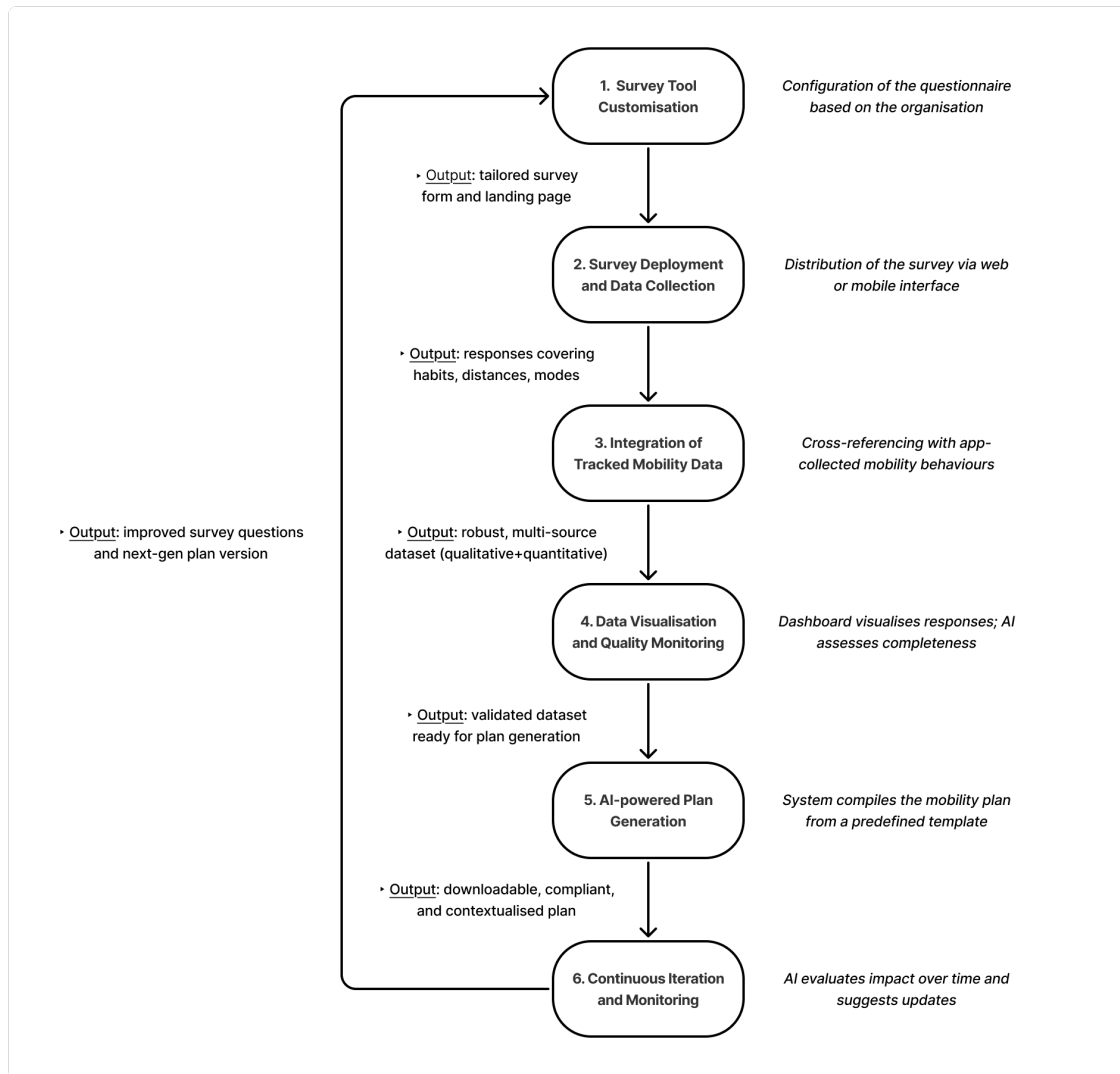


Figure 5.2: The six-phase automated mobility planning process designed for MUV’s AI-enhanced system. The workflow shows the integration of survey customisation, data collection, AI-powered analysis, and continuous optimisation for mobility management plans.

This automated planning approach positions MUV as a complete mobility management infrastructure, enabling organisations to systematically develop, implement, and optimise evidence-based transportation strategies while reducing dependency on external consulting expertise and ensuring consistency with proven behavioural change methodologies.

5.2.3 Towards personalised game dynamics: intelligent gamification engine

The analysis of the case studies presented in Chapter 4 indicates that various game dynamics exhibit differential performance concerning engagement and stimulation of active participation. However, this general observation does not account for the distinct characteristics of different communities and primarily considers an aggregate perspective rather than individual player preferences.

From this standpoint, generative AI emerges as a pivotal tool for personalising gaming experiences and incentivising behavioural change. This enables creating personalised MUV competitions through individualised training, targeted challenges, and tournaments adapted to community characteristics. Achieving this requires collecting extensive user information, organising knowledge systematically, and defining game dynamics at individual and community levels.

5.2.3.1 Multi-layered user profiling for adaptive interventions

The initial phase in developing a personalised gaming experience involves comprehending each user's characteristics and behaviours through a systematic three-layer data collection framework. This understanding enables precise modelling of user preferences and optimal intervention selection.

The **foundational layer** comprises static contextual information inferred at registration, including city of residence, primary travel habits, and available vehicles. Knowledge of the user's location enables the collection of supplementary environmental data such as climatic conditions, mobility infrastructure availability, and urban density characteristics through automated web analysis. This contextual foundation provides the geographical and infrastructural constraints within which personalisation must operate.

The **behavioural analytics layer** captures dynamic usage application patterns that reflect individual engagement preferences and responses. Key metrics include trip frequency and consistency, participation rates distinguishing between tournaments and challenges, intensity of social interactions, and achievement progression over time. Weekly updates support adaptive personalisation that responds to evolving user behaviour.

The **qualitative feedback layer** captures direct user input through targeted micro-surveys administered via periodic brief questionnaires. These surveys explore user opinions, preferences, and motivational drivers that quantitative data cannot capture. AI-driven topic selection ensures data collection focuses on information gaps most relevant to personalisation effectiveness, optimising user experience and data utility (Aubert et al. 2023).

All the information leveraged across these dimensions is summarised in Table 5.1, which details the data sources, collection mechanisms, and update protocols that enable adaptive intervention design.

Table 5.1: Overview of the three data layers used for user profiling in MUV's intelligent gamification engine.

Layer	Provided via	Provided by	Update frequency	Examples
General and background information	Registration Web scraping	User External sources	Occasional	User's city Mobility habits Available vehicles Local context data
Application-related information	App usage	User	Weekly	Trip records Competition activity Behavioural metrics Social interactions
Qualitative information	Surveys	User	Not required	User opinions Mobility preferences Gamification attitudes

This tri-layer framework generates comprehensive user profiles comprising five integrated components: mobility patterns reflecting travel preferences and modal choices, personality traits indicating competitive versus collaborative orientations, lifestyle factors encompassing activity levels and social preferences, taste indicators revealing aesthetic and content preferences, and community affinity measuring alignment with group characteristics. The profile is constructed from these five components and supplemented by two additional datasets related to the geographical context and MUV's sponsors and rewards. Collectively, these elements enable systematic personalisation that addresses individual differences while maintaining community coherence.

Figure 5.3 illustrates the complete architecture of the intelligent gamification engine, demonstrating how the behavioural data collection framework integrates with user profiling analysis and contextual information to generate personalised game experiences. The systematic data flows from foundational information through behavioural analytics to qualitative feedback create comprehensive user understanding that enables targeted intervention design while maintaining community engagement dynamics.

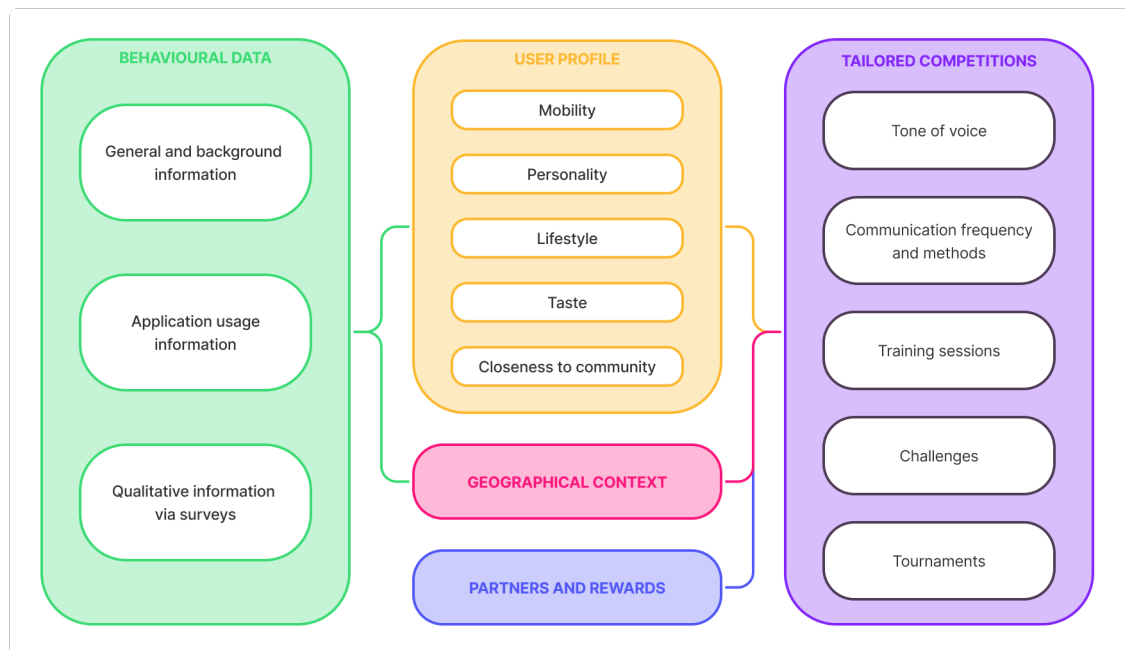


Figure 5.3: Architecture of MUV's AI-driven personalisation engine showing data integration flows and personalised output generation.

5.2.3.2 Intelligent personalisation engine

The core objective of MUV's AI-driven design system is to generate tailored competitions that optimise engagement through personalised game dynamics. As previously indicated, this process encompasses not only the formulation of various competitions but also the development of supplementary activities designed to enhance their effectiveness. This systematic approach operationalises the theoretical understanding that personalised interventions yield superior behavioural outcomes compared to universal design approaches (Rita Orji and Ndulue 2023).

The personalisation engine operates through systematic adaptation of both content delivery and game mechanics based on individual user profiles. Unlike static approaches, this system continuously refines strategies through performance feedback, creating increasingly effective interventions.

Communication optimisation adapts tone, timing, and messaging style to individual preferences identified through profile analysis. The system selects appropriate registers, ranging from informal to formal approaches, appeals to specific motivational drivers, including competitiveness, health benefits, or environmental consciousness, and optimises delivery timing based on individual engagement patterns. Critically, all communications maintain gender inclusivity and cultural sensitivity regardless of personalisation parameters.

Game dynamics adaptation extends personalisation beyond messaging to fundamental competition structures. Training sessions adapt complexity and progression to individual skill development. Challenge and tournament selections consider user preferences for competitive versus collaborative formats, optimal duration based on historical patterns, and

reward structures aligned with motivational profiles. The system categorises user profiles based on gamification types and preferences (Krath and Korflesch 2021), creating personas that represent typical users for dynamic adaptation. Once this categorisation is complete, the game dynamics can be delineated for larger groups or specific target categories.

Team formation algorithms balance individual preferences with community dynamics to optimise personal satisfaction and collective performance. The system leverages insights from the sport-as-metaphor framework established in Chapter 3, adapting athletic progression principles to individual capabilities and preferences. Users demonstrating high engagement with competitive elements receive more tournament-focused recommendations, while those preferring collaborative approaches are guided toward community challenges. This systematic matching enhances the intrinsic motivation mechanisms critical for sustained behavioural change.

5.2.3.3 Dynamic learning and community optimisation

The intelligent gamification engine employs continuous learning mechanisms that analyse individual response patterns and community-level dynamics to refine personalisation strategies. This dual-level approach ensures that optimisation considers both personal preferences and collective engagement patterns.

Individual feedback analysis monitors user responses through multiple metrics: notification engagement rates, competition patterns, and sustained platform usage. Machine learning algorithms identify successful patterns and adjust recommendations accordingly, while community-level analysis optimises group experiences through team formation success, goal achievement, and social interaction patterns.

Community-level optimisation analyses collective dynamics to enhance group experiences while maintaining individual personalisation. The system evaluates team formation success rates to improve matching algorithms, monitors collective goal achievement in collaborative challenges to optimise difficulty calibration, and tracks social interaction patterns to identify optimal community engagement strategies. These insights inform both individual recommendations and community-wide intervention design.

Performance evaluation occurs at competition conclusion through systematic analysis of engagement indicators, behavioural change effectiveness, and user satisfaction metrics. This evaluation data trains the system to enhance subsequent competition design, creating co-evolving experiences that continuously improve personalisation accuracy and engagement effectiveness.

5.2.3.4 Integration with sport-as-metaphor framework

The AI-enhanced personalisation system operates within and enhances the sport-as-metaphor framework established as MUV's theoretical foundation. Rather than replacing this framework, artificial intelligence enables more sophisticated implementation of athletic progression principles through individualised approaches that maintain framework coherence.

The **virtual mobility trainer** concept represents the ultimate personalisation of the MUV experience, where each user receives individualised coaching that evolves with their mobility behaviour patterns, motivational changes, and life circumstances. This AI-driven trainer proposes personalised training sessions, challenges, and tournament based on individual development trajectories, behavioural profiles, and contextual constraints, implementing principles from modern AI-driven personalised learning systems (Chen, 2020).

Integration with Self-Determination Theory principles occurs through systematically matching AI capabilities to psychological needs: autonomy support through personalised choice architectures, competence development through adaptive challenge progression, and relatedness enhancement through optimised social matching (Deci and Ryan 2008). The system ensures that technological sophistication serves psychological authenticity rather than replacing it.

Future development priorities include evaluation of alternative personalisation methodologies to determine optimal performance across diverse user segments, integration with MUV's ISO 14064-2 certified CO₂ calculation algorithms to enable personalised impact feedback, and development of explainable AI frameworks that maintain user trust through transparent personalisation processes.

This comprehensive AI-enhanced gamification approach positions MUV to transition from static rule-based interventions toward adaptive behavioural infrastructure that optimises individual engagement while maintaining the community dynamics and social reinforcement mechanisms proven effective in systematic behavioural change interventions.

5.3 Strategic platform evolution: synthetic data and modular architecture

Despite demonstrated efficacy in diverse contexts, systematic analysis of MUV implementations reveals two fundamental limitations constraining broader impact and analytical capabilities. First, participation constraints restrict the comprehensiveness of mobility pattern analysis for urban planning applications. Corporate implementations typically engage 15–25 % of eligible employees, while municipal initiatives represent small metropolitan population fractions. These coverage limitations compromise the representativeness of collected mobility datasets for comprehensive urban mobility planning and policy development.

Second, the platform's dependency on standalone mobile application usage creates integration barriers for organisations with existing digital ecosystems and limits scalability across diverse technological contexts. This architectural constraint prevents seamless incorporation of MUV's behavioural change and impact measurement capabilities within established corporate wellness platforms, municipal service applications, and third-party mobility service providers, restricting platform reach and adoption potential.

Strategic technological developments can address these limitations through complementary approaches that enhance analytical capabilities while expanding platform accessibility.

Synthetic data generation methodologies enable privacy-preserving augmentation of existing mobility datasets, creating statistically consistent representations that support extensive scenario analysis and urban planning applications. Concurrently, modular service architecture through Software Development Kit deployment enables seamless integration of MUV's core functionalities within diverse digital platforms, extending behavioural intervention beyond standalone application boundaries.

These innovations position MUV's evolution from an isolated gamification platform towards overarching mobility transformation infrastructure, enabling enhanced analytical capabilities for evidence-based planning and scalable deployment across diverse organisational and technological contexts.

5.3.1 Synthetic data generation for mobility analysis enhancement

The systematic analysis of MUV implementations reveals gaps in mobility data coverage that limit urban planning applications and policy impact assessment. Corporate penetration rates in diverse organisational contexts, while sufficient for demonstrating behavioural change effectiveness, provide incomplete representations of community-wide mobility patterns necessary for evidence-based transportation planning. Municipal implementations, despite achieving substantial individual impact, engage limited population fractions insufficient for comprehensive urban mobility analysis.

Contemporary AI systems can augment these analytical processes through sophisticated simulation platforms that analyse travel patterns and forecast mobility trends by integrating limited real datasets with predictive modelling frameworks. Multiple applications of AI in transport have demonstrated substantial value in improving traffic management, safety protocols, and forecasting capabilities (Abduljabbar et al. 2019). Simulating transport scenarios enables assessment of long-term impacts associated with policy interventions and infrastructure investments, optimising urban planning decisions within existing capacity constraints.

5.3.1.1 Technical framework for mobility data augmentation

Synthetic data generation offers methodologically sound solutions to coverage limitations while addressing privacy preservation requirements mandated by GDPR compliance. Generated artificially from original datasets using advanced statistical and machine learning techniques, synthetic mobility data replicates source datasets' statistical properties without exposing sensitive individual information. This approach enables creation of analytically consistent datasets that support simulation and predictive modelling while maintaining full regulatory compliance (Berke et al. 2022).

The technical implementation employs two complementary approaches adapted to MUV's specific data characteristics. *Generative Adversarial Networks* (GANs) enable trajectory synthesis that preserves temporal dependencies and spatial relationships inherent in real mobility patterns. The generator network learns to produce realistic trip sequences

incorporating modal choice patterns, timing preferences, and geographical constraints, while the discriminator ensures synthetic trajectories remain indistinguishable from authentic data. *Kernel Density Estimation* (KDE) provides complementary capability for distribution matching, ensuring synthetic datasets maintain statistical consistency with observed modal splits, distance distributions, and demographic patterns identified in source communities.

Quality assurance employs systematic validation frameworks that assess statistical fidelity and privacy preservation. Statistical similarity metrics evaluate distributional consistency across key mobility dimensions: modal split accuracy, temporal pattern preservation, spatial coverage completeness, and demographic representation balance. Privacy preservation validation ensures that synthetic datasets eliminate re-identification risks while maintaining analytical utility through differential privacy techniques and k-anonymity verification protocols.

When subjected to identical statistical analyses, synthetic datasets should produce outcomes comparable to the original data while enabling expanded coverage and enhanced representativeness. In mobility contexts, this methodology facilitates augmentation of limited or non-representative datasets, generating realistic trajectory patterns and displacement behaviours across diverse temporal, modal, and geographical dimensions while introducing sufficient stochastic variation to eliminate privacy and re-identification risks.

Table 5.2 provides a comparative analysis of key characteristics distinguishing real from synthetic mobility data across analytical dimensions relevant to urban planning applications.

Table 5.2: Comparative analysis of real versus synthetic mobility data characteristics across key analytical dimensions.

Dimension	Real Data	Synthetic Data
Statistical validity	High (when complete)	Comparable if well generated
Privacy risk	High (especially in small samples)	Low (privacy-preserving by design)
Spatial/temporal coverage	Limited to collected data	Customisable and extendable
Suitability for simulation	Requires consent and preprocessing	Ideal for testing planning scenarios
Representation of rare events	Often insufficient or unbalanced	Can be purposefully included and balanced

However, synthetic data effectiveness remains highly context-dependent and requires continuous validation across diverse mobility environments and user populations, as recent critical reviews emphasise the importance of robust model validation in complex human behaviour domains (C. Zhang et al. 2023). As illustrated in Table 5.2, synthetic data offers distinct advantages for simulation applications while addressing privacy concerns inherent in real mobility datasets.

5.3.1.2 Applications in urban mobility planning

Synthetic data augmentation enables the transformation of limited MUV datasets into comprehensive mobility analysis foundations supporting diverse planning applications. Origin-destination matrix enhancement allows expansion of tracked sustainable trips into complete community mobility portraits, enabling planners to assess infrastructure needs and policy impacts across entire urban areas rather than isolated user segments.

Scenario-based policy simulation represents the most significant application opportunity. Synthetic datasets enable testing alternative transportation policies, infrastructure investments, and behavioural intervention strategies without requiring large-scale implementation or risking adverse community impacts. Planners can model modal shift scenarios, evaluate public transport capacity requirements, and assess environmental impact projections using statistically robust yet privacy-preserving synthetic populations.

Integration with MUV's established CO₂ calculation methodology enables environmental impact scaling from individual behaviour change to community-wide transformation potential. Synthetic data augmentation supports calculating emission reduction scenarios under various policy configurations, providing evidence-based input for Sustainable Urban Mobility Plan development and climate action planning processes.

The approach addresses fundamental challenges in evidence-based transportation planning where comprehensive mobility data remains expensive, privacy-sensitive, or simply unavailable. By enabling reliable analysis from limited real datasets, synthetic data generation positions MUV as infrastructure supporting broader urban transformation rather than isolated behavioural intervention, creating pathways for individual engagement tools to contribute systematically to collective planning processes.

5.3.2 Modular service architecture: the MUV SDK approach

MUV was initially conceptualised and developed as an integrated service intrinsically tied to its mobile application, which serves as the primary interface for tracking, gaming, and impact calculation. While this unified approach enabled sophisticated behavioural intervention design, it creates significant integration barriers that limit platform scalability and market penetration. This architectural constraint necessitates that users download and actively engage with a standalone application, complicating integration with existing organisational digital ecosystems and third-party service providers.

The limitation becomes particularly pronounced in corporate and institutional contexts where organisations maintain established digital infrastructures, employee wellness platforms, and mobility service partnerships. The empirical evidence from case studies reveals that adoption barriers inherent in standalone applications significantly constrain organisational penetration rates. To overcome these obstacles and enhance market competitiveness through seamless integration with diverse service providers, MUV requires a transition towards a modular Software as a Service (SaaS) architecture.

5.3.2.1 API-first design principles and service decomposition

This evolution can be achieved through the development and deployment of a *Software Development Kit* (SDK), accompanied by standardised *Application Programming Interfaces* (APIs), following established patterns in modular architectures for embedding analytics or gamified components within external services (Tan et al. 2013). The SDK approach enables third-party platforms to integrate specific MUV functionalities while maintaining their existing user interfaces and interaction paradigms, reducing adoption barriers and expanding potential market reach.

The architectural design follows API-first principles where each functional component operates as an independent microservice with well-defined interfaces. RESTful API design ensures platform compatibility and enables standardised integration patterns across diverse technology stacks. Authentication mechanisms employ OAuth2 protocols for secure service access, while rate limiting and error handling frameworks ensure reliable performance under varying load conditions.

Data exchange protocols prioritise functionality and privacy through structured JSON schemas that minimise information exposure while enabling rich functionality. Webhook systems enable real-time event notifications, allowing integrated platforms to respond immediately to user actions, achievement unlocks, or competition updates. This event-driven architecture supports responsive user experiences while maintaining loose coupling between MUV services and host platforms.

5.3.2.2 Core module specifications and integration patterns

From a functional perspective, the MUV SDK comprises three core modules that reflect the platform’s fundamental capabilities: game dynamics management, environmental impact measurement, and mobility tracking systems. Table 5.3 details the specific functions and integration requirements for each module.

Table 5.3: Overview of the three core modules comprising the MUV SDK, their primary functions, required inputs, and generated outputs for third-party integration.

Module	Main Function	Required Input	Output
Game design	Activate challenges, quizzes, badges	User platform action	Points, rankings, engagement
Impact measurement	Calculate CO ₂ savings based on user mobility	Distance, mode, frequency	Emission reduction per user
Travel monitoring	Track trips and distances	Sensors or manual input	Mobility dataset

The **game dynamics module** facilitates activation of customisable gamification features, including dynamic rankings, personalised challenges, interactive quiz mechanisms, and thorough badge systems associated with users' mobility choices. This module implements the behavioural intervention mechanisms validated in Chapter 4, particularly the tournament structures that demonstrated superior engagement compared to individual challenge formats. Integration patterns enable host platforms to embed competitive elements seamlessly within existing user workflows.

The **impact measurement module** operationalises MUV's ISO 14064-2 certified methodology for quantifying CO₂ emissions saved through sustainable mobility choices. This module enables third-party platforms to provide users with scientifically validated environmental impact assessments without developing proprietary calculation algorithms, leveraging MUV's established expertise in mobility-based carbon footprint quantification. The module handles baseline establishment, modal shift calculation, and emission attribution through standardised API calls.

The **travel monitoring module** addresses platforms requiring mobility data collection capabilities but lacking sophisticated tracking infrastructure. This module provides validated trip detection, modal split analysis, and distance measurement functionalities that feed into gamification and impact calculation processes, creating comprehensive mobility engagement ecosystems within existing applications.

5.3.2.3 Integration architecture and scalability framework

These modules operate independently or in combination, contingent upon specific integration requirements and objectives. The modular architecture follows established SaaS design principles with RESTful API protocols, webhook event systems, and standardised authentication mechanisms that ensure secure data exchange while maintaining platform flexibility (Fielding 2000).

Container-based deployment enables dynamic scaling based on demand patterns, which is essential for accommodating varying usage intensities across different integration partners. Microservices architecture ensures that individual module failures do not cascade across the entire system, while service mesh technologies enable sophisticated traffic management and performance monitoring.

The business model operates on a pay-per-use basis determined by API call volume, enabling scalable cost structures that align with actual utilisation patterns rather than fixed subscription fees. This approach reduces barriers to initial adoption while providing sustainable revenue streams that scale with platform success and user engagement levels.

Competitive analysis reveals the absence of comparable market offerings that combine gamification, scientifically validated impact measurement, and mobility tracking in an integrated SaaS format specifically designed for mobility applications. While generic gamification platforms exist across marketing and e-commerce sectors, no mobility-specific solutions provide ready-to-integrate behavioural change capabilities with certified environ-

mental impact assessment methodologies.

Target market segments encompass mobility service providers (public transport operators, shared mobility platforms, corporate fleet management), employee wellness and engagement platforms seeking mobility-based sustainability features, and consumer-facing applications across diverse sectors. This includes banking institutions, insurance companies, large retail groups, beauty, sports, and food brands that consistently pursue solutions to enhance user engagement, offer customised experiences, and demonstrate commitment to promoting sustainable choices through quantified environmental impact communication.

This modular architecture approach positions MUV to establish leadership in the sustainability technology sector by targeting organisations committed to fostering active lifestyles and incorporating environmental responsibility into their service offerings. The primary advantages include implementation simplicity, adaptability to existing user experience paradigms, and the potential for dedicated reward mechanisms that align with partner organisation values, enabling MUV to evolve from standalone application to foundational infrastructure supporting broader sustainable mobility transformation.

5.3.3 Towards comprehensive mobility transformation infrastructure

The strategic developments outlined in this chapter—synthetic data generation and Software Development Kit deployment—represent MUV’s evolution towards an increasingly adaptable and scalable mobility transformation infrastructure. This dual strategy addresses fundamental limitations constraining platform impact while positioning MUV as an ecosystem enabler that enhances existing digital services rather than competing with them.

5.3.3.1 From platform limitations to infrastructure capabilities

Synthetic data methodologies directly address coverage constraints demonstrated across MUV implementations: corporate penetration rates of 15–25 % and municipal engagement representing small metropolitan population fractions create analytical gaps that compromise comprehensive mobility planning capabilities. Privacy-preserving data augmentation techniques transform these limited datasets into statistically robust representations supporting extensive scenario analysis and evidence-based urban planning without compromising individual privacy.

Concurrently, SDK deployment addresses architectural limitations restricting platform integration within existing digital ecosystems. The modular service architecture permits embedding MUV’s behavioural change capabilities, validated impact measurement, and mobility tracking within diverse third-party platforms, extending intervention reach beyond standalone applications. This approach addresses adoption barriers while enabling scalable deployment across corporate wellness platforms, municipal services, and consumer-facing mobility solutions.

5.3.3.2 Governance and democratic participation framework

The evolution toward behavioural infrastructure requires systematic governance frameworks that preserve democratic participation while leveraging technological capabilities. AI-enhanced mobility systems raise critical questions about algorithmic accountability, data sovereignty, and participatory decision-making that necessitate careful institutional design (Stilgoe 2020).

The governance model operates through multi-stakeholder coordination mechanisms, balancing technological efficiency with democratic participation. Citizens maintain control over mobility data through granular consent management and transparency protocols, while institutions access aggregated insights supporting evidence-based planning. This ensures that technological capabilities serve collective decision-making rather than replacing it, positioning digital tools as enablers of informed democratic participation.

Stakeholder coordination follows subsidiarity principles, where decision-making authority remains at the most local level capable of effective action. Individual mobility choices inform neighbourhood planning, community patterns support municipal strategy development, and regional aggregations enable metropolitan coordination. This creates nested governance structures that preserve citizen agency while enabling systematic coordination across jurisdictional boundaries.

5.3.3.3 Strategic positioning and value creation

Rather than competing with existing mobility platforms, this approach positions MUV as infrastructure that enhances diverse digital services with sophisticated behavioural intervention and impact measurement capabilities. The vision aligns with contemporary smart mobility paradigms where AI-driven systems enable more responsive, inclusive, and sustainable transport ecosystems (Benevolo et al. 2016; Nikitas et al. 2020).

The platform's evolution enables three distinct value propositions: enhanced analytical capabilities for evidence-based mobility planning through synthetic data augmentation, scalable behavioural intervention deployment through modular integration, and comprehensive impact measurement supporting organisational sustainability reporting and policy evaluation.

Future developments require careful alignment of technological capabilities, regulatory frameworks, and behavioural intervention effectiveness. Integrated approaches that combine technical innovation with policy coordination and stakeholder engagement prove essential for sustainable transportation transformation (Okon et al. 2024). The progressive integration of AI in mobility systems necessitates continuous negotiation between public institutions, private service providers, and citizen communities regarding governance, accountability, and control distribution.

MUV's strategic positioning as infrastructure provider enables participation in complex governance discussions while contributing technological capabilities that support transparent, evidence-based decision-making across diverse stakeholder groups. By providing

scientifically validated impact measurement, privacy-preserving data analysis, and effective behavioural intervention tools, MUV contributes to mobility ecosystem development that balances innovation with accountability, efficiency with inclusivity, and technological capability with democratic governance.

This approach positions MUV as catalyst for systemic mobility transformation, enabling evidence-based policy development, scalable behavioural change, and transparent impact measurement across diverse urban contexts and organisational environments, supporting European Green Deal implementation through systematic citizen engagement while contributing to broader understanding of technology-mediated democratic participation in urban governance.

Conclusions

This study examines the role of ICT, game design, and data analysis in promoting sustainable urban mobility, using MUV as a case study. The research demonstrates how integrating digital technologies can measurably influence individual mobility choices, achieving up to 34 % carbon footprint reduction while generating valuable data to support public policies. Key findings advance the understanding of digital behavioural interventions, highlighting the effectiveness of a people-centred, co-design approach and the potential of AI and Software as a Service models for scaling impact. The study contributes to the emerging field of behavioural infrastructures, emphasising the critical role of citizen participation in driving the twin transition toward more sustainable, equitable cities.

Summary of key findings

This study demonstrates how the strategic integration of ICTs, game design, and data analysis can measurably influence individual mobility choices while generating valuable insights for urban policy development. Through the case study of the academic spinoff MUV, this research provides empirical evidence for the effectiveness of digital behavioural interventions in promoting sustainable mobility in diverse urban contexts.

Three fundamental theoretical contributions that advance the understanding of technology-mediated behavioural change emerge: the sport-as-metaphor framework, as a shift from traditional gamification; the Context-Mechanism-Outcome framework, advocating context-sensitive design; and the multi-modal gamified architecture, enabling fair competition across varied transport modes with scientifically validated scoring.

Empirical validation across corporate (INAIL), international (LIST), educational (MOB), and municipal (Cagliari) contexts demonstrates the approach's transferability and scalability. With 4 872 participants, active users achieved an average 34 % carbon footprint reduction, and corporate penetration rates remained consistent across countries 15.77 %. Tournament formats consistently demonstrated superior engagement compared to individual challenges, validating social reinforcement mechanisms in diverse demographic segments and implementation scales.

The platform's evolution through three phases—Horizon 2020 research (2017-2020), commercial deployment (2020-present), and AI-enhanced future development—demonstrates how academic innovation can transition into impactful, scalable digital infrastructure.

Major theoretical contributions

This research advances the field of digital behavioural interventions through three distinct theoretical innovations that extend existing knowledge in game design, behavioural change, and sustainable mobility domains.

Sport-as-Metaphor framework for behavioural transformation: The systematic application of athletic paradigms to sustainable mobility represents a fundamental departure from traditional gamification approaches that merely overlay game elements onto existing activities. This framework reframes the entire mobility experience within a coherent sporting paradigm, transforming routine travel decisions into conscious, motivated choices. By positioning sustainable mobility as athletic participation rather than environmental obligation, the framework reduces psychological resistance while enhancing intrinsic motivation. Tournament structures demonstrate 77 % higher behavioural intensity than individual challenges through social reinforcement amplification, temporal anchoring effects, and progressive achievement architecture.

Context-Mechanism-Outcome (CMO) framework: The research establishes that optimal engagement mechanisms vary systematically based on three contextual dimensions: institutional embedding (closed vs. open communities), temporal architecture (intensive vs. extended implementations), and motivational structure (competitive vs. collaborative frameworks). This challenges prevailing universal design approaches, necessitating a paradigm shift toward contextually adaptive frameworks. The 4:1 efficiency differential between intensive and extended implementations, combined with comparable effectiveness of competitive and collaborative frameworks, establishes foundations for evidence-based intervention design that optimises outcomes based on contextual assessment.

Multi-modal gamification architecture: The extensive architecture accommodates diverse transport modes within unified competitive frameworks, advancing behavioural intervention theory through hierarchical point systems that reflect actual environmental impact rather than arbitrary game mechanics. The scoring algorithm incorporates mode-specific sustainability coefficients validated against ISO 14064-2 standards, ensuring game rewards align with genuine ecological benefits. This architecture enables fair competition across varied user contexts while preventing system exploitation through sophisticated threshold mechanisms that balance engagement with sustainability objectives.

Cross-cultural validation and scalability evidence

While the research scope encompasses only two European countries and several hundred participants per implementation, the findings provide substantial evidence for cross-cultural transferability. The consistency in corporate penetration rates between Italian and Luxembourg implementations demonstrates that fundamental engagement mechanisms transcend specific cultural, linguistic, and policy environments, despite substantial contextual differences, including Italy's car-dependent mobility culture versus Luxembourg's free public transport policy since 2020.

The platform demonstrates adaptability across different institutional frameworks, from hierarchical corporate environments to open municipal initiatives. The successful integration with formal policy processes (particularly the Cagliari SUMP development) indicates potential for systematic incorporation within European urban planning strategies. Nevertheless, each implementation required contextual adaptations in communication approaches, reward structures, and competitive formats, emphasising the necessity of local customisation over universal deployment.

The transition from research prototype to commercial deployment provides preliminary evidence of market viability and scalability potential. However, broader validation across more diverse cultural and economic contexts, along with extended operational periods, remains necessary to establish definitive claims about international transferability and long-term sustainability. These validation insights informed the technological evolution toward more adaptive and scalable systems.

Technological innovation impact

The research demonstrates significant technological innovations that extend beyond traditional gamified approaches to create complete behavioural infrastructure for sustainable mobility transformation. The development of AI-enhanced personalisation systems represents a paradigmatic shift from static rule-based interventions toward adaptive, intelligent behavioural support. The three-layer user profiling system (general information, application usage, qualitative surveys) enables dynamic customisation of game mechanics, communication strategies, and reward structures based on individual behavioural patterns and community characteristics.

The modular Software Development Kit architecture addresses critical integration barriers that limit platform scalability in existing digital ecosystems. By decomposing MUV functionalities into independent modules—game dynamics management, environmental impact measurement, and mobility tracking—the platform enables seamless embedding within third-party services without requiring standalone application deployment. This innovation potentially expands market reach exponentially by reducing adoption barriers for organisations with established digital infrastructures.

The implementation of synthetic data generation addresses privacy and representativeness challenges in mobility data collection. This capability enables privacy-preserving augmentation of limited datasets while supporting urban planning applications, transforming MUV from a behavioural intervention tool into analytical infrastructure for evidence-based policy development while maintaining scientifically validated methodology.

These technological advances position MUV as infrastructure for sustainable mobility transformation rather than isolated gamification platform. The evolution toward intelligent, modular, and analytically enhanced systems demonstrates how digital behavioural interventions can scale beyond individual change toward systemic urban mobility transformation.

Research limitations and challenges

Several methodological and scope limitations constrain the generalisability of findings and suggest important directions for future research. The temporal constraints of case study implementations, ranging from 5 to 52 weeks, preclude assessment of genuine long-term behavioural retention and habit formation beyond competitive periods. While the platform demonstrates strong engagement during active interventions, the sustainability of mobility behaviour changes after formal program conclusion remains insufficiently documented.

The reliance on self-reported baseline mobility data for CO₂ calculations introduces potential accuracy limitations, whether through intentional misrepresentation or unintentional recall bias. Additionally, the platform's dependency on voluntary participation creates self-selection effects, as corporate penetration rates of 15–25 % indicate appeal primarily to early adopters and environmentally motivated users rather than the broader population.

Technical constraints include the requirement for manual trip activation, which balances conscious engagement with potential user friction, and the current limitation to smartphone-based deployment, potentially excluding digitally disadvantaged populations. The requirement for contextual adaptations in each implementation, despite consistent core engagement patterns, highlights the complexity of scaling universal solutions across diverse organisational and cultural contexts.

Future perspectives and opportunities

Building on the empirical foundations and theoretical contributions established, three strategic research and development directions emerge with significant potential for advancing both scientific understanding and practical implementation of gamified mobility interventions.

Advanced longitudinal research represents the most critical scientific priority, requiring 6–24 months post-intervention follow-up studies to distinguish between temporary competitive activation and sustained behavioural transformation. Systematic validation across diverse cultural and economic contexts beyond Europe would establish definitive transferability claims and identify universal versus context-specific engagement drivers.

Technology development priorities focus on automated trip detection to reduce user friction while maintaining conscious engagement, and expansion beyond smartphone-only deployment to ensure inclusive access across diverse digital literacy levels. Integration capabilities with existing transportation systems—including public transport operators, shared mobility providers, and municipal planning departments—could transform isolated interventions into comprehensive urban mobility ecosystems.

Policy integration applications offer significant potential for scaling individual behavioural change toward systemic urban transformation. The demonstrated compatibility with SUMP development processes suggests broader applications in evidence-based transportation planning, while integration with emerging regulatory frameworks such as Corporate Sustainability Reporting Directive compliance could drive widespread adoption across European corporate environments.

Implications for urban mobility and public policy

The research demonstrates how gamified digital services can serve dual objectives: immediate behavioural change among participants and broader community awareness of sustainable mobility policies. The Cagliari SUMP integration exemplifies this dual value, where 856 participants generated both measurable emission reductions and valuable mobility insights that directly informed municipal transportation planning processes. This integration model suggests systematic applications for evidence-based policy development across European urban contexts.

The crowdsourced mobility data collection enables nuanced analyses of movement patterns that complement traditional planning methodologies. When augmented with synthetic data capabilities, this approach provides municipalities with granular insights into citizen mobility preferences while preserving privacy through anonymisation. Cities such as Amsterdam and Copenhagen offer valuable examples of effective data-driven urban transformation. Amsterdam's initiative to transform into a "smart city" involves using data analytics to improve urban living conditions (Amsterdam Smart City 2023; Barrett et al. 2016), while Copenhagen's extensive public planning strategy has successfully mitigated urban sprawl by integrating data into planning processes (Vejre et al. 2007; Destination Earth 2024).

The integration of MUV-style tools into broader city strategies prioritises citizen involvement in urban mobility planning while leveraging valuable data to make informed decisions and assess policy effectiveness. The ability to simulate policy scenarios using real behavioural data represents a significant advancement in participatory urban planning approaches, enabling cities to scale these models and support a participatory, technology-enabled shift toward sustainability.

The SaaS architecture enables integration with existing public mobility platforms, potentially reducing barriers to citizen participation while expanding data collection scope.

Municipal implementations could incorporate gamified elements into transport applications, mobility hubs, or digital city services, creating comprehensive urban mobility ecosystems that blend individual motivation with collective planning objectives. By adopting these innovative approaches, cities can systematically implement evidence-based transportation strategies that align with the European Green Deal's ambition for climate neutrality by 2050 and engage citizens as active participants in sustainable urban transformation.

Final remarks

This study demonstrates the critical role of ICT in advancing the European Union's twin digital and green transition, with urban mobility emerging as a transformative domain where technology, behaviour, and policy converge (European Commission 2020a). The MUV platform exemplifies how well-designed digital services, anchored in scientific rigour and inclusive design principles, can evolve into behavioural infrastructures that empower institutions and individuals to drive sustainable transformation.

The research contributions extend beyond technological development to establish theoretical frameworks that advance understanding of context-dependent behavioural interventions. The sport-as-metaphor approach, Context-Mechanism-Outcome framework, and multi-modal gamification architecture provide replicable methodologies for scaling digital behavioural change across diverse European contexts while maintaining scientific validity and cultural sensitivity.

Looking toward 2030 and beyond, the convergence of AI-enhanced personalisation, modular integration capabilities, and evidence-based policy support positions tools like MUV as foundational infrastructure for intelligent urban mobility systems (Nikitas et al. 2020). These behavioural infrastructures could evolve into fully integrated urban operating systems where citizen participation, real-time data flows, and adaptive policy-making create self-improving mobility ecosystems (Batty et al. 2012) that continuously align individual needs with collective sustainability goals.

Within the broader context of European climate neutrality objectives (European Commission 2021b) and Digital Decade targets, this research demonstrates how citizen-centred digital solutions can simultaneously address individual behaviour change and systemic urban transformation challenges. The evidence-based approach, validated across diverse contexts and scales, provides a scalable model for deploying behavioural interventions that support local urban mobility improvements and European-wide sustainability transitions, establishing *digital behavioural infrastructures* as essential components of resilient, equitable, and environmentally responsible urban futures.

Appendix A

Technical Implementation Details

This appendix documents the technical infrastructure underpinning the MUV platform, including data structures, training logic, impact calculation methods, and scoring algorithms. It covers the core algorithmic innovations that support the behavioural change strategies outlined in Chapter 3. The documentation is structured into four sections covering data inventory specifications, training session mechanics, tournament architectures, and CO₂ calculation methodology, demonstrating how the platform’s technical foundation operationalises scientific measurement and gamification effectiveness.

A.1 Comprehensive data inventory

Table A.1 provides a structured overview of the MUV dataset, outlining specifications for implementation and privacy compliance.

Table A.1: Categorisation of data items collected by MUV by type, source, and operational function.

Category	Item	Type	Provided by	Remarks
Registration data	Email address	Mandatory	User	Required for account creation; Subject to GDPR
	Password	Mandatory	User	Required for account creation; Stored securely in the system
	Username	Mandatory	User	Must be unique; Visible within the app
	User ID	Automatic	MUV	Generated at registration; Used to identify the user
	Registration date	Automatic	User	Timestamp marking when the user account is created
	Cancellation request	Optional	User	Timestamp marking when a user initiates account deletion

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Table A.1 – continued from previous page

Category	Item	Type	Provided by	Remarks
Personal data	First name	Mandatory	User	Required for account creation; Subject to GDPR
	Surname	Mandatory	User	Required for account creation; Subject to GDPR
	Sex	Optional	User	Improves calorie accuracy; Subject to GDPR
	Date of birth	Optional	User	Helps segment users by age; Subject to GDPR
	Height	Optional	User	Improves calorie accuracy
	Weight	Optional	User	Improves calorie accuracy
Mobility data	Frequent trip	Optional	User	Enables calculation of modal shift and CO ₂ savings
	Mobility baseline	Optional	User	Enables calculation of modal shift and CO ₂ savings
	Garage	Optional	User	Includes transport modes and subscriptions; Refines impact calculations
	Registered trips	Computed	MUV	Total trips recorded
	Valid trips	Computed	MUV	Total trips validated by the system algorithms
	Distance travelled	Computed	MUV	Total distance of valid trips
	Duration	Computed	MUV	Total duration of valid trips
	Modal split	Computed	MUV	Distribution of transport modes for user-validated trips
Impact data	CO ₂ saved	Computed	MUV	Uses ISO 14064-2 certified methodology
	Modal shift	Computed	MUV	Measures change in transport mode distribution
	Kcal expended	Computed	MUV	Calculated based on trip data and physical activity
	Daily steps	Computed	MUV	Synced with Google Health or Apple HealthKit

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Table A.1 – continued from previous page

Category	Item	Type	Provided by	Remarks
Game data	Points	Computed	MUV	Total points earned
	Participation in challenges	Computed	MUV	Tracks user involvement in challenges
	Participation in tournaments	Computed	MUV	Tracks user involvement in tournaments
	Training sessions completion	Computed	MUV	Tracks progress in training sessions
	Friends	Computed	MUV	Total friends added
	Badges gained	Computed	MUV	Total badges earned
	Rewards obtained	Computed	MUV	Total rewards redeemed
	Feedback provided	Computed	MUV	Total feedback submitted
	Correct quiz answers	Computed	MUV	Percentage of correct answers to quizzes
	Best player mentions	Computed	MUV	Total mentions as "best player" in tournaments

A.2 Training session specifications

The following tables provide detailed specifications for MUV's training session system, including complete mission inventories and progression mechanics that implement the behavioural change principles discussed in Chapter 3.

A.2.1 One-time training sessions

Table A.2 details all one-time training missions designed for user onboarding and skill development across six functional categories.

Table A.2: Complete inventory of one-time training sessions in MUV, categorised by typology, mission, and behavioural purpose.

Typology	Mission	Purpose
First start	Register your first trip	Onboard users to the platform
Mobility options usage	Register a walking trip	Promote active mobility
	Register a cycling trip	Promote active mobility
	Register a public transport trip	Encourage sustainable transport
	Register an electric vehicle trip	Encourage sustainable transport
	Register a carpooling trip	Minimise private vehicle usage
	Register a multimodal trip	Highlight diverse mobility options
Time-based trips	Register a morning trip (06:00-12:00)	Explore time-based trip variations
	Register an afternoon trip (12:00-18:00)	Explore time-based trip variations
	Register an evening trip (18:00-00:00)	Explore time-based trip variations
	Register a night trip (00:00-06:00)	Explore time-based trip variations
	Register a trip over the weekend	Promote sustainable leisure mobility
Profile customisation	Complete your profile	Encourage personalisation and data quality
	Add your most frequent trip	Tailor user experience
	Set up your garage	Encourage personalisation and data quality
	Verify your email	Ensure account validity
	Update your avatar	Encourage personalisation
Outward interactions	Add a friend	Foster user interaction
	Invite a friend to join	Expand user base
	Send us feedback	Provide platform improvement suggestions
	Rate MUV on the app store	Enhance app visibility
Award earning	Get the first badge	Reward initial engagement
	Win a reward	Motivate user participation
Game dynamics discovery	Sign up for a challenge	Introduce competition dynamics
	Join a tournament	Introduce competition dynamics

A.2.2 Recurring training sessions

Table A.3 specifies the complete progression system for recurring training missions with Bronze, Silver, and Gold achievement levels across five performance areas.

Table A.3: Complete inventory of recurring training sessions in MUV with progressive achievement levels (Bronze, Silver, Gold) across five performance categories.

Typology	Mission	Bronze Level	Silver Level	Gold Level	Purpose
Trips registered	Total trips	10	100	1 000	Promote the consistent use of sustainable travel
	Trips on consecutive days	7	14	30	Foster daily engagement in mobility tracking
	Total frequent trips	10	50	200	Encourage frequent trip tracking
Points scored	Total points	10 000	100 000	1 000 000	Promote long-term participation
	Points per week	5 000	10 000	20 000	Foster weekly engagement
Distance traveled	Total km traveled	1 000	10 000	100 000	Highlight cumulative achievements in travel
	Daily steps	2 500	5 000	10 000	Promote active and healthy lifestyles
Impact generated	Kcal expended	10 000	100 000	1 000 000	Showcase the health benefits of mobility
	Kg of CO ₂ saved	0.1	10	1 000	Emphasise environmental impact reduction
Competition involvement	Played challenges	2	10	50	Encourage participation in competitions
	Played tournaments	1	2	4	Encourage participation in competitions
	Tournament best player nominations	2	10	50	Recognise top tournament performers

A.3 Tournament structure specifications

Table A.4 provides detailed specifications for MUV’s tournament phase architecture that enable flexible tournament design across diverse organisational contexts.

Table A.4: Complete inventory of MUV tournament phases, including duration, competition type, operational procedures, and team capacity parameters.

Phase	Duration (weeks)	Competition type	Operational mechanics	Teams involved
Ranking	1 to 3	Leaderboard	Teams are split into divisions; the highest-scoring teams in each division advance	8 to 1 024
Group	3 to 5	Weekly one-on-one matches	Teams compete within groups; the teams with the most wins in each round advance	4 to 192
Playoff	2 to 4	Weekly one-on-one knockout matches	Teams progress through a knockout board, with the final match deciding the champion	4 to 32

Tournament implementation follows modular design principles, allowing competitions to comprise one, two, or all three phases depending on organisational requirements and participant volumes. The ideal tournament progression advances from preliminary ranking through intermediate group competition to final playoff elimination. However, flexibility in phase selection enables adaptation to diverse contexts, such as combining group and playoff phases for medium-scale implementations or providing ranking-only competitions for large-scale awareness campaigns.

This modular architecture ensures tournaments remain inclusive and engaging for teams of varying sizes and skill levels while enabling organisers to tailor competitive intensity, duration, and complexity to specific institutional contexts and participant characteristics. The scalable design accommodates implementations ranging from small departmental competitions (4–16 teams) to large-scale inter-city tournaments (100+ teams), maintaining competitive balance and sustained team participation across diverse scenarios.

A.4 Scoring system specifications

The following tables provide detailed technical specifications for MUV's scoring algorithms, including mobility coefficients, multiplier systems, and calculation parameters that implement the behavioural incentive mechanisms discussed in Chapter 3.

A.4.1 Mobility coefficients

Table A.5 presents the complete coefficient system used in MUV's point calculation algorithm. These values reflect the environmental impact and effort associated with each transport mode, promoting fairness across diverse transport choices while incentivising the most sustainable options.

Table A.5: Mobility coefficients assigned to different transport modes in MUV's scoring system, reflecting their environmental impact and sustainability ranking.

Transport Mode	Mobility Coefficient	Rationale
Walking	1.0	Zero emissions, maximum health benefit
Cycling	0.5	Zero emissions, high health benefit
Electric bicycle	0.3	Minimal emissions, moderate health benefit
Electric scooter	0.3	Minimal emissions, moderate health benefit
Bus/Tram	0.2	Shared transport, reduced per-capita emissions
Metro	0.2	Shared transport, reduced per-capita emissions
Electric car	0.1	Zero direct emissions, but lower efficiency
Electric motorcycle	0.1	Zero direct emissions, but lower efficiency
Train	0.1	Shared transport, long-distance efficiency
Carpooling	0.05	Shared private vehicle, reduced individual impact

These coefficients were calibrated using mobility data from over 5 000 participants in the MUV2020 research project, ensuring empirical validation of the relative weightings across different transport modes.

A.4.2 Score multiplier system

Table A.6 details the complete multiplier system implemented in MUV's scoring algorithm. These multipliers are cumulative and calculated based on trip total points, providing dynamic incentives that respond to contextual factors and user behaviours.

Table A.6: Score multipliers in MUV, showing bonus descriptions, calculation parameters, and behavioural rationale.

Multiplier	Bonus Description	Allowed Values & Rationale
Weather	Rewards sustainable travel under challenging weather conditions	Good (0%), Poor (+5%), Bad (+10%), Grave (+15%), Extreme (+20%). Incentivises commitment despite barriers.
Peak hours	Encourages modal shift during traffic congestion periods	Yes (+10%), No (0%). Rewards travel during 07:00-09:00 and 17:00-19:00 when sustainable choices have maximum impact.
Frequency	Reinforces consistent app usage and habit formation	No (0%), 2 days (+5%), 3 days (+10%), 4 days (+15%), 5+ days (+20%). Progressive rewards for consecutive tracking days.
Routinary	Recognises and rewards regular sustainable commuting patterns	Yes (+10%), No (0%). Applied to user-defined frequent trips (e.g., home-work) detected automatically by the system.
Altitude	Acknowledges additional physical effort for active mobility modes	No elevation (0%), Moderate incline (+5%), High incline (+10%). Applied only to walking and cycling trips.

These multipliers implement behavioural psychology principles by providing variable ratio reinforcement schedules that maintain long-term engagement while rewarding behaviours that face systematic barriers or generate enhanced environmental benefits.

A.5 CO₂ emission calculation methodology specifications

This section provides extensive technical specifications for MUV's ISO 14064-2 certified methodology for calculating CO₂ emission reductions through sustainable mobility behavioural change interventions.

A.5.1 Mobility baseline profile definition

The baseline defined by MUV comprises two different mobility profiles, one general and one related to the most frequent trips. Each profile is characterised by two key components: the **distance travelled** and the **modal split**. Consequently, each user's mobility baseline can be represented by a quartet of values, comprising two values that delineate the generic profile and two that define the frequent trip profile.

For the generic profile:

$$D_g \tag{A.1}$$

$$m_g = \{m_{g,w}, m_{g,b}, m_{g,s}, m_{g,pt}, m_{g,t}, m_{g,c}, m_{g,m}\} \tag{A.2}$$

For the frequent trip profile:

$$D_f \tag{A.3}$$

$$m_f = \{m_{f,w}, m_{f,b}, m_{f,s}, m_{f,pt}, m_{f,t}, m_{f,c}, m_{f,m}\} \tag{A.4}$$

Distances (D) are expressed in kilometres, while modal split vectors (m) denote the percentage distribution of the different transport modes: walking, bicycle, electric scooter, public transport, train, car, and motorbike.

A.5.2 Carbon footprint calculation parameters

The weekly carbon footprint is determined by multiplying the distances travelled by each mode with their respective average emissions per passenger. Only modes that generate CO₂ emissions—public transport, train, car, and motorbike—are considered. If the user has entered specific vehicle details (e.g., size, fuel type, and year of registration) in the garage section of the application, custom emission factors are applied; otherwise, average values are used.

The emission coefficients per passenger-kilometre, presented in Table A.7, are based on average values published by the European Environment Agency (European Environment Agency 2020b) and the German Federal Environment Agency (German Federal Environment Agency 2019), which provide widely adopted benchmarks for evaluating the environmental impact of transport modes in Europe.

Table A.7: Average CO₂ equivalent emissions per passenger-kilometre for different transport modes in the European context.

Transport mode	Average CO ₂ eq emissions (g/km)	Variable
Car	140	e_c
Motorcycle	100	e_m
Public transport	80	e_{pt}
Train	40	e_t

These average figures, which depend on numerous variables, such as the average vehicle occupancy rate, the energy mix utilised, and the type of vehicle, refer to the European context.

The baseline carbon footprint for both profiles is calculated as follows:

$$CF_g = D_g \cdot (m_{g,pt} \cdot e_{pt} + m_{g,t} \cdot e_t + m_{g,c} \cdot e_c + m_{g,m} \cdot e_m) \quad (A.5)$$

$$CF_f = D_f \cdot (m_{f,pt} \cdot e_{pt} + m_{f,t} \cdot e_t + m_{f,c} \cdot e_c + m_{f,m} \cdot e_m) \quad (A.6)$$

For carpooling calculations, specific coefficients ($ecp2$, $ecp3$ and $ecp4$) account for vehicle occupancy variations. These parameters are derived from the estimated average consumption per vehicle, considering that the impact of cars removed from circulation changes based on the number of passengers, as detailed in Table A.8.

Table A.8: CO₂ equivalent emissions per passenger-kilometre for carpooling with different occupancy levels.

Transport mode	Average CO ₂ eq emissions (g/km)	Variable
Carpooling - 2 people	70	e_{cp2}
Carpooling - 3 people	47	e_{cp3}
Carpooling - 4 people	35	e_{cp4}

A.5.3 Algorithm structure and implementation

After defining the user's average emission profile, the algorithm calculates the weekly tracked distances TD_g and TD_f , which are derived by summing the distances of all valid trips. The tracked modal splits tm_g and tm_f represent the percentage of kilometres travelled by each mode. Unlike the baseline, these splits do not include private cars or motorbikes, as MUV only tracks sustainable trips. Instead, carpooling (cp) and electric car (ec) modes are added. The four new variables are defined as follows:

$$TD_g \quad (A.7)$$

$$tm_g = \{tm_{g,w}, tm_{g,b}, tm_{g,s}, tm_{g,pt}, tm_{g,t}, tm_{g,cp}, tm_{g,ec}\} \quad (A.8)$$

$$TD_f \quad (A.9)$$

$$tm_f = \{tm_{f,w}, tm_{f,b}, tm_{f,s}, tm_{f,pt}, tm_{f,t}, tm_{f,cp}, tm_{f,ec}\} \quad (A.10)$$

To compare emissions, it is necessary to determine how much of the two baseline distances were tracked by the user in the reference week. The algorithm introduces *untracked distance variables* (UD), which represent the fractions of distance not tracked through MUV for both generic and frequent profiles:

$$UD_g = \begin{cases} D_g - TD_g & \text{if } TD_g \leq D_g \\ 0 & \text{if } TD_g > D_g \end{cases} \quad (A.11)$$

$$UD_f = \begin{cases} D_f - TD_f & \text{if } TD_f \leq D_f \\ 0 & \text{if } TD_f > D_f \end{cases} \quad (A.12)$$

Such variables are consistently non-negative. If the tracked distance exceeds the baseline, the travel tracking is considered complete, and the untracked portion is set to zero.

The emissions for both tracked and untracked travel are calculated separately:

$$CF'_{g,tracked} = TD_g \cdot (tm_{g,pt} \cdot e_{pt} + tm_{g,t} \cdot e_t + tm_{g,cp2} \cdot e_{cp2} + tm_{g,cp3} \cdot e_{cp3} + tm_{g,cp4} \cdot e_{cp4}) \quad (A.13)$$

$$CF'_{g,untracked} = UD_g \cdot (tm_{g,pt} \cdot e_{pt} + tm_{g,t} \cdot e_t + tm_{g,c} \cdot e_c + tm_{g,m} \cdot e_m) \quad (A.14)$$

The total emissions are then computed by summing both components:

$$CF'_g = CF'_{g,tracked} + CF'_{g,untracked} \quad (A.15)$$

The same procedure applies to the frequent trip profile. The algorithm calculates CO_2 savings by comparing the baseline emissions with the newly calculated carbon footprint generated during MUV usage:

$$S_g = \begin{cases} CF_g - CF'_g & \text{if } CF'_g \leq CF_g \\ 0 & \text{if } CF'_g > CF_g \end{cases} \quad (A.16)$$

$$S_f = \begin{cases} CF_f - CF'_f & \text{if } CF'_f \leq CF_f \\ 0 & \text{if } CF'_f > CF_f \end{cases} \quad (A.17)$$

The cumulative weekly savings are:

$$S = S_g + S_f \quad (\text{A.18})$$

It is important to note that the value of S cannot be less than zero. If tracking sustainable travel leads to a larger carbon footprint, an error in the baseline calculation is probable, and the user is requested to update the data.

A.5.4 Practical application example

The following example demonstrates the practical application of the methodology in quantifying emission reduction.

Consider an Italian user who commutes to work five days per week, covering a distance of 10 km each way entirely by car, and travels an additional 50 km weekly, with a modal distribution of 50 % car, 30 % public transport, and 20 % walking. The baseline values are:

$$D_g = 50 \text{ km}$$

$$m_g = \{m_{g,w}, m_{g,b}, m_{g,s}, m_{g,pt}, m_{g,t}, m_{g,c}, m_{g,m}\} = \{0.2, 0, 0, 0.3, 0, 0.5, 0\}$$

$$D_f = 10 \text{ km} \times 5 \times 2 = 100 \text{ km}$$

$$m_f = \{m_{f,w}, m_{f,b}, m_{f,s}, m_{f,pt}, m_{f,t}, m_{f,c}, m_{f,m}\} = \{0, 0, 0, 0, 0, 1, 0\}$$

The baseline emissions are:

$$\begin{aligned} CF_g &= D_g \cdot (m_{g,pt} \cdot e_{pt} + m_{g,c} \cdot e_c) \\ &= 50 \text{ km} \cdot (0.3 \times 80 \text{ g CO}_2\text{eq/km} + 0.5 \times 140 \text{ g CO}_2\text{eq/km}) \\ &= 4.7 \text{ kg CO}_2\text{eq} \\ CF_f &= D_f \cdot m_{f,c} \cdot e_c \\ &= 100 \text{ km} \times 1 \times 140 \text{ g CO}_2\text{eq/km} \\ &= 14 \text{ kg CO}_2\text{eq} \end{aligned}$$

After using MUV, the user tracks 50 km of home-to-work carpooling trips (50 % with two occupants and 50 % with three occupants) and 30 km of general sustainable travel (equally distributed among walking, cycling, and bus). The untracked distances are¹:

$$\begin{aligned} UD_g &= \max\{0, D_g - TD_g\} = \max\{0, 50 \text{ km} - 30 \text{ km}\} = 20 \text{ km} \\ UD_f &= \max\{0, D_f - TD_f\} = \max\{0, 100 \text{ km} - 50 \text{ km}\} = 50 \text{ km} \end{aligned}$$

¹Since the tracked distance is less than the baseline distance in both cases, the untracked portion is positive and no capping to zero is necessary.

The emissions for untracked trips are calculated utilising the baseline modal split:

$$\begin{aligned} CF'_{g,untracked} &= 20 \text{ km} \cdot (0.5 \times 140 \text{ g CO}_2\text{eq/km} + 0.3 \times 80 \text{ g CO}_2\text{eq/km}) + 20 \text{ km} \times 0.2 \times 0 \\ &= 1.88 \text{ kg CO}_2\text{eq} \end{aligned}$$

$$\begin{aligned} CF'_{f,untracked} &= 50 \text{ km} \times 1 \times 140 \text{ g CO}_2\text{eq/km} \\ &= 7 \text{ kg CO}_2\text{eq} \end{aligned}$$

For the distance traced with MUV, the emissions are:

$$\begin{aligned} CF'_{g,tracked} &= 30 \text{ km} \times 0.33 \times 80 \text{ g CO}_2\text{eq/km} + 0.33 \times 0 + 0.33 \times 0 \\ &= 0.8 \text{ kg CO}_2\text{eq} \end{aligned}$$

$$\begin{aligned} CF'_{f,tracked} &= 50 \text{ km} \times (0.5 \times 70 \text{ g CO}_2\text{eq/km} + 0.5 \times 47 \text{ g CO}_2\text{eq/km}) \\ &= 2.92 \text{ kg CO}_2\text{eq} \end{aligned}$$

Consequently, the total emissions in the reference week are as follows:

$$CF'_g = CF'_{g,tracked} + CF'_{g,untracked} = 0.8 \text{ kg CO}_2\text{eq} + 1.88 \text{ kg CO}_2\text{eq} = 2.68 \text{ kg CO}_2\text{eq}$$

$$CF'_f = CF'_{f,tracked} + CF'_{f,untracked} = 2.92 \text{ kg CO}_2\text{eq} + 7 \text{ kg CO}_2\text{eq} = 9.92 \text{ kg CO}_2\text{eq}$$

The emissions saved are calculated as the difference between the baseline profile and the profile determined over the week of use:

$$S_g = \max\{0, CF_g - CF'_g\} = \max\{0, 4.7 \text{ kg CO}_2\text{eq} - 2.68 \text{ kg CO}_2\text{eq}\} = 2.02 \text{ kg CO}_2\text{eq}$$

$$S_f = \max\{0, CF_f - CF'_f\} = \max\{0, 14 \text{ kg CO}_2\text{eq} - 9.92 \text{ kg CO}_2\text{eq}\} = 4.08 \text{ kg CO}_2\text{eq}$$

Finally, the total value of CO₂ saved per week is:

$$S = S_g + S_f = 2.02 \text{ kg CO}_2\text{eq} + 4.08 \text{ kg CO}_2\text{eq} = 6.1 \text{ kg CO}_2\text{eq}$$

Extrapolating this behaviour over an entire year (52 weeks), assuming consistent implementation, would result in an annual reduction of 317.2 kg CO₂eq. Based on data from the European Parliamentary Research Service (European Parliamentary Research Service 2024), this represents approximately 5 % of average Italian per-capita emissions.

Appendix B

Mobile application system architecture

This appendix presents the complete technical and design specifications of the MUV mobile application, including implementation components and user interface architecture that support the behavioural engagement strategies outlined in Chapter 3. It covers both backend integration and user experience design elements essential for sustained motivation. The documentation is structured into two sections covering technical implementation stack and mobile user interface specifications, demonstrating how the application’s architecture operationalises user engagement and accessibility principles.

B.1 Technical implementation specifications

This subsection provides technical specifications for MUV’s mobile application architecture, including detailed information about third-party integrations, system configurations, and implementation parameters that support the behavioural change mechanisms described in Chapter 3.

B.1.1 Third-party libraries and components

Given React Native’s cross-platform nature, the application integrates multiple specialised libraries to bridge the gap between JavaScript code and native platform functionalities. Table B.1 details the complete technology stack and functional roles.

Table B.1: Third-party libraries and components supporting MUV's mobile application.

Category	Library/Component	Functional purpose
Native Platform Interaction	React Native	Core cross-platform framework
	React Native Device Info	Device specifications and capabilities
	React Native Permissions	Runtime permission management
Background Tracking	React Native Background Job	GPS coordinate collection in background
	React Native Geolocation Service	Precise location tracking and monitoring
	React Native Background Timer	Scheduled background tasks
Activity Recognition	React Native Sensors	Motion sensor data collection
	Google Activity Recognition	ML-based activity classification
	Apple CoreMotion	iOS native activity detection integration
Communication Protocols	React Native WebSocket	Real-time bidirectional data exchange
	Axios	HTTPS calls and secure transmission
	React Native Net Info	Network connectivity monitoring
State Management	Redux	State management and persistence
	React Native Async Storage	Local data storage and caching
	React Navigation	Screen navigation and routing
User Interface	React Native Vector Icons	Consistent iconography across platforms
	React Native Paper	Material Design components
	React Native Animatable	Smooth transitions and micro-interactions
Analytics and Monitoring	React Native Flipper	Debugging and performance monitoring
	Crashlytics	Error reporting and crash analysis
	React Native Performance Monitor	Real-time performance metrics

These libraries collectively enable MUV to focus development efforts on core behavioural change mechanics rather than reinventing standard mobile functionalities, significantly accelerating the implementation of gamification features and sustainability metrics while maintaining cross-platform consistency and native performance standards.

B.1.2 Push notification system configuration

The push notification system employs a comprehensive configuration framework that supports the diverse engagement mechanisms required for sustained behavioural change. Table B.2 details the complete notification taxonomy and delivery parameters.

Table B.2: Taxonomy of MUV's push notifications by type, trigger, timing, and behavioural intent.

Notification type	Trigger conditions	Delivery timing	Behavioural purpose
Real-time Tracking	User stationary ≥ 10 minutes during active tracking	Immediate	Tracking engagement
	Speed incompatible with selected mode	Immediate	Ensure tracking accuracy
	GPS signal lost during tracking	Immediate	Technical assistance
Competition Updates	Challenge/tournament start	Scheduled	Activate participation
	Weekly match results available	Post-calculation	Social reinforcement
	Team progress notification	Event-triggered	Achievement recognition
	Best player nomination	Post-analysis	Individual recognition
Achievement Recognition	Daily step goal reached	Live detection	Immediate reinforcement
	New badge earned	Post-calculation	Progress feedback
	Reward drawing selection	Event-triggered	Extrinsic motivation
	Milestone achievements	Threshold-based	Long-term engagement
Social Interaction	Friend request received	Immediate	Social network expansion
	Community invitation	Event-triggered	Group participation
	Friend achievement sharing	User-initiated	Peer influence
Administrative	Survey availability	Scheduled	Data collection
	Service maintenance alerts	Planned events	User communication
	App update notifications	Version-triggered	Technical maintenance

Delivery optimisation parameters

The notification system implements intelligent delivery optimisation to maximise engagement while preventing notification fatigue. Key parameters include:

- **Frequency caps:** Maximum 5 daily notifications; tracking alerts excluded.
- **Timing windows:** Optimised for 8-10 and 17-20 based on user activity patterns.
- **Priority weighting:** Competitions (high), achievements (med), administrative (low).
- **User preferences:** Granular opt-out controls for each notification category.
- **Adaptive learning:** Delivery timing adapts to user engagement patterns.

B.2 Mobile user interface specifications

This section provides full specifications for MUV's mobile application user interface components, including detailed interaction flows, visual design elements, and functional categorisations that support the behavioural engagement mechanisms described in Section 3.3.2.2.

B.2.1 Mobility mode visual system

The visual design system employs consistent colour coding and iconography across transport modes to reinforce mode categorisation and support rapid visual recognition in daily usage.

Visual design specifications

Table B.3 details all supported mobility modes, including categories, colours, and images.

Table B.3: Visual and categorical specifications for mobility modes in the MUV application interface.

Mode	Category	Colour	Icon	Live tracking image
Walking	Muscular	Green		
Cycling	Muscular	Green		
E-bike	Electric	Pink		
E-scooter	Electric	Pink		
Electric motorbike	Electric	Pink		
Electric car	Electric	Pink		
Bus	Public transport	Yellow		
Coach	Public transport	Yellow		
Metro	Public transport	Yellow		
Train	Public transport	Yellow		
Carpooling	Shared car	Blue		

Tracking activation and interaction design

The tracking experience activation process supports behavioural engagement by implementing intuitive mechanics and friction-reduction principles:

- **Activation process:** Users initiate tracking by tapping the prominent "Play" button in the centre of the navigation bar and selecting their chosen mobility mode.
- **Quick access options:** The interface allows inclusion of up to four preferred mobility modes as favourites, reducing friction and accelerating the activation process.
- **Adaptive button states:** The central button adapts to current tracking state, transforming from "Play" (start tracking) to "Switch" (change mode during tracking) to "Stop" (terminate trip).

This meticulously designed tracking interface combines functional utility with motivational elements, making sustainable travel both easy to record and intrinsically rewarding.

B.2.2 Feed card system architecture

The feed card system provides structured feedback and engagement mechanisms through nine distinct categories designed to support different aspects of user journey and behavioural reinforcement. Table B.4 presents comprehensive categorisation and functional specifications.

Table B.4: Functional overview of feed card categories in MUV application, showing purposes, content types, and interactivity levels.

Category	Purpose and content	Interactive
Onboarding	Guides new users through initial setup including avatar customisation, friend connections, frequent trip configuration, and alarm establishment	Yes
Trip tracking	Provides comprehensive feedback on trip validation status covering valid trips (points, distance, duration, multipliers), invalid trips (invalidation reasons, review requests), and pending analysis notifications	Mostly
Achievements	Recognises milestone accomplishments including step goals achievement and frequency of application usage consistency	Partially
Social connections	Manages social network expansion through friend request handling and new connection establishment	Yes
Challenges	Delivers updates across challenge lifecycle including availability notifications, participation confirmations, completion recognition, threshold achievements, and conclusion summaries	Yes
Communities	Handles community engagement processes including membership invitations and participation confirmations	Yes
Tournaments	Covers comprehensive tournament lifecycle communications including launch announcements, start notifications, match progress updates, team status reports, and conclusion ceremonies	Yes
Rewards	Notifies users about achievement recognition including badge acquisitions and reward earnings	Yes
System notifications	Delivers administrative communications including survey distributions, maintenance alerts, and general service announcements	Partially

Trip feedback specifications

The most prominent feed cards relate to completed trips, providing differentiated feedback based on validation outcomes:

- **Valid trips:** Summary screens display points earned, distance travelled, duration, and achieved multipliers. Users can view trip routes on integrated maps and provide feedback through brief surveys.
- **Invalid trips:** Explanatory screens detail invalidation reasons and offer review request options if users believe classification errors occurred.
- **Pending analysis:** Status indicators communicate ongoing validation processes.

B.2.3 Context menu functional specifications

The context menu provides organised access to secondary functions through eleven strategically categorised items that complement core tracking and gamification elements. It acts as an organisational layer that keeps the main interface clean while ensuring all features remain accessible within a logical structure in a straightforward manner (requiring only two interactions). Table B.5 presents complete functional specifications.

Table B.5: Complete context menu items in the MUV application, showing icons, functional categories, and user activities.

Item	Icon	User activities and functions
Profile		Check performance metrics, mobility habit analysis, achievement tracking, and environmental impact assessment
Friends		View friend list management and send friend requests for social network expansion
My community		Check community data (for existing members) or search for communities to join (for non-members)
Frequent trip		Update existing frequent trip configurations or add new frequent trip definitions
Garage		Update existing garage entries or add new vehicle and transport subscription information
Places		Check MUV-affiliated locations and their associated bonus point opportunities
Showcase		View comprehensive trophy collections and badge achievement galleries
Rewards		View available reward catalogues and redemption opportunities
Invite your friends		Invite friends to join MUV platform for social network expansion
Help		Read comprehensive MUV FAQ and access support documentation
Settings		Update personal and account data, manage privacy options, configure notification preferences, delete profile, and logout

Functional organisation categories

The context menu items are organised into four strategic categories based on functional relationships and estimated usage frequency:

- **Profile management:** User profile, friends list, and community screens facilitate identity expression and social connections.
- **Mobility configuration:** Frequent trip and garage sections enable mobility profile personalisation, improving tracking accuracy.
- **Engagement and rewards:** Places, showcase, and rewards sections provide access to tangible sustainable mobility benefits.
- **System and support:** Help, settings, and invitation tools provide practical features supporting continued engagement.

This organisation reflects user-centred design principles that balance feature accessibility with interface simplicity, ensuring advanced functions remain available without cluttering primary navigation experiences.

B.2.4 Accessibility and inclusion implementation details

This subsection provides comprehensive implementation specifications for MUV's accessibility and inclusion framework, detailing the technical approaches and specific parameters that operationalise the inclusive design principles described in Section 3.3.2.3.

B.2.4.1 Gender-inclusive design implementation

MUV's gender-inclusive framework encompasses interface design, language usage, and data collection practices. Table B.6 details specific implementation parameters across application components.

Table B.6: Detailed specifications for gender-inclusive design across MUV application components.

Component	Implementation approach	Specific parameters
User registration	Inclusive sex selection options	Four options: Male, Female, Intersex, Prefer not to say
Interface language	Gender-neutral communication	Avoidance of gendered pronouns, inclusive terminology throughout
Visual identity	Diverse representation	Balanced gender representation in illustrations, non-stereotypical colour schemes
Avatar system	customisable gender expression	Multiple avatar options independent of registered sex
Data analytics	Privacy-preserving analysis	Gender data used only for health calculations, optional for analytics

B.2.4.2 Accessibility for users with mobility impairments

The research initiative with Paul Valéry University, Montpellier represents MUV's initial systematic approach to inclusive mobility tracking for users with physical disabilities. The wheelchair tracking functionality development encompasses several technical challenges requiring specialised solutions:

- **Movement detection:** GPS velocity analysis adapted for manual wheelchair propulsion patterns.
- **Activity classification:** Machine learning algorithms trained on wheelchair-specific movement signatures.
- **Energy expenditure calculation:** Metabolic equivalent (MET) values adjusted for wheelchair locomotion.

- **Environmental impact assessment:** CO₂ calculation methodology recognising wheelchair travel as sustainable mobility mode.
- **Social integration:** Competition frameworks enabling inclusive participation across mobility capabilities.

These technical specifications collectively ensure that MUV's accessibility and inclusion framework extends beyond surface-level accommodations to provide genuinely inclusive experiences that respect user diversity while maintaining the behavioural effectiveness of the gamified mobility intervention.

Appendix C

Web dashboard technical specifications

This appendix provides comprehensive technical specifications for the MUV web dashboard interface, including system architecture and visualisation capabilities that support the analytical framework outlined in Chapter 3. It covers both client-server infrastructure and data presentation mechanisms essential for organisational decision-making. The documentation is structured into three sections covering dashboard architecture, user interface structure, and data visualisation specifications, demonstrating how the platform's analytics operationalise evidence-based mobility management.

C.1 Dashboard architecture and components

C.1.1 System architecture overview

The MUV web dashboard employs a client-server architecture optimised for organisational analytics and secure data access with the following technical specifications:

- **Frontend technologies:** HTML5, JavaScript, Chart.js for data visualisation.
- **Authentication:** OAuth2 protocol implementation
- **Database integration:** PostgreSQL with PostGIS for geospatial data.
- **API layer:** Django REST Framework endpoints
- **Caching:** Redis implementation for performance optimisation.
- **Security:** HTTPS encryption and role-based access control.

C.1.2 User Interface Structure

The dashboard's interface is organised into a hierarchical structure that facilitates intuitive navigation and efficient data analysis. This architecture enables both high-level overviews and detailed examination of specific metrics, supporting different analytical needs and user workflows. The dashboard structure consists of four primary sections:

- **Home:** The landing page provides quick access to high-priority items from other sections, including community, competition summaries, quick navigation to detailed analytics.
- **Community:** Presents comprehensive community-level data visualisation including user activity metrics and engagement patterns, mobility habits, and environmental impact metrics.
- **Challenges:** Displays detailed information about individual or collaborative competitions, including participation rates, leaderboards, achievements, and sustainability outcomes.
- **Tournaments:** Offers visualisations of tournament structures, team performances, match results, best players and collective impact metrics.

Figure C.1 illustrates the dashboard's home view, showing how different data elements are combined to create a cohesive analytical environment.

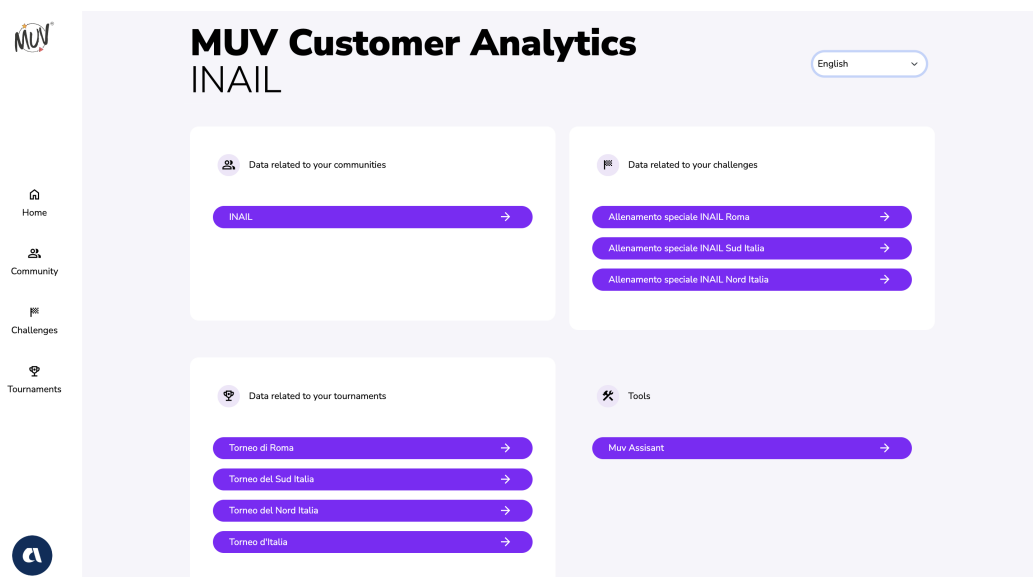


Figure C.1: MUV web dashboard home view, displaying the central landing page with clustered data elements from communities, challenges, and tournaments for efficient monitoring.

C.1.3 Data visualisation specifications

C.1.3.1 Community data

The Community section of the dashboard provides organisations with insights into their members' mobility behaviour and environmental impact. The data is organised into four functional subsections, each addressing specific analytical needs and supporting different aspects of programme management and evaluation.

User activity metrics

This subsection offers fundamental engagement statistics that help organisations assess programme reach and participation:

- **Total community membership:** The overall registered user count.
- **Active user count:** The number of members completing at least one valid trip.
- **Temporal engagement trends:** Graphical representation of weekly registrations and active users.
- **Demographic distribution:** Gender and age group breakdown when available.

These metrics enable stakeholders to track adoption rates, identify engagement patterns, and measure the programme's penetration within their target population.

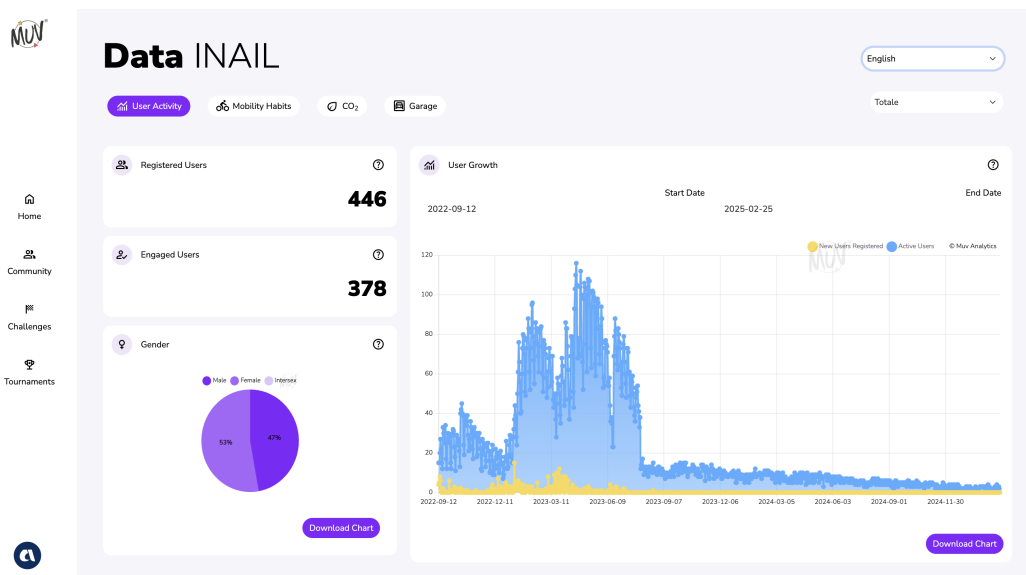


Figure C.2: MUV web dashboard user activity visualisation, showing community statistics, active user counts, temporal engagement trends, and demographic distribution.

Mobility habits analysis

This subsection focuses on the tangible transportation choices made by community members:

- **Sustainable distance covered:** Total kilometres travelled using sustainable mobility modes.
- **Physical activity outcomes:** Aggregate calories expended through active transportation.
- **Modal split visualisation:** Graphical representation of transport mode distribution.

These visualisations help organisations understand their community's transportation preferences and identify opportunities for targeted interventions to shift behaviour toward more sustainable options.

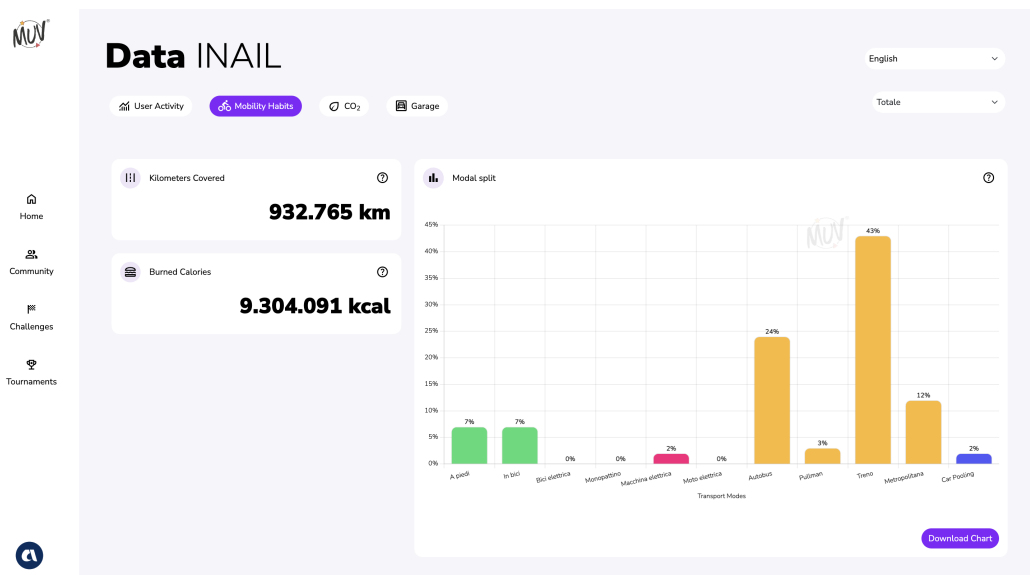


Figure C.3: MUV web dashboard mobility habits analysis, displaying sustainable distance covered, physical activity outcomes, and modal split visualisation for community members.

Environmental impact assessment

The CO₂ subsection quantifies the environmental benefits generated through sustainable mobility choices:

- **CO₂ savings:** Aggregate equivalent emissions reduction.
- **Weekly trend visualisation:** Graph showing the evolution of CO₂ savings over time.
- **Behavioural change rates:** Percentage of users achieving emission reductions.

These metrics translate individual behaviour changes into meaningful environmental impact data, reinforcing the connection between personal choices and collective outcomes.

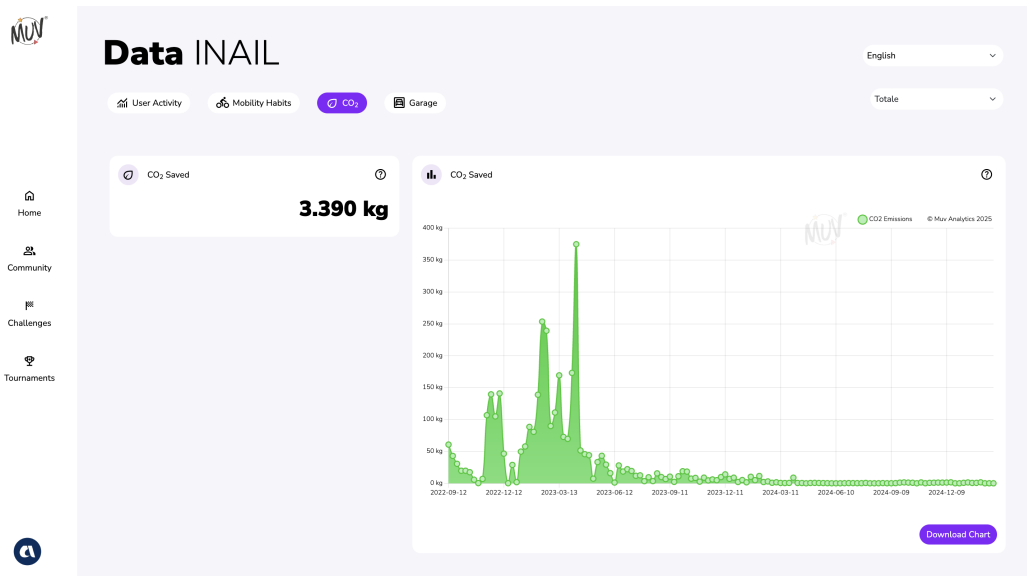


Figure C.4: MUV web dashboard impact assessment, showing total carbon savings and weekly trend visualisation of CO₂ emissions avoided through sustainable mobility choices.

Vehicle profile analysis

The Garage section provides insights into community members' private vehicle ownership:

- **Fuel type distribution:** Breakdown of registered vehicles by energy source.
- **Vehicle segment analysis:** Distribution by size and category.
- **Emission standards compliance:** Analysis by European emissions classification.

This information helps organisations understand their starting point for mobility interventions by providing context about the existing vehicle fleet and identifying opportunities for targeted sustainable mobility promotions.

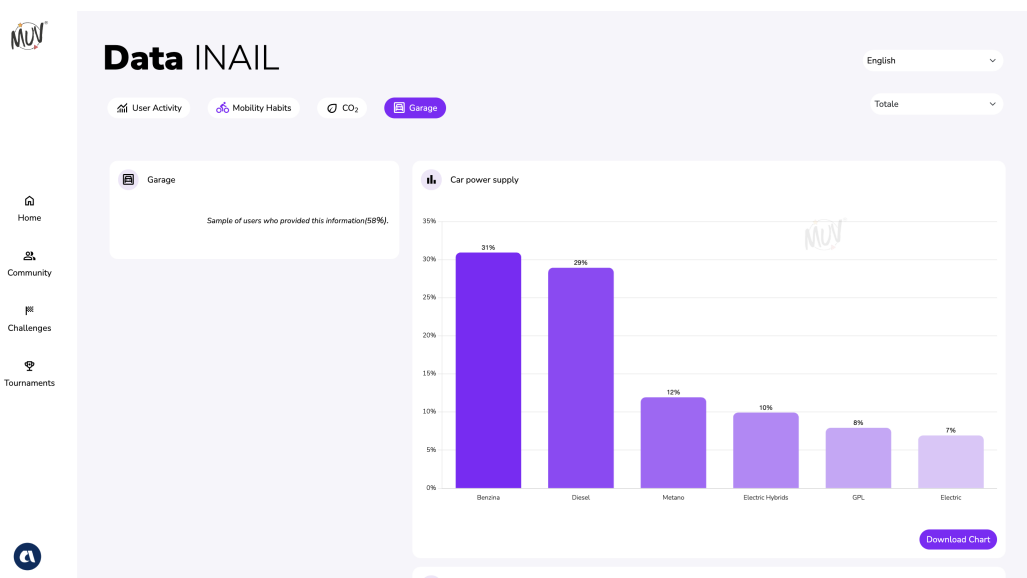


Figure C.5: MUV web dashboard vehicle profile analysis, displaying fuel type distribution, vehicle segment analysis, and emission standards compliance for community members' private vehicles.

C.1.3.2 Competition data

The dashboard provides detailed visualisations of both challenge and tournament data, enabling organisations to monitor competition dynamics and assess their effectiveness in promoting sustainable mobility. While the analytical subsections mirror those found in the community view, additional competition-specific information enhances understanding of engagement patterns and outcomes. Challenge visualisations are organised into four interconnected subsections:

- **Challenge details:** This introductory subsection presents fundamental competition information including start and end dates, active or finished status, permitted mobility modes, and participant rankings with accumulated points. For collaborative challenges, it also displays the three achievement thresholds and indicates which have been reached by the community.
- **User activity:** Similar to the community view, this section tracks participation rates and engagement patterns, but specifically within the challenge timeframe, allowing for assessment of how the competition influenced user participation.
- **Mobility habits:** This visualisation presents transportation choices made during the challenge period, enabling comparison with baseline community patterns to identify competition-induced behavioural shifts.
- **Environmental impact:** The CO₂ savings view quantifies the environmental benefits generated specifically through the challenge, providing a measurable outcome metric for the competition.

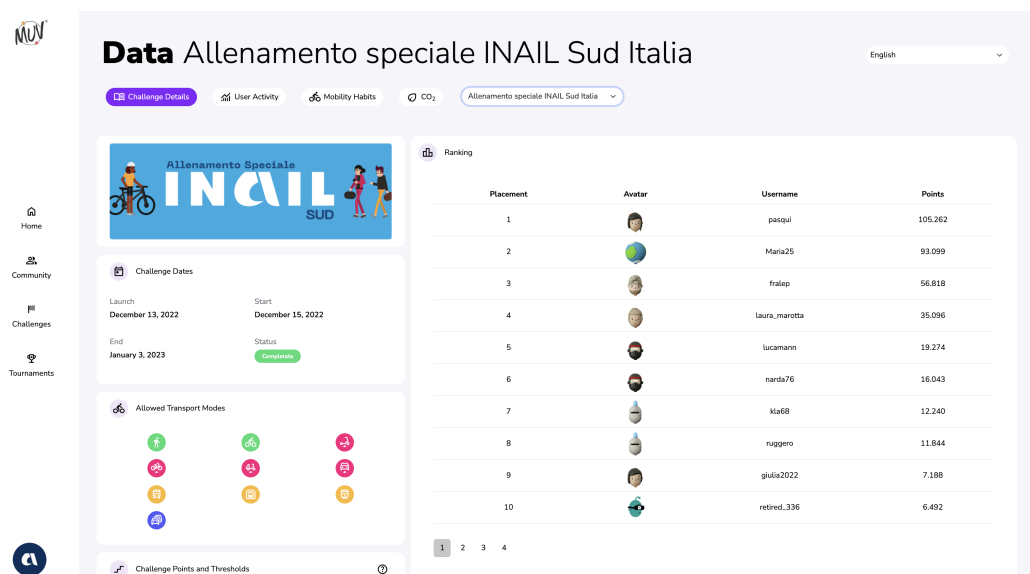


Figure C.6: The challenge details view in the web dashboard, showing competition information, participant rankings, achievement thresholds, and status indicators.

Tournament visualisations follow a similar structure but incorporate additional team-based metrics:

- **Tournament details:** Beyond the standard timeframe information, this section presents the schedule of weekly matches with results, identifies top performers from each team, and displays either a ranking table or playoff bracket depending on the tournament format.
- **Team performance:** This view provides comparative analysis of team achievements, supporting the social and competitive elements that drive engagement.

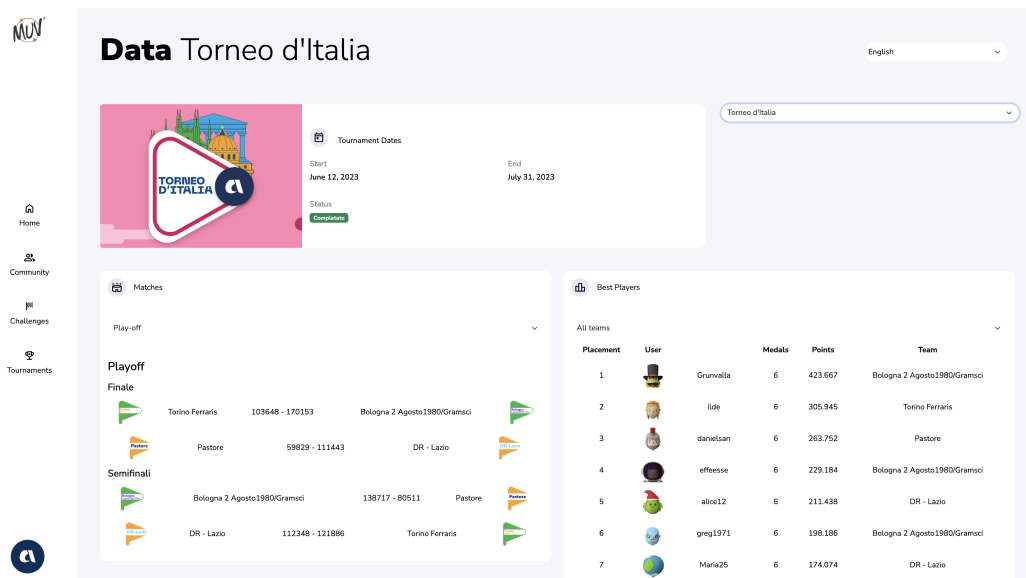


Figure C.7: The tournament details view in the web dashboard, displaying match schedules, team results, best players, and the competition bracket or ranking table.

The competition data visualisations complement the community analytics within the dashboard ecosystem. They support organisations in making evidence-based decisions about their sustainable mobility programmes and identify potential sustainability ambassadors from among high-performing participants. The combined insights enable more strategic design of future interventions and more accurate measurement of their environmental impact.

C.1.3.3 Internal analysis and monitoring

The dashboard serves critical internal control purposes beyond its external user-facing functions. It provides comprehensive analytics on system performance, user behaviour, and intervention effectiveness, metrics essential for data-driven management of the mobility platform.

The monitoring system tracks four primary categories of operational data:

- **Trip analytics:** The system calculates weekly statistics for each mobility mode, categorising trips as valid, invalid, revalidated, or total. These metrics help identify patterns in tracking accuracy and potential technical issues affecting user experience.
- **User feedback:** The feedback submissions are aggregated and categorised by reason, enabling systematic quality improvement and issue resolution in accordance with the continuous development approach described in Section 3.3.1.2.
- **Engagement metrics:** The platform monitors daily active users (DAU), weekly active users (WAU), and monthly active users (MAU), along with their respective ratios. These industry-standard engagement metrics quantify user retention and platform stickiness—critical indicators for assessing the effectiveness of behavioural interventions discussed in Section 3.1.
- **Comparative performance:** All metrics can be segmented across different communities and competitions, facilitating comparative analysis that identifies successful implementation patterns and areas requiring attention.

C.1.4 Future development roadmap

Future planned enhancements to the monitoring system include AI-powered analytics for predictive insights into mobility trends and engagement patterns. These developments will extend beyond monitoring into intervention, offering personalised AI-based recommendations to users for improving their sustainable travel habits, further implementing the principles of tailored feedback and reinforcement discussed in Section 3.1.2.2.

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