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THE IMPACT AND SAFETY ASSESSMENT OF SUSTAINABLE MOBILITY BY
USING INNOVATIVE TECHNOLOGIES AND TOOLS

Presentata da: Leonardo Cameli

Coordinatore Dottorato

Enrico Sassoni

Supervisore

Claudio Lantieri

Co-supervisore

Andrea Simone

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Abstract

This doctoral dissertation encompasses a comprehensive body of research conducted at the Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM) at the University of Bologna over a three-year doctoral program. The primary objective of this investigation is to demonstrate how the evolution of sustainable mobility has become increasingly integrated across various phases of project development, utilizing diverse methodological tools and technological innovations. Sustainable urban mobility has emerged as a critical factor in enhancing citizens' quality of life across both developed and developing nations. From an environmental perspective, a sustainable mobility system necessitates the reduction of fuel emissions and energy consumption, with an overarching aim of promoting low-carbon transportation solutions. Concurrently, a mobility system that achieves both social and economic sustainability must ensure universal accessibility while fostering enhanced employment opportunities through improved connectivity and mobility networks. Environmentally conscious transportation modes, including non-motorized alternatives (pedestrian and cycling infrastructures), electric vehicles (EVs), and hybrid propulsion systems, constitute fundamental components in achieving sustainability objectives. However, the successful implementation of these solutions requires a strategically planned approach at the municipal policy level, incorporating comprehensive urban planning frameworks and sustainable transportation initiatives. This research aims to develop and validate a comprehensive methodological framework for integrating sustainable mobility practices across various phases of urban planning and development. Through a systematic analysis of technological tools and implementation strategies, this study seeks to establish evidence-based protocols for effectively incorporating sustainable mobility solutions into urban infrastructure projects. The investigation employs both quantitative and qualitative methodologies to evaluate the efficacy of different sustainable mobility approaches from up to bottom scales. Starting from a detailed study of the European policies and from the new form of micromobility, the case studies offered by Bologna sites (Italy) has been analysed within the European plan CrAft. The analysis moved also to investigate the virtual and BIM approach integrated for sustainable mobility solution. In conclusion, two different methodologies for monitoring the active mobility infrastructures were carried out. The applied methodology is a valuable tool that may be used in the future in similar urban contexts. The dissertation also presents innovative methodologies for monitoring active mobility infrastructure, offering tools adaptable to similar urban contexts. This research ultimately strives to bridge the gap between theoretical sustainable mobility concepts and their practical implementation, providing urban planners and policymakers with robust, data-driven guidelines for sustainable transportation development.

Table of Contents

1. Introduction.....	1
1.1 Problem Statement.....	1
1.2 Research goals	2
2. Research Program	5
3. Activity 1: Different territorial policy and plans to support sustainable mobility	8
3.1 Introduction	8
3.1.1 European Sustainable Development Goals (SDGs)	10
3.1.2 The concept of SUMP in European Cities	13
3.2 Objective and Methods	17
3.2.1 SUMP Best Practices	17
3.2.2 New Trends of Micromobility.....	20
3.3 Outcomes	24
3.3.1 E-scooter case Study in Norway	25
4. Activity 2: Sustainable Mobility Planning for urban regeneration actions.....	29
4.1 Introduction	29
4.1.1 Bologna in CrAFt Project.....	30
4.1.2 City as a Commons approach in Bologna	32
4.2 Objective and Methods	35
4.2.1 Sustainable Urban Mobility Indicators (SUMI).....	35
4.2.2 The Healthy Street Project	39
4.2.3 The NEB Impact Model	41
4.3 Outcomes	48
4.3.1 Tactical Urbanism for sustainable mobility action: Bologna case studies.....	48
4.3.2 The application of the Impact Model: DumBO Project	52
5. Activity 3: Evaluation of active mobility project with VR and BIM approach	58
5.1 Introduction	58
5.1.1 BIM Modelling Approach.....	59
5.1.2 Virtual Reality Tools.....	62
5.2 Objective and Methods	66
5.2.1 BIM Modelling Framework	66
5.2.2 Virtual Reality for Public Space Auditing	70
5.3 Outcomes	79
5.3.1 BIM Application on Italian Cycle Route	79
5.3.2 Implementation of Immersive Virtual Environments in 'La Vallee' District....	84

6. Activity 4: Monitoring of the active mobility in cycle-pedestrian infrastructure.....	96
6.1 Introduction	96
6.1.1 Pedestrian Safety in urban environment.....	97
6.1.2 Cyclist Safety in urban environment.....	103
6.2 Objective and Methods.....	106
6.2.1 Analysis of innovative pedestrian crossing.....	106
6.2.2 Evaluation of Cycle Infrastructure	118
6.3 Outcomes.....	123
6.3.1 Analysis of the innovative lightning crossing.....	123
6.3.2 Cycle Infrastructure Monitoring: Florence Case Study	131
7. Conclusion	144
Bibliography	148
List of Annexes	160

Keywords

Sustainable Mobility

Urban regeneration

Key Performance Indicators (KPI)

Virtual Reality

Bicycle Sensors

1. Introduction

1.1 Problem Statement

Between 2012 and 2022, the number of fatalities in cyclist crashes fell slightly (2%) whereas these numbers dropped substantially more for other modes of transport (24% on average). In 2022, around 2,000 cyclists died in traffic with many more seriously injured. This percentage is considerably higher than for other weak road users, such as pedestrians with 9% involvement, moped with 3%, and motorcycles with 16% [1]. In 2023, Italy recorded 3,039 road traffic fatalities, representing a 3.8% decrease from the previous year, while injuries increased by 0.5% to 224,634 cases, and road accidents showed a marginal increase of 0.4%, totalling 166,525 incidents. The mortality data reveals significant variations across different transport modes, with elevated fatality rates among electric scooter operators and cyclists (including electric bicycle users), while pedestrian casualties remained constant, and other road user categories exhibited declining mortality trends. Specifically, fatalities among bicycle and electric bicycle users reached 212 cases, marking a 3.4% increase from the 205 deaths recorded in 2022. Electric scooter-related incidents, which have been systematically monitored since 2020, demonstrated a notable upward trend: accident involvement increased from 2,929 cases in 2022 to 3,365 in 2023, with injuries rising from 2,787 to 3,195 cases. Most significantly, the 30-day mortality rate for electric scooter users increased from 16 fatalities in 2022 to 21 in 2023 [2]. Overall, the number of fatal road accidents increased in 2022 compared to 2020, while remaining below the levels preceding the Covid-19 pandemic [3]. In this situation, the growing demand of cyclability must to be considered to render these data [4]. The finding that bicycle use is particularly increasing in urban areas is confirmed by recent French data [5]: in 2023, compared to 2022, on average 5% more bicycles passages were observed, based on counts at different locations in France. However, increases were only observed in urban areas (+6%). In suburban and rural areas the number of observed passages had remained more or less stable. In urban communities the popularity and the use of micromobility is rapidly increasing, especially for the “last-mile” transportation solutions. This mode of transport covers the gap between conventional transportation hubs (train station, bus stops, modal interchange parking spots, etc.) and the final destinations, especially in cases where infrastructures are very crowded [6]. Micromobility can offer flexibility and efficient door-to-door accessibility, while public transport is characterised by higher speeds and greater spatial reach. The resulting synergy of high speed (and thus spatial reach) of public transport with the door-to-door accessibility

provided by micromobility creates a degree of access, speed and comfort that can compete with that of private motorised vehicles [7]. Therefore, this combination makes modal shifts more attractive as well as potentially contributing to making cities more liveable, less congested and with reduced levels of air and noise pollution. In order to fully exploit the potential of micromobility towards a transition to more sustainable urban mobility systems, it is essential to analyse and study micromobility in the context of access to the first and last mile to and from public transport [8]. At the moment, transport infrastructure networks are currently developing both in terms of technology used and implementation. The growth in transport demand requires any nation to create resilient infrastructures to support this increase in travel. Methodologies are needed to monitor the design phase to minimise waste of resources and emissions, but also to encourage a modal shift towards soft mobility. Considering the sustainable development goals (SDGs) set by the European Union for safety and the environment, many conventional transport systems are changing, but significant challenges still remain towards a full transition to sustainable transport [9]. Policies and actions are being developed across the cities to encourage cycling for both physical and environmental well-being in the urban context [10], [11].

1.2 Research goals

This doctoral research addresses the complex challenges facing contemporary urban mobility systems, particularly in light of emerging safety concerns and the rapid evolution of micromobility solutions. Recent statistical evidence underscores the urgency of this investigation: while Italy reported a 3.8% overall decrease in road fatalities in 2023, there has been a significant increase in casualties among micromobility users, with electric scooter-related fatalities rising by 31.25% between 2022 and 2023. This concerning trend is further contextualized by broader European data indicating merely a 2% reduction in cyclist fatalities over the past decade (2012-2022), highlighting the persistent vulnerabilities in urban transportation systems. The primary aim of this research is to develop and validate an integrated methodological framework for implementing sustainable mobility solutions across various scales of urban planning. This comprehensive framework seeks to address the multifaceted challenges of modern urban transportation, from policy development to practical implementation. The research particularly focuses on the integration of micromobility solutions within existing transportation networks.

A fundamental component of this research involves the analysis of existing European sustainable mobility policies and their effectiveness in promoting safe, accessible transportation options. This analysis extends to examining how cities are adapting to the growing prevalence of micromobility solutions, with particular attention to the challenges and opportunities presented by the increasing adoption of electric scooters and bicycles in urban areas. The research investigates the critical relationship between infrastructure design and user safety, evaluating monitoring methodologies for active mobility infrastructures while evaluating the effectiveness of existing safety measures for vulnerable road users.

Central to this research is a detailed case study analysis of Bologna's mobility infrastructures within the European CrAft framework. This analysis serves as a practical testing ground for the development and validation of an Impact Model, developed within the Craft Consortium, for active mobility infrastructure. The case study approach allows for the practical application and refinement of the proposed methodological framework, providing valuable insights into the challenges and opportunities of implementing sustainable mobility solutions in a real urban context.

Following this concept, the visiting period carried out at the Hogeschool von Amsterdam (University of Applied Sciences of Amsterdam) from 1st September 2023 to 31st December 2023 was focused on developing this impact model. This period aimed to analyze mobility and infrastructures in a study area through the conception and exploitation of urban mobility indicators and innovative technologies. The work implied technical developments, to make a before-after comparison between the design scenarios. The indicators used by the Amsterdam municipalities has been analyzed through GIS software in order to adapt them to the NEB impact model studying the bibliography, several indicators were developed and calculated on Bologna case study. In addition, using the experience of the Dutch colleagues on the eye tracking, the Tobii Pro Lab Software was used to understand and develop a methodology to investigate the road users behavior.

In addition, in the last part, technological dimension of sustainable mobility is explored through the examination of Virtual Reality and Building Information Modeling (BIM) approaches in mobility planning. This investigation includes assessing how technological innovations can enhance infrastructure resilience and developing protocols for implementing smart mobility solutions that align with both safety requirements and sustainability goals. The research emphasizes the importance of integrated planning approaches that consider both physical infrastructure requirements and digital innovation opportunities.

In the end, the monitoring phase was examined using two different methodologies. The first involved the use of cameras to monitor pedestrian behavior during crossing, with various light configurations tested in an experiment conducted in Bologna. The second method entailed the dynamic monitoring of cycling infrastructures using sensors installed directly on the bicycle and worn by the test participant. Both experiments aimed to explore different techniques for monitoring urban cycling and pedestrian infrastructures.

This doctoral research would give a significant contribution to the field of sustainable urban mobility by addressing the critical gap between theoretical concepts and practical implementation, particularly in the context of emerging micromobility solutions. The findings will provide urban planners and policymakers with robust, data-driven tools for developing safer, more sustainable urban mobility networks that can adapt to changing transportation needs while maintaining high safety standards and promoting environmental sustainability.

2. Research Program

Figure 1 is a synoptic table representing the research framework based on a series of original research activities, divided by several steps, aimed to understand in-depth the development of a sustainable mobility projects to promote safety and accessibility in urban areas, in the different project phases..

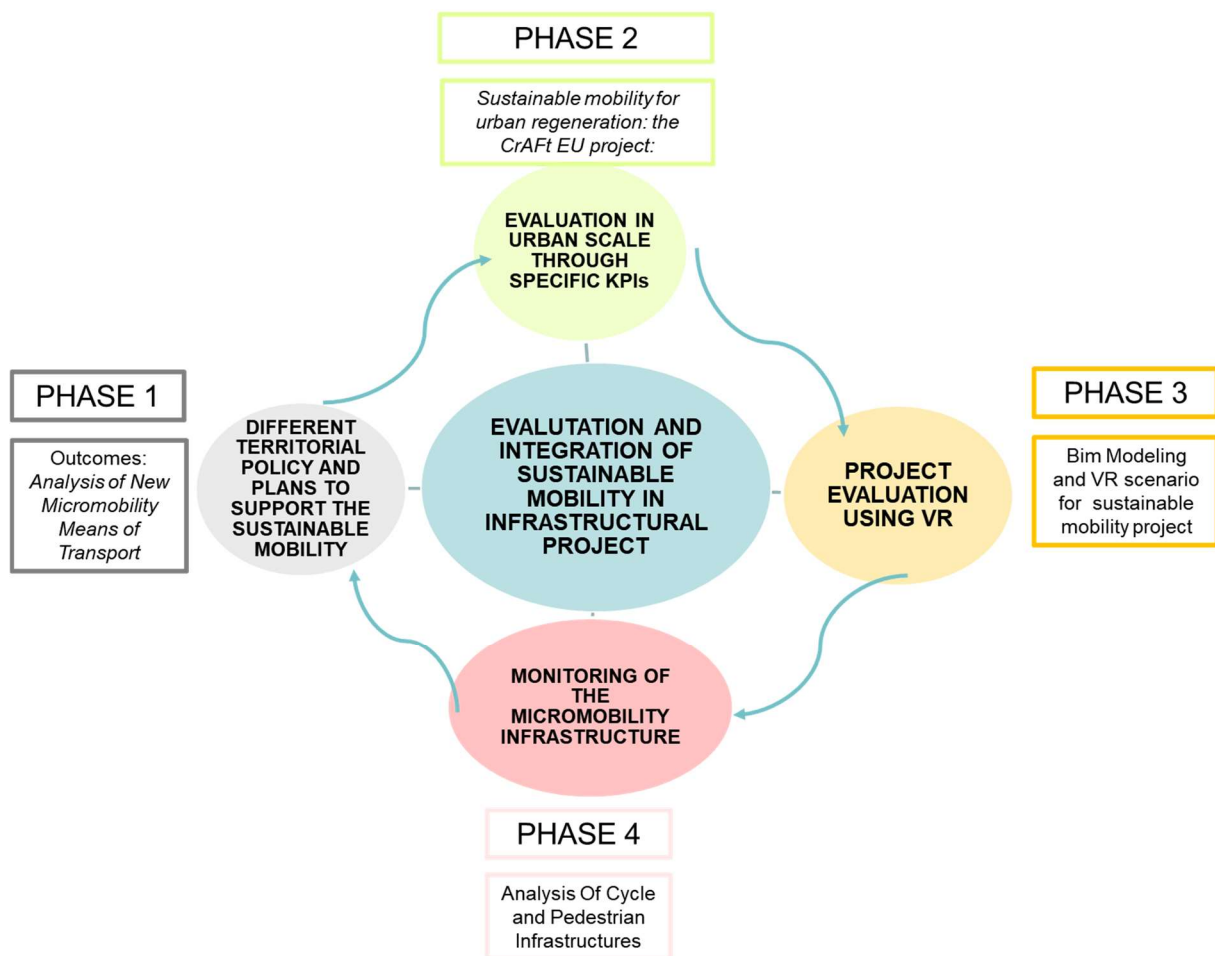


Figure 2-1 – Synoptic Table of PhD research

Per poter sviluppare un'analisi dei nuovi tool a disposizione, nelle diverse fasi progettuali, dagli step preliminari a quelli di monitoraggio, ogni diversa fase analizza lo stato dell'arte e l'utilizzo di nuova strumentazione da integrare in ciascuna fase.

The first activity, developed during my PhD research, concerned the analysis about how sustainable mobility is addressed at both the European and national levels in terms of planning. This led me to study various transportation plans where active mobility is integrated and promoted. After reviewing the state of the art in sustainable urban planning, the analysis was focused on new forms of micromobility that are developing around the world, for active

mobility but often face legislative and infrastructural challenges. To assess this gap, an investigation of e-scooter transportation was carried out, with a case study conducted in Trondheim.

Moving to the second phase of research, sustainable mobility actions were investigated for their use in urban regeneration actions. In this way, the focus of second phase moves to the European “Creating Actionable Future” (CrAft) Project. It aims to create a set of urban regeneration indicators that will be included in an “impact model” for assessing urban quality, supporting the design choices and the monitoring phase of the interventions. The research activities want to define a series of specific indicators that also helps to describe easily the state of the system and to assess sustainable mobility development. In detail, the Impact Model wants to offer a set of primary KPIs that are already largely known and used by most cities, composed in a way that helps cities to address the leverage points between different sectors. It does not replace the indicator sets cities already use, it complements them as a guidance instrument to improve shared understanding and support cross-cutting decision-making between stakeholders from different sectors and disciplines. In particular, thanks to the data provided by the municipality of Rimini and Bologna, it was possible to analyze different regeneration projects of these cities. The selected indicators follow the parameters provided at the national and European levels adapted to the context considered. Such indicators can be used in other similar contexts since they evaluate the environment under consideration not only to the current state but also after the future requalification of the area, monitoring the progress of the project and comparing the two different scenarios. The main objective of the research will be the promotion of active mobility and public transport through the creation of a set of indicators that can give the shape of the state of art, and proposals for the future. During this activity, I did a research period at the University of Applied Sciences in Amsterdam. Thanks to the Craft consortium and data available from the Amsterdam municipality dataset, I developed a set of indicators to assess the impact of sustainable mobility in urban regeneration projects.

Moving from a macroscopic point of view to the infrastructure design phase, in order to shape the sustainable mobility impact in the project phase, the third activity was focused to the implementation of a micro-mobility projects into two different new technologies: the Building Information modelling (BIM) and the Virtual Reality (VR) approach. In the first part, the aim was to understand if the so-called I-BIM (infrastructure building information modelling) methodology supports the designer of a sustainable mobility infrastructures in the different phases of construction and execution of the design considering all project aspects. In the other hand, using a VR headset a scenario to study pedestrian behavior in a new public space of Paris.

The research aims to understand whether virtual reality can help choose the optimal configuration from the perspective of both users and experts.

In the last activity, the monitoring of the existing soft infrastructure for active mobility was analyzed through different methodologies. The interaction among vehicular flow, pedestrian mobility and cycle mobility focuses attention on safety, especially in all critical points of the transport network, such as crossings and unsignalized intersections. In the first part of this phase, I analyzed video-data from an innovative crossing path that uses a special configuration of light and signals. There are seven different configuration and the aim is to understand which was the safest one. In the end, the final topic of this research was to define a methodology to assess the quality of cycle route based on the cyclist behavior and the state of the pavement, using an instrumented bicycle equipped with several kinematic and cognitive sensors. After configuring all the sensors, the bicycle was used for tests in Florence, on a loop route, to assess the safety of different cycling sections.

3. Activity 1: Different territorial policy and plans to support sustainable mobility

3.1 Introduction

Sustainable mobility has emerged as a critical area of focus for urban planners and policymakers attempting to address the new challenges posed by urban transportation in recent years. Congestion, air pollution, and social inequities have resulted from rapid urbanization, population growth, and increased motorization. Sustainable urban mobility aims to transform urban transportation systems into more efficient, accessible, and environmentally friendly networks that meet residents' needs while minimizing negative consequences.

In the last years the urban planning aims to reduce congestion, but it also promotes environmental sustainability, public health outcomes, and social inclusion. Cities can mitigate the negative effects of car-centric mobility patterns by prioritizing sustainable modes of transportation such as walking, cycling, and public transit. Accessibility, in the context of sustainable mobility and public transport, refers to the ease and convenience with which individuals can reach their desired destinations using transportation systems. It encompasses physical, economic, and social dimensions, aiming to ensure that transportation networks are inclusive, efficient, and environmentally friendly. From a physical perspective, accessibility involves the availability and proximity of transportation infrastructures, such as airports, train stations, bus stops, and cycling and walking paths. It also encompasses the connectivity and intermodal integration of different transport modes to provide seamless travel experiences.

Furthermore, accessibility includes considerations of infrastructure design, such as the presence of ramps, elevators, and other features that enable people with disabilities to navigate transportation systems. In terms of economic accessibility, the concept pertains to the affordability of transportation options. It considers factors such as ticket prices, fare structures, and the cost-effectiveness of different modes of transport [12].



Figure 3-1. Diffent goals target by sustainable urban mobility

Economic accessibility aims to ensure that transportation is affordable for all individuals, regardless of their socioeconomic status, reducing disparities in access to opportunities and services. Social accessibility focuses on the inclusivity and equity of transportation systems. It considers the needs of diverse user groups, including the elderly, individuals with disabilities, families with children, and those from marginalized communities [13]. Social accessibility entails providing services and facilities that cater to the specific requirements of different user groups, promoting equal access to transportation and enabling social participation. In conclusion, accessibility plays a vital role in promoting sustainable mobility and public transport for several reasons:

1. **Efficient Transportation:** Enhancing accessibility enables efficient movement of people and goods, reducing congestion and travel times. By providing convenient and reliable transportation options, accessibility encourages modal shift from private vehicles to public transport, cycling, and walking, leading to reduced traffic congestion and improved overall transportation efficiency.
2. **Environmental Sustainability:** Accessible and sustainable transportation options help reduce greenhouse gas emissions, air pollution, and the ecological footprint associated with transportation. By promoting the use of public transport, cycling, and walking, accessibility contributes to mitigating climate change and improving air quality, thus supporting broader sustainability goals.
3. **Social Inclusion:** Accessible transportation systems promote social inclusion by ensuring that everyone has equal opportunities to access education, employment, healthcare, and other essential services. They help overcome physical and

socioeconomic barriers, enabling individuals from diverse backgrounds to participate fully in society.

4. Health and Well-being: Accessible and sustainable modes of transport, such as cycling and walking, not only reduce pollution but also promote physical activity and improve public health. By providing infrastructures and services that facilitate active transportation, accessibility contributes to healthier lifestyles and reduces the risk of chronic diseases associated with sedentary lifestyles.

For facing this aspect, the European Union and Italy as well, are working in this direction considering different tools and plan to achieve these objectives.

3.1.1 European Sustainable Development Goals (SDGs)

The signatories of the United Nations Framework Convention on Climate Change (UNFCCC), on 11 December 1997 on COP3, approved the Kyoto Protocol which contains the commitments of industrialized countries to reduce the emissions of certain greenhouse gases, responsible for overheating of the terrestrial globe [9]. The European Union, which entered into the agreement on April 29, 1998, is the main international supporter and has committed itself to reducing greenhouse gas emissions by 8% within 2010. In the following period, through the "Europe 2020" program, the European Union has undertaken to reduce greenhouse gas emissions by 20% compared to 1990, to increase the amount of energy obtained from renewable sources by 20% and to increase energy efficiency by 20%). To achieve these objectives, the European Community has issued two fundamental laws:

- The EU Emission Trading System (ETS) which operates according to the principle of limitation and trading of emissions, set a ceiling on the total quantity of some greenhouse gases, including CO₂, N₂O and PFC, for certain industrial sectors considered particularly energy eaters.
- The obligation of EU countries to reach 20-20-20 agreements. In 2015, during the United Nations Sustainable Development Summit, a document entitled "Transform our world. The 2030 Agenda for Sustainable Development". The document determines the commitments on sustainable development that will have to be implemented, starting from 2016 and by 2030, identifying 17 global objectives (SDGs - Sustainable Development Goals) and 169 targets. The objectives are universal - they address both developing and advanced countries and are based on the integration between the three dimensions of sustainable development (environmental, social and economic), as a

prerequisite for eradicating poverty in all its forms. On 11 December of the same year through the COP21 in Paris 195 countries adopted the first universal agreement on the world climate which commits all contractors to prevent the global temperature from rising above 2 ° Celsius above the pre-industrial level, a threshold above which climate change is considered potentially irreversible. The contractors also undertake to reduce greenhouse gas emissions and, after 2050, to limit greenhouse gas emissions to achieve resilience.



Figure 3-2: Sustainable Development Goals (SDGs) - L'UE e le Nazioni Unite: obiettivi comuni per un futuro sostenibile - Commissione europea (europa.eu)

Sustainable mobility plays a crucial role in achieving several of these objectives, as it directly impacts environmental, economic, and social dimensions of development. Indeed, Goal 11 focuses on making cities and human settlements inclusive, safe, resilient, and sustainable. Sustainable mobility is fundamental to achieving this goal by promoting infrastructures that reduce environmental impacts and improve urban quality of life. Advancing public transportation, encouraging cycling, adopting electric vehicles, and reducing traffic emissions contribute to lowering air and noise pollution, thereby enhancing public health and overall well-being in cities.

The transportation sector is one of the largest contributors to global greenhouse gas emissions. Promoting low-carbon mobility is essential for addressing Goal 13, which seeks urgent action to combat climate change. Encouraging the use of electric vehicles, reducing dependence on fossil fuels, and adopting shared mobility solutions can significantly decrease CO₂ emissions,

mitigating adverse environmental effects. Goal 7 emphasizes ensuring access to affordable, reliable, sustainable, and modern energy for all. The transition towards electric vehicles and the development of efficient charging infrastructures powered by renewable sources are directly linked to this objective. Additionally, promoting energy-efficient transport modes, such as bicycles and renewable-powered public transport, helps reduce reliance on fossil fuel-based energy. Achieving sustainable mobility requires a commitment to technological innovation and the development of modern, resilient infrastructures. This includes electric transport networks, safe cycling lanes, electric vehicle charging stations, and intelligent public transport systems. These innovations not only reduce the social and environmental costs of transportation but also create opportunities for sustainable economic growth, aligning with Goal 9.

Improving air quality and reducing noise pollution through sustainable mobility practices is essential for public health. As outlined in SDG 3, reducing harmful vehicle emissions can help prevent respiratory and cardiovascular diseases. Moreover, promoting active transportation modes, such as cycling and walking, fosters healthier lifestyles, reducing obesity rates and chronic diseases. Sustainable mobility offers significant opportunities for economic growth and job creation, particularly in the clean energy and technology sectors.

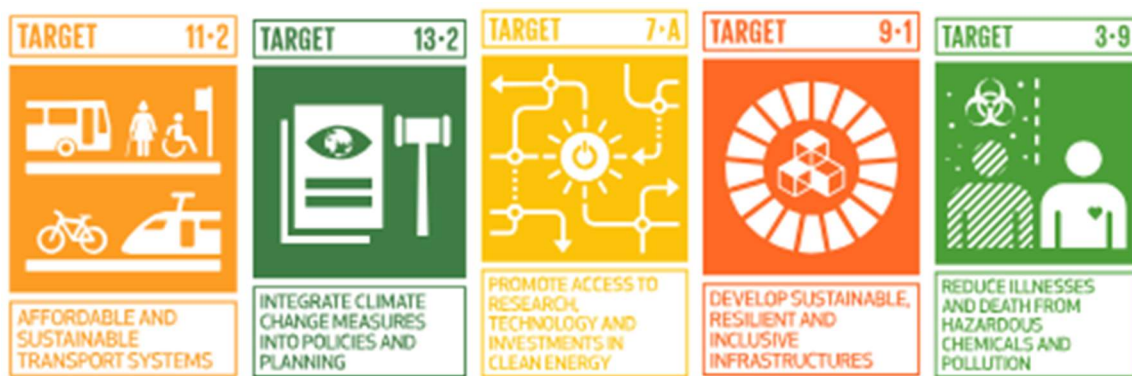


Figure 3-3: SDG and Sustainable Mobility actions Homepage | ICCROM | Our Collections Matter

Investment in sustainable mobility can also enhance freight transport efficiency, reducing costs and boosting competitiveness. SDG2030 agenda and sustainable mobility are deeply intertwined. The adoption of sustainable transport practices contributes to the achievement of various SDGs, positively influencing quality of life, social equity, and planetary health. A mobility system that minimizes environmental impacts, reduces inequalities. To perceive the aims related to sustainable mobility, the European commission release different document for creating apposite plan.

3.1.2 The concept of SUMP in European Cities

Many cities in Europe and around the world have developed Sustainable Urban Mobility Plans (SUMP), while numerous European Union funded projects and programs have contributed valuable knowledge that helped cities to develop this new generation of mobility plans. The concept SUMP is clearly a European success story to which many stakeholders have contributed and from which many cities (and citizens) have benefited. Its success is based on strong European policy coordination and support, practical guidelines that are based on systematic consultation with practitioners, and an active community of practice. SUMP is Europe's de facto urban transport planning concept. The policy that facilitated its establishment has been systematically developed by European policy makers since 2005. Its most important milestone was the publication of the Urban Mobility Package at the end of 2013 where the European Commission defined in an Annex the concept of Sustainable Urban Mobility Plans. At the same time, the first version of the Guidelines was released based on the following assumption:

“A Sustainable Urban Mobility Plan is a strategic plan designed to satisfy the mobility needs of people and businesses in cities and their surroundings for a better quality of life. It builds on existing planning practices and takes due consideration of integration, participation, and evaluation principles [14].”

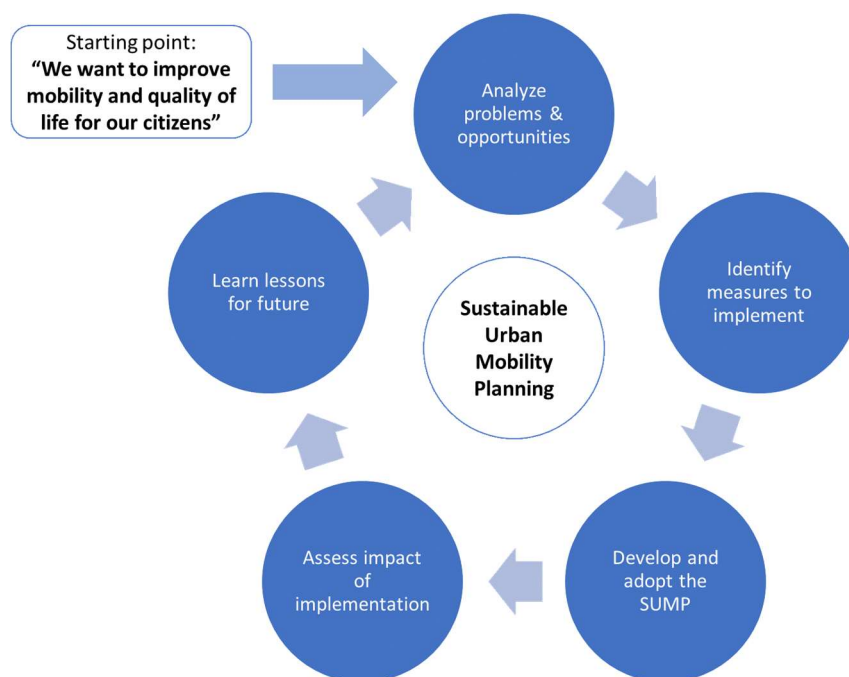


Figure 3-4: Sustainable Urban Mobility Planning

A Sustainable Urban Mobility Plan is based on the principles described in more detail below:

1. It's a plan for sustainable mobility in the "functional urban area". Depending on the local context, this might be a city and its surrounding area, an entire polycentric region. Planning on the basis of actual flows of people and goods is an important criterion to make a plan relevant and comprehensive, even if municipal boundaries may follow a different logic and make this difficult to achieve.
2. Cooperate across institutional boundaries: needs to be based on a high level of cooperation, coordination and consultation across different levels of government and between institutions (and their departments) in the planning area.
3. Involve citizens and stakeholders: it focuses on meeting the mobility needs of people in the functional urban area, both residents and visitors, as well as institutions and companies based there. It follows a transparent and participatory approach, actively involving citizens and other stakeholders.
4. Assess current and future performance: it provides a comprehensive review of the existing situation and establishes a baseline against which progress can be measured. To do this, the SUMP process identifies objectives and ambitious but realistic targets which are consistent with the established vision, and then defines performance indicators for each of these.
5. Define a long-term vision and a clear implementation plan.
6. Develop all transport modes in an integrated manner: The SUMP puts forward an integrated set of measures to improve quality, security, safety, accessibility, and cost effectiveness of the overall mobility system. A SUMP includes infrastructural, technical, regulatory, promotional and financial measures.
7. Arrange for monitoring and evaluation: progress towards the objectives of the plan and meeting the targets are assessed regularly based on the chosen performance indicators. Appropriate action is required to ensure timely access to the relevant data and statistics. Ongoing monitoring of the new projects or measures can suggest revisions of targets and, where necessary, corrective action in implementation.
8. Assure quality by external quality reviewers.



Figure 3-5: The 12 Steps of Sustainable Urban Mobility Planning - A decision maker's overview

Based on this assumptions, Italy followed them and the Italian Transportation Ministry releases a document to implement and realize the SUMP in the different cities with more than 100.000 inhabitants, called “Vademecum” [15]. It is intended to be an agile tool to support Italian municipalities and metropolitan cities in the drafting of the SUMP. The presentation of the operational guidelines for the drafting of the SUMP is based on the procedural steps provided by the Italian Guidelines, which outline a planning process that can be divided into 2 main blocks: preliminary activities and the actual drafting of the SUMP.

Preliminary activities are defined in the procedural steps dedicated to the definition of the interdisciplinary/inter-institutional working group and the designing the participatory process. These activities must be preceded by an accurate estimation, by the administration drafting the SUMP, of the financial resources available and potentially activated to carry out both the planning process of the SUMP and its implementation. In between the preliminary activities and the drafting of the SUMP lies the definition of the Plan area, which, although not framed as a procedural step in its own right, is a crucial activity of the early stages of planning that influences and affects several procedural steps.

The drafting of the PUMS is then divided into four well-defined procedural steps:

- 1) Preparation of the cognitive framework;

- 2) Definition of objectives;
- 3) Construction of the planned scenario;
- 4) Definition of the monitoring plan.

The Italian Guidelines provide for two further procedural steps:

- Strategic Environmental Assessment (SEA or VAS in Italy): it must accompany the entire planning process of the SUMP up to its approval, assessing on a case-by-case basis whether specific parts of the Plan are subject to the SEA procedure;
- Adoption and approval of the SUMP: the Italian Guidelines recommend publishing the SUMP adopted by the Municipal or Metropolitan Council for 30 days, so that citizens and stakeholders can submit any comments to be answered with appropriate counter-deductions in the text of the SUMP to be submitted for approval by the Municipal or Metropolitan Council.

For these two steps, specific procedures are foreseen by national and regional regulations as well as by the regulations of the administration drafting the SUMP, to which the Italian Guidelines also refer and for which this Vademecum does not therefore present detailed operational guidelines. In general, the composition of the working group should keep the number of participating actors at a manageable level. It is possible to envisage a ‘core’ working group that follows the entire planning process and different configurations of ‘extended’ working groups involving a larger number of actors in relation to specific issues. Moreover, the working group should not be considered a rigid structure but, once the initial core is defined, the working group can expand to meet the needs that emerge along the planning process. As is also stated in the Italian Guidelines, an effective working group is composed of individuals inside and outside the administration. To this end, the administration must first analyze its internal competencies.

3.2 Objective and Methods

3.2.1 SUMP Best Practices

More and more cities across Europe and beyond are implementing SUMPs. In literature a lot of European cities has described their experience with different activities to integrate and promote different sustainable modes of transport. For example, it was possible to see how Tampere, Finland used the construction of a new tram in the city to introduce new mobility management actions; how Monzón, Spain linked its SUMP development with a Sustainable Energy and Climate Action Plan; how Thessaloniki, Greece set up a mobility forum for action planning or how Malmö, Sweden developed its own accessibility index as part of its indicator set [14]. All cities can learn from one another, whether they have already implemented a SUMP or are just beginning to plan. The experience generously shared by these cities allow new SUMP cities to avoid potential pitfalls and to face the challenges of developing their own SUMP with increased knowledge and confidence. While courageous, innovative ideas don't always work out as planned, something can be learnt from every experience. These good practice examples has briefly showed in the next pages [16]. Different cities with several methodologies try to involve the SUMP concept in their urban mobility plan. London's sustainable transport strategy, guided by the Mayor's Transport Strategy, centers around the Healthy Streets Approach, a people-first methodology designed to make streets healthier, safer, and more inclusive [17]. This strategy integrates public health goals directly into transport planning. It is built on 10 evidence-based indicators aimed at making streets attractive, comfortable, and accessible for all. The overarching objectives of the strategy include achieving an 80% sustainable transport mode share by 2041, ensuring 20 minutes of active travel per person per day, and reaching zero deaths on London's transport network by the same year. In addition, public health staff were embedded in the transport authority to ensure that decisions were informed by data and research. Regular data analysis demonstrated the effectiveness of the strategy, securing continued support. In the end, community backing was vital to the plan's success. The approach was able to draw support from residents by addressing their concerns through tangible improvements to street safety and livability. Key challenges included securing cross-departmental collaboration and consistently measuring progress. Success was underpinned by political will, community engagement, and the consistent use of data to measure impact. Public health integration into urban planning proved essential for addressing health disparities and reducing inequality.

In the other hand, Gothenburg's plan is focused on road safety inspired by the Vision Zero philosophy, which aims to eliminate road deaths and serious injuries. The strategy treats the traffic network as a "complete system" designed to minimize human error. Since its adoption, Gothenburg has implemented over 2,500 traffic-calming measures, such as raised pedestrian crossings, road humps, and roundabouts, particularly in residential areas with speed limits of 30 km/h. Safety measures are integrated into road designs, ensuring that even if a driver makes a mistake, the road infrastructure reduces the likelihood of serious accidents. Roundabouts, for instance, were used to reduce vehicle speeds gradually ahead of potentially hazardous intersections. The Swedish Transport Research Institute found that these measures contributed to reducing serious injuries by 75% between 1990 and 2003. In the end, implementing Vision Zero required extensive community consultation and addressing the natural resistance to traffic calming measures. Residents demanded more such measures, especially in high-density residential areas, which supported the broader policy.

Moving to another example, Bologna's Sustainable Urban Mobility Plan (SUMP) [18] is notable for its integration of both territorial and thematic aspects of mobility planning. The plan covers the entire metropolitan area and aligns with land-use and logistics planning. A key feature was the creation of a joint office between the Metropolitan City and Bologna City Council to manage the SUMP and other related plans as a single entity. Close collaboration between the Metropolitan City and Bologna City Council was essential. The integrated approach ensured that transport and urban development plans were aligned, particularly with the development of the Metropolitan Territorial Plan (MTP). Bologna placed strong emphasis on engaging stakeholders, particularly through the establishment of a Freight Board, which brought private sector logistics companies into the planning process. This partnership ensured that urban logistics, a complex sector dominated by private businesses, was incorporated into the SUMP. The SUMP was developed alongside other urban planning strategies, including the General Urban Traffic Plan (PGTU), the Sustainable Urban Logistics Plan (SULP), and the Metropolitan Bike Plan. By integrating these plans, Bologna ensured a holistic approach to transport and logistics, addressing both people's movement and freight delivery needs. Bologna's main challenge was finding effective ways to influence private businesses in the logistics sector. However, by focusing on creating a shared vision and benchmarking against other European cities, the city was able to introduce policies that improved the sustainability of logistics operations. The cities of London, Gothenburg, and Bologna offer valuable lessons in sustainable transport planning. London's Healthy Streets Approach highlights the importance of embedding health and community well-being into urban mobility strategies, while

Gothenburg's Vision Zero demonstrates how safety-first traffic system design can significantly reduce road accidents. Bologna's integrated planning approach showcases the benefits of aligning land use, mobility, and logistics within a single framework, underscoring the need for stakeholder engagement at all levels. Together, these examples provide a rich framework for cities aiming to build more sustainable, inclusive, and safe urban transport systems.

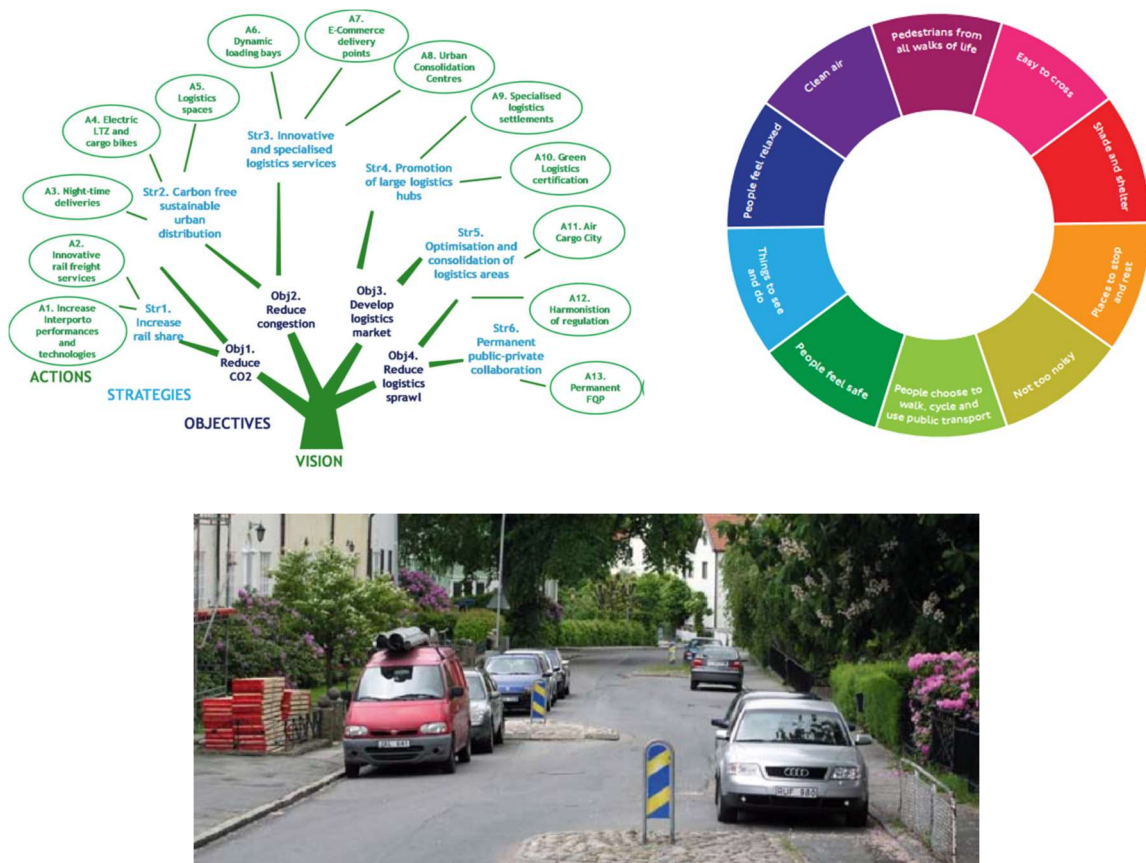


Figure 3-6: Key concept of Bologna, London and Gothenburg SUMPs

As is clearly defined, in best practices and in the definition of SUMP objectives, cycling has become a central element in mobility policies everywhere in recent years. Each trip made by bicycle not only consumes almost no resources (economic, energy) and has no impact on the environment, but also generates well-being for those who use it and, through reduced congestion, also for those who do not. Moreover, equipping and managing the city for cycling (and pedestrian) mobility represents an incomparably lower cost to public administration than those required by other modes of transport and generates benefits that go far beyond cycling (and pedestrian) use alone. The mobility-friendly city is a more beautiful, safe and welcoming city for everyone, including motorists. It is therefore clear that, in the face of increasingly

stringent environmental objectives and, conversely, equally stringent constraints of scarce public resources, cycling is - if not the only one - certainly one of the most important viable and effective responses. Bicycling is a healthy, efficient, economical, and environmentally friendly mode of transport [19]. Riding a bicycle produces virtually no local and global air pollutants. Even pedal assist e-bikes have much lower CO₂ emissions per kilometer when compared to automobiles with combustion or electric engines [20]. The very energy needed to propel a bicycle burns calories and generates valuable physical activity leading to significant health benefits for the rider [21]. During the last 30 years many cities and countries have promoted bicycling for daily trips to increase livability and the sustainability of transport systems. Bicycles are very space efficient, requiring only a fraction of the space needed to move and park automobiles. For individuals bicycling is much cheaper than owning and operating a car. For the public sector building bikeways and bicycle parking facilities only costs a fraction compared to the large expenses for building and maintaining roadway infrastructures and car parking structures. Not only the bicycles, but nowadays the micromobility is composed by different modes of transport and different services to use them [22].

3.2.2 New Trends of Micromobility

Nowadays the concept of micromobility is constantly evolving. For this reason, the definition of micromobility is rather broad, as it is designed to be tested in the future and cannot be limited to a certain type of vehicle or source of energy. It can be used to facilitate the regulation of new vehicles placed on the market and to create a category that includes all micro-vehicles regardless of the vehicle characteristics, such as number of wheels or driving position. The “E-scooter” is classified as a type of vehicle called powered standing scooter. This one must satisfy some conditions to enter in the micromobility category: weight below 500 kg, provision of a motor and availability as a shared service. The speed range of e-scooter, that makes its driving force, is strictly dependent on the battery of the model, but usually it is between 12-40 km/h [23]. This vehicle is smaller (occupying less space on the streets), lighter (making its transport easier) than a bicycle and requires less maintenance.

However, e-scooters have small batteries (i.e., less travel autonomy) and if they run out, there are no alternative ways to use them. The lack of pedals reduces flexibility and makes them a less healthy transport mode for users [24]. The two main types of shared systems exist and could be station-based or dockless sharing systems. While in a station-based system users can start or end their trips only at pre-defined locations, the dockless system allows users to start or end their trips (almost) anywhere in the city. Due to issues related to parking in public spaces,

many cities have started to define specific areas where it is possible to park dockless micro-vehicles [25].



Figure 3-7: E-scooter sharing system

Taking into account the Italian experience, the statistics observatory of sharing mobility recorded around 35 million journeys made in 2021 - 61% more than in 2020 and 25% more than in 2019. A decisive role in this data is played by the strong diffusion of e-scooter-sharing services, that alone in 2021 recorded half of the total rentals made in Italy (17.8 million), more than doubling the previous year's performance. On the demand side, bikesharing also managed to rebound compared to 2020, +56% for free-floating bikesharing with 4.6 million rentals and +22% with 3.4 million rentals for station-based bikesharing. The 'ecological quality' of the sharing fleet has also improved, both in terms of power supply and mass reduction. 94.5% of the sharing vehicles are already zero-emission because they are either fully electric vehicles (i.e. with no local emissions) or because they are motorless vehicles, like the large majority of bikesharing bikes. On the other hand, the analysis of the accident rate of micro-mobility sharing vehicles does not confirm a widespread public perception of the scooter as an inherently unsafe vehicle. The Sharing Mobility Observatory has collected and compared accident data on vehicle by users [26]. What emerges from this comparative analysis is that the scooter-sharing service registers a level of accidents, per km travelled, only slightly higher than e-scooter sharing, exactly 2.07 accidents per 100,000 km compared to 1.72 for scooter, both distant from bikesharing with a value of 0.74. Relating accidents to the number of trips, the ranking changes and scootersharing is the service with the highest accident rate per trip, 7.77 accidents per 100,000 rentals, followed by scooter sharing with 5.01 accidents, and finally bikesharing with 1.35 accidents per 100,000 trips. Concerning the analyzed dataset, the absolute number of accidents with injuries involving micro-mobility sharing vehicles (bicycles, mopeds and

scooters) in 2021 was 935, broken down as follows: 100 accidents for bikesharing, 634 for e-scooter sharing and 201 for scootersharing. With 2.07 accidents per 100,000 km, e-scooter sharing is the type of service with the highest level of accidents among those that are part of micro-mobility sharing. Focusing the attention to e-scooter development that has a growing demand but connected to safety problem, in the outcomes a research related to this issue will be carried out.

Different methods are developed to assess the growing of the new form of micromobility and especially the e-scooter. The main methodologies, to evaluate the flows and the characteristic of the interaction with other road users, consist of observational studies with cameras [27], [28], or human operation on the field [29]. Another way to analyze e-scooter and path choices, was through the use of GPS data given by the e-scooter companies [30]. In this way, it is possible to understand which part of mobility infrastructures around the city improves. In particular, thanks to the collaboration with the Trondheim University, in this PhD research, was defined a dedicated methodology to study the e-scooter in site. A traffic radar (Genesis VP Directional) was used to measure the speed of e-scooters. The radar instrument was installed in a hidden point, adjacent to the road section so as not to affect the user's behavior. For precise measurements the angle of inclination of the radar, regarding the direction of the users' motion, was as small as possible. If necessary, the measured speed based on the angle was corrected according to the manual instrument (Figure 3.8).

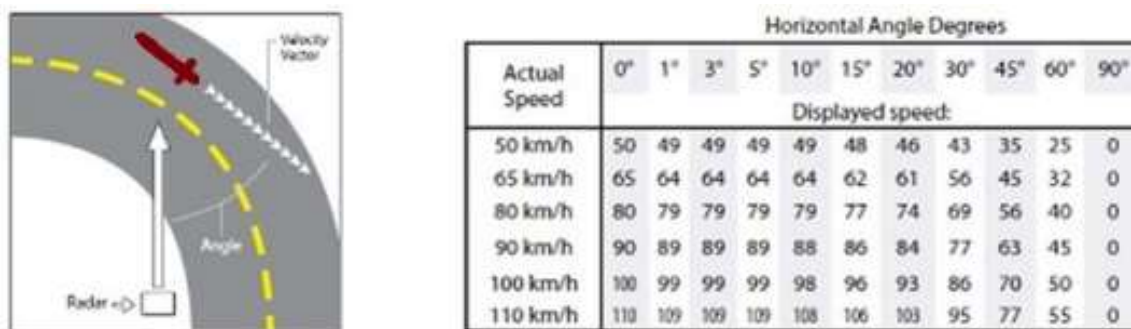


Figure 3-8: Relationship between antenna target angles and speed

During the e-scooter ride, a hidden observer collected other information to define the type of user and their behavior such as:

- Gender and age of driver;
- Type of e-scooter used (shared or private).
- The path used by e-scooter riders (cycle path, cycle lane, sidewalk, pedestrian zone, or roadway).

- Number of people on the e-scooter at the same moment.
- The distance observed between the e-scooter and the other road users when overtaking. Overtaking is defined as the process of overcoming a slower means of transport or a person travelling in the same direction. Distances were measured at the beginning of the overtaking. The observer fixed some reference points on the analyzed section, empirically defining the distances and measuring them. The differences were divided into four categories: no interaction with others, distance 1m, distance 50cm and distance 30cm (Figure 3.10).

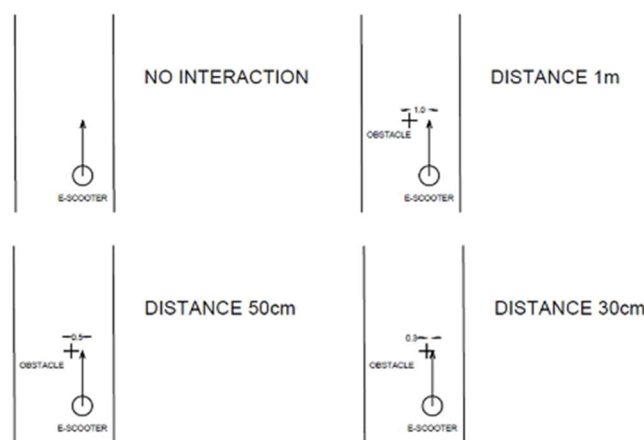


Figure 3-9: Different type of distances considered

- Driver behavior in the presence of other users. It was divided into three categories: straight, when the e-scooter's users go straight without any influence from obstacles although these are very close; "zig-zag", when the drivers don't decrease the speed to avoid or to overcome obstacles. The last category includes drivers who reduce speed in the presence of other users (Figure 3.10).



Figure 3-10: Different type of driver behaviour considered

In the next paragraph, taking into account this methodology, the results from a real case study in Norway will be outlined in order to understand the e-scooter's behaviour and try to propose safety improvements based on the experimental evidences. This analysis contributes to the

existing literature by highlighting the need for harmonized regulations while acknowledging local contextual factors that influence e-scooter implementation and usage patterns.

3.3 Outcomes

The regulatory framework governing electric scooters exhibits substantial heterogeneity across jurisdictions, significantly impacting safety outcomes. A comprehensive understanding of the relationship between dockless e-scooter systems and existing bike-sharing services is paramount for developing equitable transportation policies and appropriate infrastructure planning. Empirical evidence suggests distinct usage patterns: while bicycles predominantly serve commuting purposes, e-scooters are primarily utilized for recreational activities and tourism-related mobility [30]. Research conducted in Austin demonstrated that velocity patterns for both modes of transportation correlate with journey purposes. Lower average speeds were observed during leisure-oriented periods (weekends and off-peak hours) compared to commuting times (weekdays and peak hours) [31].

Although e-scooters can attain comparable speeds to bicycles, empirical measurements indicate that bicycles maintain a marginally higher average velocity (12 km/h versus 10 km/h for e-scooters). The interrelation between these mobility modes was further evidenced by a Chicago-based study, which documented a 10.2% reduction in bike-sharing utilization following e-scooter implementation in shared vehicle zones [32]. Safety considerations represent the most critical differentiating factor between these transportation modes. Salt Lake City investigations revealed a notable increase in accident rates following e-scooter introduction, with subsequent studies attributing this elevation in injuries to non-compliant and high-risk behaviors among both shared and private e-scooter users [33]. Considering the danger associated with the use of e-scooters, Europe is trying to find rules for e-scooters, but unfortunately there is no 'conformity' or union within the countries of the European Union. A report of the European situation [34] was realized by the Forum of European Road Safety Research Institutes (FERSI), a non-profit organization forming a flexible network of European road safety research organizations. A short questionnaire was created to make an inventory of the information available in different countries, in terms of legal status, use and safety.

According to the FERSI survey, several nations, including Norway, Italy, and Denmark, categorize e-scooters within the bicycle classification framework. Switzerland, Portugal, and Sweden employ a speed-based classification system. Conversely, Austria, Belgium, Germany, France, and Spain have implemented specialized legislation, frequently adapting existing

cycling regulations. Speed limitations typically range between 20 and 25 km/h, with specific local variations (such as Italy's 6 km/h restriction in pedestrian zones). This survey highlights how countries are working to find a legal status for this means of transport and are still working to develop more targeted or specific legislation. Municipal authorities face multifaceted challenges concerning safety protocols and urban space utilization. The development of evidence-based policies necessitates comprehensive field analyses examining velocity patterns, behavioral tendencies, and interactions with other road users. Understanding path selection factors is crucial for policymakers and mobility planners to facilitate the effective integration of e-scooters into urban transportation networks [35].

3.3.1 E-scooter case Study in Norway

Trondheim is the third largest city in Norway by number of inhabitants with a high percentage of students, the right place to experiment the use of shared e-scooters by a private company, the Ryde Technology AS. In Summer 2019, this company distributed about 200 e-scooters around the city [36]. The measurements analyzed in this study were taken within one month, from mid-September to mid-October 2019, between 8:00 a.m. and 6:00 p.m. with the peak time between 1:00-2:00 p.m. Six different road sections were defined in the city center of Trondheim. Different type of road were analyzed in order to define findings about the behavioral or kinematic changes in the user's approach. The different roads are showed in the figure 3-11.



Figure 3-11- Pictures of the measurement points

A total of 204 e-scooters were observed and the percentage of the different categories of e-scooter users was collected. In Trondheim most of e-scooter users are males, although female users were present (31,9%) too. As for the age, e-scooters are mostly used by young people (18-35 years). In addition, users who proceeded straight maintained a higher speed than the other categories (15.80 km/h), followed by the zigzag (14.58 km/h) and speed-reducing users (12.82 km/h) when meeting other road users. With reference to the chosen path, the highest speed was recorded on the road (17.21 km/h) followed by the cycle path (16.59 km/h). Users on the pedestrian zone or sidewalk were the slowest (13.49 km/h and 14.61 km/h respectively).

This empirical investigation examined the complex interplay between e-scooter user behavior, infrastructure utilization, and speed patterns across various urban environments. Through systematic observation and rigorous statistical analysis, several significant patterns emerged regarding user interactions and infrastructure preferences. The study's examination of speed patterns and user interactions revealed behavioral variations across different infrastructure types. On cycle paths, the research documented that users maintaining minimal distances (less than 50 centimeters) during overtaking maneuvers demonstrated the highest velocities, reaching approximately 16 km/h.

Conversely, within pedestrian zones, a different pattern emerged, where riders maintaining greater distances (approximately 1 meter) during overtaking exhibited higher speeds. This behavioral distinction potentially reflects the influence of peak-hour conditions, during which users typically operate at increased velocities due to time constraints and scheduling pressures. To establish robust statistical relationships between various factors and observed speeds, the research employed a Generalized Linear Model (GLM), complemented by Student's t-Test analyses for categorical variable correlations. This methodological approach revealed significant variations in speed patterns across different infrastructure types. Notably, Inherredsveien road consistently demonstrated the highest average speeds, a phenomenon partially attributable to its slight gradient characteristics. In contrast, Nordre Gata, designated as a pedestrian zone, recorded the lowest speeds, reflecting necessary velocity reductions to ensure pedestrian safety and maintain appropriate user interactions.

The analysis of crowding conditions revealed consistent relationships across user categories, with those maintaining larger overtaking distances (1 meter) achieving the highest speeds, followed by users operating without interactions. Users overtaking with minimal clearance (less than 50 centimeters) consistently demonstrated the lowest speeds. The behavioral analysis

highlighted a substantial 2 km/h differential between the fastest and slowest speed categories, underscoring the significant impact of user interactions on operational velocities.

A particularly aspect of the research emerged through the application of a binomial logit model to analyze infrastructure preferences, specifically focusing on sidewalk and cycle path usage patterns. This analysis, encompassing 131 measurements across three distinct street configurations, revealed compelling patterns in user behavior. In environments featuring complete separation between roadways and cycle paths, users demonstrated an unequivocal preference for cycle path utilization. However, in scenarios where cycle lanes were adjacent to roadways without physical separation, age-dependent behavioral patterns emerged. Younger users, aged 18-35 years, exhibited a higher propensity for sidewalk usage, while their older counterparts (above 35 years) demonstrated a stronger preference for cycle lane utilization. The statistical methodology revealed that infrastructure choice predominantly correlated with road geometry and environmental factors, with minimal variation across user categories beyond probability values. These findings offer valuable insights for urban planning and policy development, particularly highlighting the importance of physical separation in promoting safe and efficient e-scooter integration within existing transportation networks.

In conclusion, E-scooter users analyzed in Trondheim showed similarities within the European contest. In FERSI survey [34] the main users of different European countries were analyzed. Half of the countries (such as Norway and Germany) indicated that young adults were the main users of e-scooters. Same trend is recorded in Minneapolis [37]. A similar result was measured in Italy [38] where it was shown that the average speeds of cyclists varied between 14.6 and 22 km/h. It was also interesting to identify the characteristics of the road chosen and how it influenced the behavior of drivers. The analysis showed that e-scooter-users reduced speed in the presence of vulnerable users on the same way or in crowded conditions since they had to pay more attention to avoid interactions. Drivers on roadways were the fastest, followed by those who rode on the cycle path. Moreover, speed of e-scooters decreased during overtaking when the distance between them and other users decreased and when they found other road users on their way. This trend was confirmed by the behavior of cyclists, whose speed was influenced by the presence of other road users. In fact, when the path was shared with pedestrians, the cyclists' speed decreased accordingly [39].

On the contrary, as for the road infrastructures chosen, the characteristics of users and the crowding of the road with respect to the speed, the same conclusions were reached as the analysis of the collected data. At the end of the backward analysis carried out thanks to GLM

results, it was possible to conclude that the factors that mainly influenced the GLM model (and the speed accordingly) were Street and Behavior. Significant factors for the model were also Path and Crowding, fundamental to give relevance to the model when analyzing the variation of speed. In Norway, e-scooters are allowed to use all parts of the road, and they are supposed to use the sidewalk only when pedestrian traffic is low and are not dangerous for pedestrians. This research in Trondheim confirmed the European trend in the use of the cycle path. The same behavior was recorded in a study carried out in Virginia, that suggested e-scooter riders were willing to travel longer distances riding on cycle paths (59%), multi-use paths (28%) and the remaining percentage on other way [40]. The users' speeds showed that in the section with pedestrian zone and cycle path or in the local roads the average speed was higher than that of a two-lane road (two lanes in two directions) with pavements, one on each side.

4. Activity 2: Sustainable Mobility Planning for urban regeneration actions

4.1 Introduction

Once analyzed the sustainable mobility trends and the new form of micromobility, in this research phase, the scale of investigation moves to the mobility planning. Making this step back into urban planning and the implementation of active mobility in the cities, a lot of KPIs are available for the cities to monitor the state of art or new mobility configuration. In this research part, the impact of new urban regeneration projects connected to the active mobility and a tool to assess the impact of them were realized. Each city is unique and has to find itself at a different stage in the trajectory toward climate neutrality. The challenges differ in specific characteristics from one city to another, necessitating a standardized yet adaptable approach. In this way, The European Commission launches the New European Bauhaus (NEB), which wants to translate the European Green Deal on the ground, in buildings, in public spaces, and other application field[41].

Following this European wave, the CrAFt project aims to address these transition bottlenecks directly by providing a comprehensive set of activities to support cities in the development and implementation of collaborative local governance models, regardless of their starting point. The project seeks to co-create and test NEB-inspired collaborative local governance models in three Sandbox Cities to identify stakeholders' needs and match them with concrete opportunities. The Sandbox Cities (Bologna, Amsterdam and Prague) will document and optimize the real-life performance of the collaborative governance models at different stages of development, learning from and inspiring others while disseminating project knowledge.

Within CrAFt, three Sandbox Cities and 60 Reference Cities will contribute to refine and implement a NEB-inspired Impact Model. The Impact Model will help identify essential leverage points for systemic change toward climate neutrality by incorporating all aspectual layers of sustainability, including ecological, infrastructural, social, cultural, economic, aesthetical, and legal considerations. The Impact Model does not replace the indicator sets cities already use; instead, it complements them by providing a guidance instrument to improve shared understanding and support cross-cutting decision-making between stakeholders from different sectors and disciplines. For this purposes, Bologna was selected as a Sandbox city and will be used as a test field for observing and measuring the changes in action.

4.1.1 Bologna in CrAFt Project

The EU project “Creating Actionable Futures” (CrAFt) [42] is part of the New European Bauhaus (NEB) initiative of the European Union and will place the transition to climate neutrality at the heart of urban stakeholders. The cities join a growing European urban movement that brings together their citizens, policymakers, arts, and academia that would typically not work together to co-shape the transition to climate neutrality. CrAFt offers a community where changing business-as-usual becomes easier as many other cities are going on a similar journey.

CrAFt is a 3-year project launched in May 2022 with eight lead partners all across Europe (Norwegian University of Science and Technology (NTNU), University of Bologna, European League of Institutes of the Arts, Czech Technical University in Prague, Amsterdam University of applied sciences, European Cultural Foundation (ECF), International Union of Property Owners and Locality Europe). CrAFt supports the Mission Board on Climate-Neutral and Smart Cities and the NetZeroCities platform in designing and deploying Climate City Contracts, based on knowledge from CrAFt’s 3 Sandbox Cities (Bologna, Prague, and Amsterdam) and 60 CrAFt Cities. The project engages key stakeholders such as citizens and communities, property owners and tenants, cultural, artistic and creative sectors, universities and arts and design schools.



Figure 4-1 Sandbox cities and cooperating cities in CrAFt project

In the CrAFt project, Bologna has shared its experience especially in terms of urban regeneration and participatory process. Indeed, Bologna is a Sandbox city and it was been used as a test field. This city in the last years developed the “city as a commons approach” [43]. The City as a Commons model proposed by Foster and Iaione comes from the research of Elinor Ostrom [44], whose design principles need to be adapted to rethink the governance of cities according to the City as a Commons. The innovative perspective offered by the City as a Commons proposes a different insight into the city administration based on co-creating, co-designing, and co-governing practices.

This governance model is called “urban collaborative governance” and focuses on social and economic equity or inclusion. In Bologna, the City as a Commons approach is deeply interconnected with the concept of participation and collaborative governance. Additionally, it is based on co-creation and “living labs” tools. The City as a Commons approach is founded on the capacity of the city to adapt, transform, make, and remake according to the citizens’ needs and requirements. Participatory processes, such co-designing, and co-governing, are promoted by the cooperation between local administrations, municipalities, citizens, and other facilitators such as local associations, economic actors, and other stakeholders. They convey the concept that the city consists of urban commons everyone takes care of and enables regeneration practices. The “City as a Commons” concept is linked to cities' openness and capacity to make, remake, adapt, and transform themselves according to their inhabitants' needs and “to compete for the people and goods that help to grow and sustain them” [45].

The term participation is related to empowerment in order to support inclusiveness, diversity, and democracy. In the innovative social theory, the bottom-up processes are a significant tool for the activation of the communities. Furthermore, participatory processes are conceptualized as “self-organization”, civic-initiated action to influence the urban environment [46], [47]. In urban development, co-creating relies in part on the knowledge and experience of private sector processes, which are applied to public service delivery [48]. In addition, this term refers to the general knowledge about citizens and their experience with public services. Citizens can actively contribute through their knowledge and ideas in order to create new collaborations. In particular, the concept of co-creation is a “mosaic” of ideas and norms from varied research traditions and activities, as well as sectors such as urban planning, design, and innovation.

In this system, the state is a facilitator and a relational state, which redistributes its decision-making power and influence to the public. In this vision, municipalities have to engage their citizens and foster collaboration between them and public authorities to convey the idea that

the city is a common resource everyone should take care of. In this regard, Bologna can be considered an important example of implementing the City as a Commons approach and a “collaborative city” that used and still uses the language of the commons according to the principles mentioned above of “urban collaborative democracy”. In the following section few examples of how Bologna integrate this approach in its urban choices.

4.1.2 City as a Commons approach in Bologna

The "COVID-19" emergency has imposed and continues to impose, to live in the city and its spaces in a different way, in particular the space focused on social relations and mobility. In this situation, the dimension of "proximity" and the presence of public spaces spread throughout the city, represent an enormous value in the qualitative dimension of people's lives. Bologna in the future, from this point of view, can only confirm and strengthen the path taken through the planning tools it has equipped itself with in recent years, accelerating implementation times and implementing some actions also of an experimental nature. In responding to the needs and requirements that have emerged and been mapped in the various parts of the city in recent years, these will immediately affect the reconfiguration of spaces, thus giving answers to citizens.

Since the publication in 2014 of the Regulation on Collaboration Between Citizens and the City for the Care and Regeneration of Urban Commons[49], more than 800 collaboration pacts have been signed between the Municipality, local associations and citizens to promote the realization of regeneration actions in defined urban areas. The Municipality of Bologna, together with the Urban Innovation Foundation (IU Fondazione Rusconi Ghigi) and the University of Bologna (UNIBO) have participated in and fostered many collaborative initiatives through laboratories in the districts where the citizens, local associations, and stakeholders can join and start a shared path based on listening, dialogue, and prototyping. Bologna was the first city to implement the city as a Commons approach and the “co-city” protocol, articulated in the following phases: “cheap talking” (meant as dialogue interaction), mapping, practicing, prototyping, practicing, and modeling.

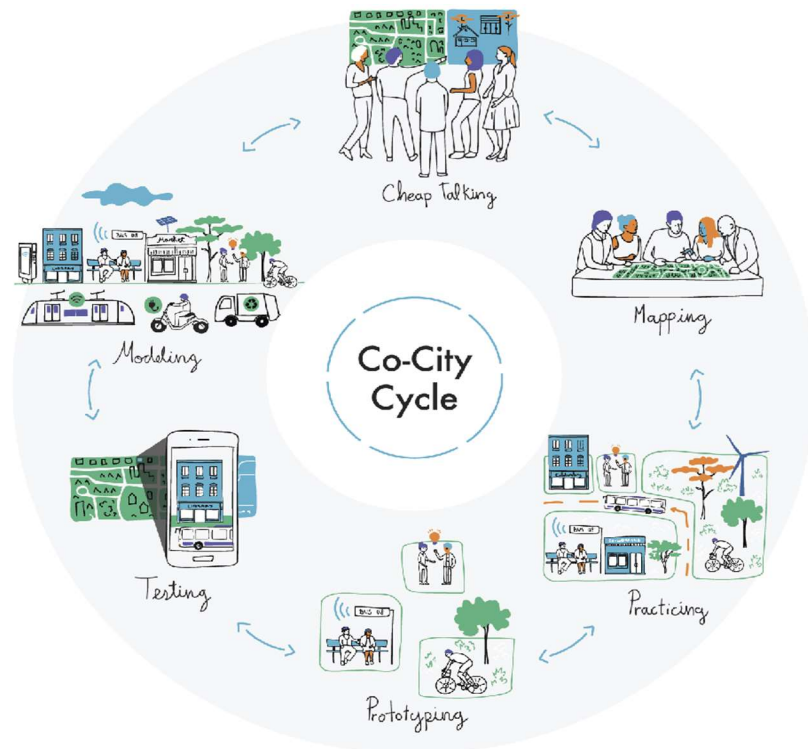


Figure 4-2 - The CO-CITY Protocol © LabGov, <http://labgov.city/wp-content/uploads/sites/19/Protocol-.pdf>

All these concepts and practices are the basis for a new form of civic engagement called “living labs”. These labs got popular, especially under the heading of smart cities and inclusive activities. In Living Labs, citizen and user involvement is central, and innovation takes place as a result of bringing together complementary knowledge, skills and resources in real-life experimentation. In this way, the Regulation on Collaboration Between Citizens and the City for the Care and Regeneration of Urban Commons was the first regulation for care and regenerating the urban commons identified as mostly public spaces, abandoned buildings, infrastructures, and urban green areas.

The Regulation identifies the collaboration pacts as the legal instrument for establishing public-community partnerships between citizens/local inhabitants, local officials/PA, local NGOs and local businesses. The first two years of implementation of Bologna Regulations positively affected the city in terms of the number of collaborative initiatives but, at the same time, highlighted the importance of creating a network of stakeholders and collective economic institutions that could provide significant financial support, acting at the neighborhood level and throughout the entire city.



Figure 4-3- District Labs (fondazioneinnovazioneurbana.it)

In this way, the municipality of Bologna, has activated tactical urban planning actions in different areas within the city. These are particular interventions for the transformation of poorly organized road areas, designed to obtain new spaces for socializing and mitigating the environmental impact of the city increasing the functional and architectural quality of urban space. Tactical Urbanism: it is a process of urban transformation that allows the use of space to be quickly changed with temporary and not expensive elements, analyzing their effectiveness and defining the final adaptive design following the users' reactions to the space. The aim is to understand how experimentations work and identify, directly from citizens' reactions, which aspects need to be changed according to the final intervention. The areas, chosen for this process, typically have traffic and environmental problems and the implementation of tactical urbanism usually regards the temporary pedestrianization of this type of area. The key to tactical urbanism is that the final design should better respond to the needs of the inhabitants and the environment because people have already had the opportunity to experience the space through temporary experimentation and opportunities to suggest improvements.

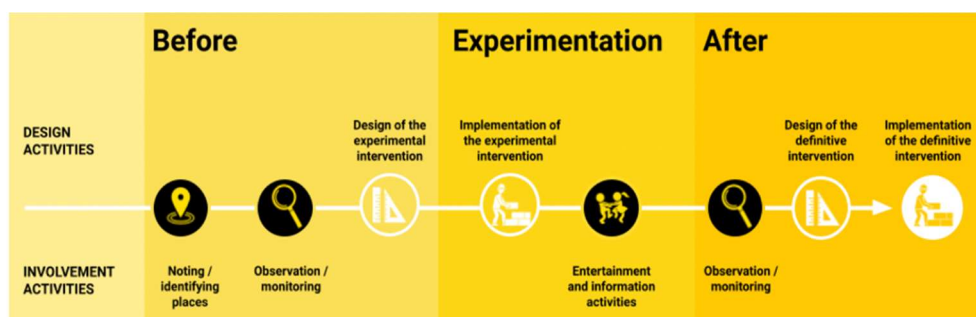


Figure 4-4: Workflow of the Tactical Urbanism processes. © FIU

4.2 Objective and Methods

Taking as a base-framework the Impact Model, the research has been focused on the sustainable mobility impact. Therefore for the first step of the research has been to retrieve and collect several indicators which might be used in the evaluation of environmental and mobility performance. The visiting period in the University of Amsterdam was useful to define the indicators to apply in a case study. These specific indicators would be useful to measure the impact of future interventions or monitor the actual situation in a certain area from different perspectives. To enrich the importance of findings, firstly it was important to collect and report the most valuable and inspiring tools and sources.

4.2.1 Sustainable Urban Mobility Indicators (SUMI)

The first one was the Sustainable Urban Mobility Indicators (SUMI) [50] and it's a useful tool for cities and urban areas to identify the strength and the weaknesses of the mobility system and to find potential solutions for the improvement of the area. The European Commission selected a consortium led by Rupprecht Consult – Forschung & Beratung GmbH (Germany) to support the testing of Sustainable Urban Mobility Indicators. The starting point for the SUMI project was the "SMP2.0 Sustainable Mobility Indicators" developed by the World Business Council for Sustainable Development (WBCSD) [51]. The framework of SUMI is critical in evaluating and assessing the performance of sustainable urban mobility. It provides a systematic approach to measuring, monitoring, and comparing urban mobility indicators, providing valuable insights into transportation system effectiveness and progress toward sustainable mobility goals.

SUMI is founded on internationally recognized sustainable development and urban planning principles. It is consistent with key frameworks and guidelines such as the UN Sustainable Development Goals and the European Commission's Urban Mobility Package. SUMI allows cities to evaluate their performance consistently, compare their results to other cities, and identify areas for improvement by using a standardized set of indicators. Researchers gain a better understanding of the underlying concepts, principles, and challenges in achieving sustainable transportation systems by delving into the theoretical foundations of sustainable urban mobility. SUMI offers a systematic approach for evaluating urban mobility performance and progress toward sustainability goals.

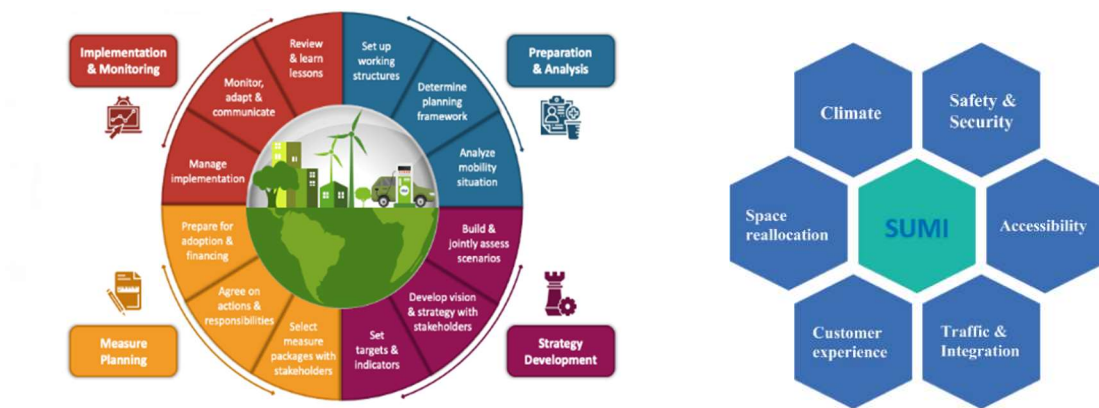


Figure 4-5- SUMI Framework

The SUMI framework considers many aspects of sustainable urban mobility, such as modes of transportation, infrastructure quality, accessibility, public transportation services, environmental impact, and social equity. SUMI enables a comprehensive evaluation of urban mobility by taking these dimensions into account, facilitating evidence-based decision-making and policy formulation. The SUMI framework is based on the idea that efficient, safe, dependable, environmentally friendly, and socially inclusive urban mobility is possible. It is consistent with the broader concepts of sustainable development and the need to address urban issues such as congestion, air pollution, traffic accidents, and unequal access to transportation services. Researchers gain a better understanding of the guiding principles and concepts that inform the assessment and measurement of urban mobility performance by investigating the theoretical underpinnings of sustainable urban mobility and SUMI. This knowledge serves as a solid foundation for conducting empirical research and implementing the SUMI framework in real-world settings. SUMI is an indicator set (19 KPIs), used to evaluate and monitor, and which target audience are small cities, medium-sized cities, large cities and metropolitan region (Table 4.1).

Table 4-1. SUMI Indicators

No.	Indicator	Definition
1	Affordability of public transport for the poorest group	Share of the poorest quartile of the population's household budget required to hold public transport (PT) passes (unlimited monthly travel or equivalent) in the urban area of residence
2	Accessibility of public transport for mobility-impaired groups	This indicator determines the accessibility of public transport services to persons with reduced mobility. Such vulnerability groups include those with visual and audial impairments and those with physical restrictions, such as pregnant women, users of wheelchairs and mobility devices, the elderly, parents, and caregivers using buggies, and people with temporary injuries.

3	Air pollutant emissions	Air pollutant emissions of all passenger and freight transport modes (exhaust and non-exhaust for PM2.5) in the urban context
4	Noise hindrance	Hindrance of population by noise generated through urban transport.
5	Road deaths	Road deaths by all transport accidents in the urban area on a yearly basis.
6	Access to mobility services	Share of population with appropriate access to mobility services (public transport).
7	Greenhouse gas emissions (GHG)	Well-to-wheels GHG emissions by all urban area passenger and freight transport modes.
8	Congestion and delays	Delays in road traffic and in public transport during peak hours compared to off peak travel (private road traffic) and optimal public transport travel time (public transport).
9	Energy efficiency	Total energy use by urban transport per passenger km and ton km (annual average over all modes).
10	Opportunity for active mobility	Infrastructures for active mobility, namely walking and cycling.
11	Multimodal integration	An interchange is any place where a traveler can switch from one mode of travel to another, with a minimum/ reasonable amount of walking or waiting. The more modes available at an interchange, the higher the level of multimodal integration
12	Satisfaction with public transport	The perceived satisfaction of using public transport.
13	Traffic safety active modes	Fatalities of active modes users in traffic accidents in the city in relation to their exposure to traffic.
14	Quality of public spaces	The perceived satisfaction of public spaces.
15	Urban functional diversity	Functional diversity refers to a mix of spatial functions in an area, creating proximity of mutual interrelated activities
16	Commuting travel time	Duration of commute to and from work or an educational establishment, using any types of modes.
17	Mobility space usage	Proportion of land use, taken by all city transport modes, including direct and indirect uses.
18	Security	The perceived risk of crime and passenger security in urban transport
19	Modal split	Modal split according to: • passenger kilometers • vehicle kilometers • number of trips • the number of vehicle kilometers per trip ran for freight: • goods vehicles kilometers • freight tons kilometers

The structure and components of the SUMI framework may vary depending on the assessment's specific context and purpose. Researchers and practitioners can customize the framework by selecting relevant modules and indicators. Furthermore, the SUMI framework frequently includes both objective and subjective indicators. Quantitative data and measurable factors, such as infrastructure quality or modal split percentages, are used to develop objective indicators. Subjective indicators, on the other hand, are self-reported responses that capture perceptions and attitudes, such as satisfaction with public transportation services or perceived accessibility.

Overall, the SUMI framework's structured nature and modular design enable a comprehensive assessment of sustainable urban mobility. SUMI provides valuable insights into the performance of urban mobility systems and facilitates evidence-based decision-making by capturing various dimensions and utilizing both objective and subjective indicators. The SUMI framework in research provides a systematic and standardized approach to evaluating urban mobility performance across cities or regions. Researchers can use the SUMI questionnaire to collect data, analyze the results, and draw meaningful comparisons and conclusions. SUMI allows practitioners to assess existing urban mobility systems, assisting them in understanding the strengths and weaknesses of their cities' transportation networks. This knowledge can be used to develop targeted interventions and policies to improve mobility options, improve infrastructures, and promote environmentally friendly modes of transportation. Furthermore, the SUMI framework makes benchmarking and performance tracking easier over time. Practitioners can track the progress of their cities' sustainable mobility initiatives, identify trends, and evaluate the effectiveness of implemented measures by conducting regular assessments using SUMI.

While the SUMI framework provides useful insights into sustainable urban mobility, it is important to recognize the challenges and limitations associated with its implementation. One of the most pressing issues is the availability and quality of data. The SUMI framework collects data via surveys and questionnaires, which can be time-consuming and resource intensive. Obtaining representative samples and ensuring high response rates can be difficult, especially in large and diverse cities. Furthermore, respondent biases or recall errors can have an impact on data accuracy and reliability. Addressing these issues necessitates careful planning, adequate resources, and stringent data collection protocols. Another difficulty is the requirement for contextual adaptation. The SUMI framework provides a general framework, but its application requires customization to fit the specific urban context under consideration. In terms of transportation infrastructures, cultural norms, and mobility patterns, urban areas differ. As a

result, researchers and practitioners must tailor the framework and indicators to the specific characteristics of each city or region.

Furthermore, the SUMI framework may be limited in its ability to capture the dynamic nature of urban mobility systems. Technological advancements, changes in travel behavior, and evolving policy frameworks all have an impact on sustainable urban mobility. As a static assessment tool, the SUMI framework may struggle to capture these dynamic changes effectively. To address this limitation, researchers and practitioners should consider supplementing SUMI assessments with additional data sources, such as real-time monitoring or qualitative studies, to gain a more comprehensive understanding of urban mobility dynamics. In conclusion, interpreting and communicating SUMI results can be difficult. The framework provides quantitative and qualitative data, which necessitates the use of appropriate analysis techniques as well as effective communication strategies in order to translate the findings into actionable insights. Interpreting the results meaningfully and effectively communicating them to various stakeholders can help to increase uptake of findings and influence policy and decision-making processes. Recognizing these challenges and limitations enables researchers and practitioners to navigate the complexities of applying the SUMI framework more effectively.

4.2.2 The Healthy Street Project

Another significant analyzed framework is the “Healthy Streets” project [52] developed by Lucy Saunders, a specialist in public health and transport. It refers on the approach of policies and strategies to deliver healthier and more inclusive cities where people can freely choose to walk, cycle and use public transport. It’s mainly devoted to vulnerable road users. This new vision and approach aims to improve the whole experience through a more pleasant, safe, attractive streets, where the most common traffic externalities like noise, air pollution, accessibility and lack of seating and shelter are not barriers that prevent VRUs from getting out. The Healthy Streets Approach is composed by 10 Indicators. To measure the “healthiness” of streets Transport for London (TfL) has developed an “Healthy Street Toolkit” [53], [54] which is useful to embed the Healthy Street Approach into the three main phases of a project: initial assessment, project implementation and project evaluation .



Figure 4-6– The 10 Healthy Street Indicators

Those toolkits are:

- Guide to the Healthy Streets Indicators[14]: A qualitative assessment tool summarizing the essential aspects of the 10 Healthy Streets Indicators by using questions as prompts. Best used at the early stages of any project development process, it is simple to understand for all stakeholders (including non-transport professionals). [13] There are two main indicators: Pedestrian from all walks of life and People choose to walk, cycle and use public transport. The other eight indicators focuses on the essential elements require to support these two main indicators. However the guide underlines that the experience of being on a street affects all the human sense, so this means that all the 10 indicators are interrelated.
- Healthy Streets Check for Designers (HSCD) [15]: It's a spreadsheet tool to be used by designer as support. This tool needs to be used once the drawbacks of the street have been find out, with respect to the current situation. So, it's suitable to make sure that any proposed change results in improvements by checking the scheme against the 10 Healthy Street Indicators (comparing it with the existing situation).
- Healthy Streets Survey [16]: This is the last of the Healthy Street Tools and was develop to monitor progresses toward the Healthy Street Approach. In coherence with the Healthy Street objective of put people at the center of the decision about how to design, manage and use public spaces; it aims to capture the real-life user experience and user perception of London's streets with respect to the 10 Healthy Streets Indicators and focusing on the current street at present time. The questionnaire is based on an on-street interview which should least 5-10 minutes and to the people would be asked 22 core questions.

As matter of fact, it can be said that Healthy Streets Approach is an integrated system of policies and strategies to put people, and their health, at the center of decision making, the aim is to change the design focus, jumping from a car-oriented city to a people-oriented city. This new approach starts from the statement that there aren't "heathy" and "unhealthy" streets, it's more focus on outcoming the strength and weaknesses of each case study stating that all streets can be improved in order to encourage people to improve the active mobility in a safe way. Moreover, this is a participatory approach in the sense that the "Guide to the Healthy Streets Indicators" state that to create a heathy street a wide range of people need to work together (TfL, London's boroughs, the police, property developers and landlords, as well as businesses and communities can all influence the experience of using streets) [14]. In conclusion, the developed tool is a spreadsheet to be used by designer as support. Taking inspiration of these projects, subsequently in this research, based on the methodology and the indicators found in literature, will contribute to define the sustainable mobility indicators.

4.2.3 The NEB Impact Model

These two projects were very inspiring to apply the impact model framework. Impact model (IM) is the main outcomes by the CrAft results and publications [55]. This framework would be an instrument to uncover the web of interlinked outcomes that a project, process or intervention generates in an urban context. It can also be used to steer complex interventions by understanding and listing the web of interlinkages on beforehand, so that one can leverage on desired co-benefits. At the same time, unwanted side-effects can be charted as well. Their negative impact can then be prevented or, at least, mitigated. In this way, the IM can give a representation of all the aspect that are involved in a regeneration project, from the social to the more technical aspects. In particular, CrAft's NEB IM is an assessment and guidance tool geared at a whole systems approach for use in complex urban interventions. The Impact Model can be optimally put to work at the district and urban scale levels of intervention. It is built in such a way that cities can use their existing indicator sets and monitoring processes as building blocks for the integrated planning, steering, monitoring, and evaluation goals of the Impact Model. This tool has the following characteristics:

- a tool to cooperate: to talk, discuss, negotiate, and discover – together;
- open, flexible and context sensitive: existing assessment and guidance tools can be plugged in;
- filling gaps: complementing cities' pre-existing indicator sets;

- The Impact Model will thus help identify essential leverage points for systemic change towards climate neutrality and resilience, by including all aspectual layers of sustainability (ecological, infrastructural, social, cultural, economic, aesthetical, legal, etc.) into innovative models for local collaborative governance and value creation. By functionally linking environmental aspects (materials, energy, water, health, pollution, biodiversity, ...) to the cultural, social, economic, legal and governance aspects in one perspective, the Impact Model allows to integrate cross-sectoral co-benefits from the early phases onwards, and thus to reduce the risk of suboptimal, unilateral or siloed approaches. The Impact Model considers 5 main intervention domains, called ‘pillars’, and 17 impact categories. The 5 pillars consist of the well-known triple bottom line for sustainable development (planet, people, prosperity); the 17 impact categories refer to essential aspects of integrated sustainable development (ecological, infrastructural, social, cultural, economic, aesthetical, legal, etc.). In order to achieve a balanced approach towards integrated sustainability, inclusivity and beauty, they recommend that all 17 categories are taken into consideration. Within the 17 impact categories, it has been identified a variety of relevant indicators, The Impact Model suggests a list of 46 indicators, intended as an indicative set of primary Key Performance Indicators (KPIs).

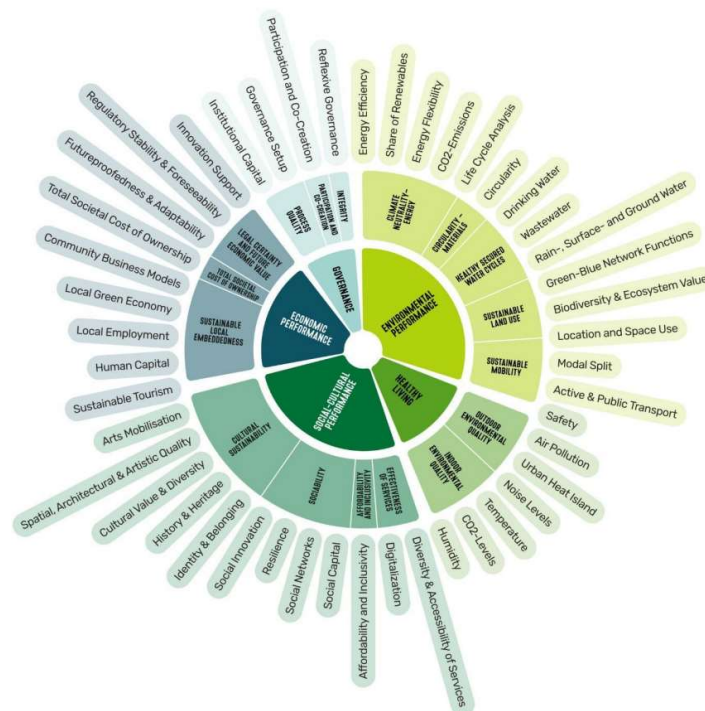


Figure 4-7 - CrAFt NEB Impact Model with 5 pillars, 17 categories and 46 suggested indicators

The list will guide the selection of indicators from existing sets and reporting tools already in use by the city or found in literature, the project or the process at stake. At the same time, the pillars, the impact categories and the suggested indicators help to detect possible gaps as well as to find more opportunities. The indicators may be evaluated by using proxies, until a more appropriate indicator will be founded or developed. For example, a proxy for the accessibility of a service may be the average distance to that service. The indicators may be assessed by a mix of quantitative and qualitative methods. For instance, social network quality in a district may be assessed both by counting the number of neighborhood associations and community events, and by asking residents and users for a qualitative judgement of the social networks in that specific neighborhood. The IM preferably should work from the early stages of a project, process or intervention. In this way, project actors and stakeholders can eventually identify conflicting of interests during the process.

The Impact Model is preferably set to work from the early programming phases of a project, process or intervention. In this way, project actors and stakeholders can chart a maximum of potential co-benefits and coupling opportunities; while conflicting interests can be identified early for developing a solution. Going into deepen to the IM, an overview of the main indicators was listed:

- **Climate neutrality – Energy:** Full climate neutrality is difficult to define, as it concerns all energy, material and water streams with their direct/indirect contributions to the GHG of a project or activity. Energy includes the amount of energy used in buildings, infrastructures and transport and its environmental quality. The first parameter is optimized by reducing energy use to a level that is environmentally optimal while, as much as possible within the current economic paradigm, being economically feasible or profitable. The second parameter is optimized by moving to 100% renewable and/or sustainable energy sources. Taking into account thermodynamics and urban metabolism principles, a third principle of cascade use can be introduced. Hereby waste energy from one application can be used as input energy for another application, thus reducing overall primary energy demand and introducing another optimization step. And last, flexibility is an optimization mechanism that makes use of energy buffering/storage, exchange of energy streams, demand side management and sector coupling (heat & cold versus electricity) to further optimize the energy use in a district, city or region. The present approach minimizes CO₂-emissions related to energy use in an indirect way, by optimizing the energy use with a cocktail of strategies (efficiency, renewable production, cascading, flexibility). A more complete emission assessment, mostly

applicable to city-wide interventions, considers all greenhouse gas emissions, among which the most important are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and the F-gases

- **Circularity – Materials:** Full circularity involves a complex interplay of direct and indirect aspects of materials (and energy plus water) use. In a narrower sense, circularity can be reached by assuring that all material loops under scope are fully closed. The goal is to minimize the negative environmental impact of materials use, and to arrive at a maximum of circularity within the urban metabolism. Assessment of material streams with regard to environmental impact is indeed best served through an LCA (life cycle analysis) and/or MFA (material flow accounting) analysis.
- **Healthy, secured water cycle:** Healthy, secured and sustainable water cycles include 2 main aspects: responsible use and management of drinking water, rainwater, and greywater, and accommodating for climate change adaptation, nature restoration and buffer capacity in order to mitigate the negative effects of both extreme rainfall and extreme drought. Drinking water consumption expressed as use per person per day is to be minimized without jeopardizing required servicing levels. Rainwater use is to be maximized; greywater can be recycled or upcycled, and any residual heat can be extracted for reuse into the built environment.
- **Sustainable land use:** Land use in this context refers to the characteristics of the project site. It includes location (the right function or mix of functions at the right place), space use and quality of local ecosystems. Location refers to the inherent sustainability of the project location. Space use regards the redevelopment rate, where (brownfield) redevelopment is preferred. Quality of local ecosystems regards the conservation, restoration, creation and compensation of local ecosystems, biodiversity and the underground.
- **Sustainable mobility:** Assessing its environmental quality is proposed by evaluating the proximity and accessibility of an urban center (in order to first reduce the mobility demand following a 'tries' approach), the servicing level by active and public transport, the adopted parking norms in urban environments, and the maturity of mobility as a service (Maas) and e-mobility infrastructure roll-out.
- **Outdoor environmental quality:** Physical safety including risks related to physical integrity, crime, or risks for children and elderly people. Social control helps to increase physical safety and should be a parameter of good urban design. For local air quality, a

proxy can be used by assessing local NO₂-concentrations and comparing these to established norms or standards. Noise levels may for example be addressed through the WHO's L-level standards. One important distinction is between noise levels during the day, versus the night. Traffic safety remains a form of physical safety, but given the importance of mobility in realizing sustainable and loveable environments a distinct address is recommended. Outside temperatures can soar in cities during warm weather, creating an urban heat island (UHI).

- **Indoor environmental quality:** The main suggested indicators are temperature and humidity levels, indoor CO₂-concentrations and noise levels. Outside air pollution, for instance from urban highways, may enter indoor spaces and cause similar detrimental conditions for the working and living conditions inside buildings.
- **Effectiveness of services:** This topic addresses the effectiveness of the core social services that are provided in a given urban context. It relates to the functional mix, diversity and accessibility of services and amenities for a particular location. As digitalization is becoming ever more important, accessibility and quality of digital services needs to be guaranteed.
- **Affordability and inclusivity:** The level of inclusion, affordability and social fairness of services and amenities are a primary social qualities. Affordability implies, for example, that a proper share of social and/or affordable housing is available. Inclusivity assures that all social or age groups, people with reduced mobility or vulnerable groups have good access to all needed services, and are properly being represented and involved.
- **Sociability:** Sociability refers to the ability of a place to support and foster healthy, lively social exchanges and social networks. Urban generation projects should therefore at least aim at minimally disrupting valuable existing social structures. The capacity of a place to adapt to future conditions in a socially sustainable way is crucial. Resilience is a primary aspect to include in this perspective; but also characteristics such as the intrinsic quality of housing, changing demographics, or the design of car-based facilities, may be subject to future-proofing. Social innovation supports future-proofing social functions and is an important enabler in the perspective of today's societal challenges. In this way, a strong local social capital can be built, both in terms of social well-being and of education. This is a bridge to indicators describing education and public health, which are often included in sets of (urban) indicators.

- **Cultural sustainability:** Cultural sustainability spans a vast domain of aspects like cultural value and diversity, identity, and spatial and aesthetic quality. Spatial quality deals with spatial, landscape and architectural quality, including aspects such as gradations of public and private character and articulation of the different programmatic elements with respect to each other. Identity indicates the degree to which the built environment is loaded with identity, culture and history – or at a higher level of abstraction, meaning. Cultural sustainability strongly relates to the role the arts can play in enhancing all of this – not only by creating beauty in the narrowest sense of the word, but also by promoting inclusiveness and diversity, mobilizing, empowering and emancipating individuals and communities.
- **Sustainable local embeddedness:** Local temporary and permanent employment relates to the number of qualitative jobs the project generates in both forms and how well these are anchored in the local labor market. Educational/capacity building projects can be linked to such efforts, thus increasing the local human capital. This can be complemented by support to the local green economy, or how the activity contributes to circular and climate-neutral functioning while reinforcing the local anchoring of such activities.
- **Legal certainty and future economic value:** This aspect deals with the future-proofedness of economic investments and enterprises, both from the viewpoint of regulatory stability and foreseeability, and from a perspective of future economic value.
- **Process quality:** Especially in a context of societal transitions, good governance processes make the difference. Good governance is needed both in the development phase of a solution, as well as in its operational phase. Process quality measures the quality of the integrated process and project management and the process quality in the development phase has a permanent effect on the performance of the realized project.
- **Participation and co-creation:** it examines the extent to which the various stakeholders participate in the decision-making process, in which form and how this leads to solid support for the project or the development.
- **Integrity:** it checks in how far the project or development realizes true sustainability, and in how far the share or stakeholders' agendas, investments and actions support this.

In the implementation of the impact model, the primary objective is to establish an expeditious methodology for evaluating and assigning scores to each indicator using a five-point Likert scale (1-5), preceded by a binary "on/off" designation (0/1) that enables the activation or deactivation of indicators applicable to specific cases. The resultant outcomes will subsequently

be applied to a case study, presented in the following section, evaluating both the current state of the complex and the intervention scenario through the developed assessment tool. This approach facilitates the identification of strengths and weaknesses within the project proposal or the case under examination, including its present condition. Prior to defining and composing the indicator set, three primary application domains were established, within which the indicators can be deployed to assess impacts across three fundamental levels (as illustrated in Figure 4.7):

1. Urban Level: Encompasses territory comparable to municipal or provincial jurisdictions
2. District Level: Defines the observational scale at the specific neighborhood level
3. Building Level: Addresses impacts at the individual building scale

This hierarchical framework enables a comprehensive evaluation across multiple spatial scales, ensuring that impacts are assessed systematically from the macro urban context down to the micro building level. The multi-scalar approach facilitates a nuanced understanding of how interventions at one level may influence outcomes at others, thereby supporting more informed decision-making processes in urban development and building renovation projects.



Figure 4-8 – Scalability of the Impact Model

4.3 Outcomes

The correlation between sustainable mobility and urban transformation was investigated through an analysis of active mobility's impact on regeneration projects. The study examined the temporary utilization of dormant spaces and vehicle-dominated areas. Subsequently, an initial implementation of the impact model was conducted, specifically focusing on sustainable transport metrics. The DumBO project within the Ravone area (Bologna) served as a compelling case study in urban regeneration. This chapter of the doctoral research explores the application of the Impact Model (IM), with particular emphasis on Key Performance Indicators (KPIs) related to sustainable mobility. Through the integration of insights derived from Mobility Urban Plans at various spatial scales [56], [57] combined with indicators identified in the academic literature, the research evaluates the tool's potential application within the study area.

4.3.1 Tactical Urbanism for sustainable mobility action: Bologna case studies

Tangible examples of how sustainable mobility can give a contribute to urban regeneration, are in Bologna. New areas of experimentation have already been identified in March 2023. In particular, these are experimental interventions for the construction of school squares, aimed to solving the problems of viability affecting the conflict between cars and pedestrians in the hours of entry and exit of students. These kind of projects involve the reorganization of the vehicle flows and people, stimulating diversified ways of accessing the school complex. In particular, "kiss & ride" areas will be created at different distances from the building to prevent the concentration of cars in front of the school.

In this way, new pedestrian areas are conceived as experimental interventions of pedestrianization of road sections now used for car traffic or parking, through creative interventions of tactical urban planning, aimed at creating new large spaces to be used for recreational sports and cultural proximity functions [58]. Pedestrianization has been imagined with different gradients and intervention characteristics. In addition to those directly related to the requests of traders for the dehors, will be of three categories:

- Spaces for pedestrians near school entrances with widening of spaces near schools, speed limitation, etc.

- Design of playground with the insertion of urban furniture, green and any physical game elements (sitting, planter, baskets etc.)
- Urban regeneration through tactical urbanism.

The interventions in most cases will be born with a first phase of experimentation, a subsequent evaluation, and, if this is successful, an implementation for a definitive transformation of the public space. In order to enhance the urban contexts of intervention, from the environmental point of view will apply design solutions that encourage sustainable mobility, implement the presence of vegetation also cultivable, include the use of mineral materials as well as clear paints to reflect the sun's rays or where and when possible, provide for de-paving and water use.

The guiding criteria for the choice of areas of intervention were poor availability of public space, presence of other projects in progress or attractive poles that can be of support to the success of the intervention, criticality analysis and feasibility assessment without works (for experimentation) or with reduced works (floor painting/light furniture) and sustainability of the intervention in terms of use and management. Based on the results of the technical evaluations, a first selection of potentially feasible interventions was made, which were subsequently submitted to the competent assessors and the opinion of the districts. Two research cases, that express the application of tactical urbanism in Bologna has reported [59]. The area consists of an 80-meter-long pedestrian route in a driveway (intersection of Via Milano and Via Corrado Mazzoni) [60]. This zone is marked by the presence of public housing sectors, where traffic primarily consists of pedestrians, bicycles, scooters, and wheelchairs. This action wanted to explore alternative ways of using public space through an innovative temporary set-up that would allow public space's cultural, recreational and sporting functions to maximize its potential. The various elements (Figure 4.7) can be interpreted by those who live and enjoy them.

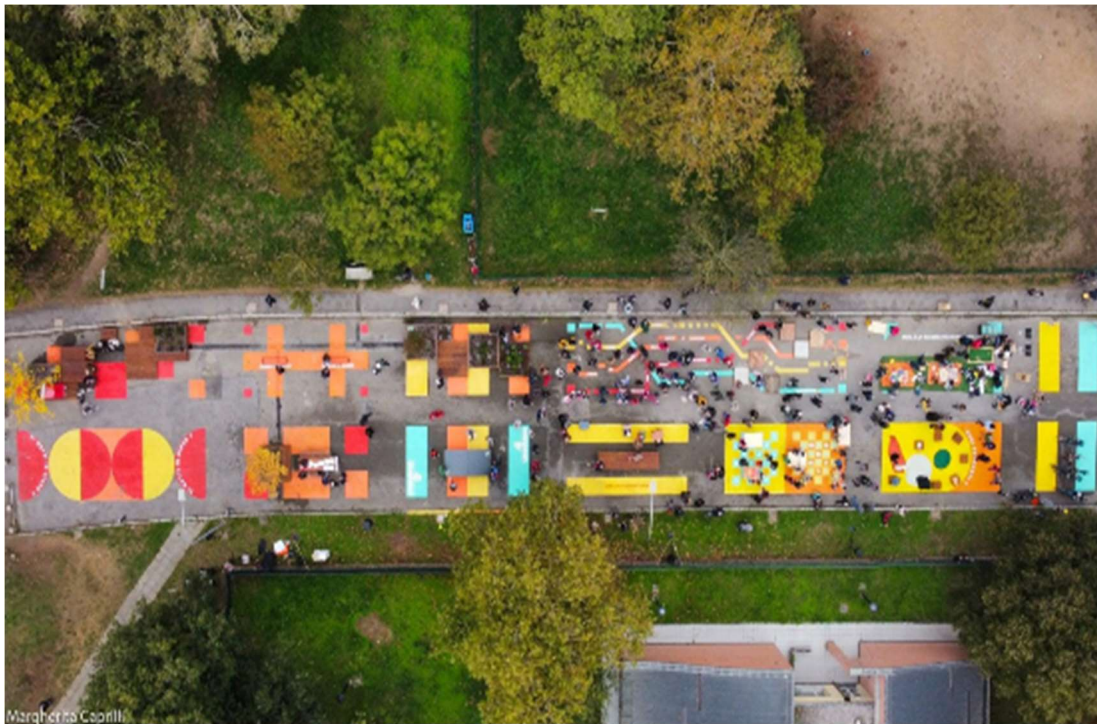


Figure 4-9 - Aerial photo of the transformed urban area located in via Milano © Margherita Caprilli, FIU

The colors, materials and compositions used aim to encourage curiosity, supporting people to participate in the area transformation process. Observation and monitoring of the public space were conducted using methods that are based on empirical evidence obtained using rigorous analytical tools. The goal is to understand the impacts of an intervention on people and the urban context.

Specifically, the tools used for the monitoring activities were the count of the number of people and vehicles in the space, questionnaire through various channels, and interviews. The results show that the urban renaissance activities were effective in creating an inclusive public space, demonstrating a significant increase in the number of visitors and users of the area. Furthermore, the monitoring showed a 60% reduction in vehicular traffic in the area with an increase in the perception of safety by the people in the area. The report also highlights the positive impact on commercial activities and property values in the area, thanks to the transformation of public spaces. Another urban tactical action in the city of Bologna was the realization of the first schoolyard near the middle school in via Fioravanti [61]. The experimental and temporary intervention involved the creation of a schoolyard with elements dedicated to the students and, generally, to all the people who attend the area (Figure 4.8).

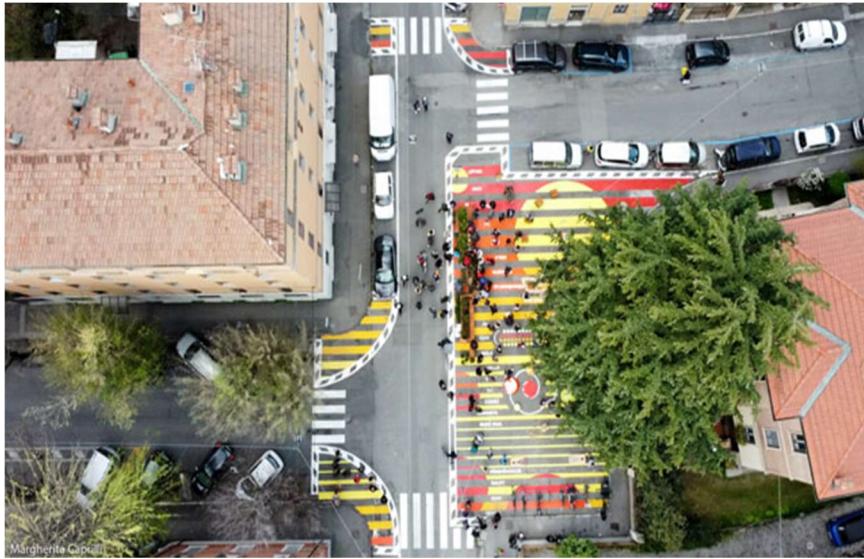


Figure 4-10 - Aerial photo of the transformed urban area located in via Procaccini © Margherita Caprilli, FIU

This project planned to pedestrianize an area of about 300 square meters through paint on the ground, vertical signs and other elements for the pedestrians (benches, wooden tanks and ornamental plants). The colors, materials and compositions used are chosen to foster curiosity and support people in imagining and practicing uses, thus taking part in the space's transformation process. In the morning, pedestrianization is active between 7:40 and 8:10, while in the afternoon it is active between 13:50 and 14:30. At these times, the nearby shops are closed with barriers to close motor vehicles traffic. The intervention lasted about 12 months. The area was also the subject of the study conducted by Systematica and Transform Transport, aimed at monitoring pedestrian and vehicular flows during the pre and post-intervention phases [62]. Monitoring was carried out through observations supported by a video camera and automated image analysis techniques. The study produced a series of temporal and spatial analyses related to the observed flows in the area (e.g., density maps, space use, average speeds, road crossing behaviors, etc.). Following these principles, the camera was installed in the corner of Via Procaccini and Via di Vincenzo (north side), at the height of about 3m and with a mean axis of framing parallel to Via Procaccini facing the area of intervention. The results of the analyses were elaborated in order to:

1. Identify the activation times of the study area before and after the redevelopment of the scholar square, through metrics describing the cumulative pedestrian density and the cumulative residence time;
2. Define the global characteristics of space use, discretized on a 1m x 1m grid, through metrics related to cumulative dwell time and average speeds;

3. Characterize the uses related to the study areas following the redevelopment of the square (e.g. roadway, square, furnishings, etc.);
4. Calculate the overall difference in use before and after surgery.

The results of the analysis showed a 43% increase in the cumulative residence time recorded in the area following the redevelopment intervention. In particular, the cumulative residence time in the square, transformed from a crossing area to a rest and play area, increased by +216%. Strong changes in the spatial distribution of pedestrians in the study area are also highlighted. New characteristics of use related to the furnishings in the square emerge, which present the most significant cumulative residence times in the area.

4.3.2 The application of the Impact Model: DumBO Project

Bologna is home to a unique project, a temporary urban regeneration place known as DumBO. The term stands for “Multifunctional Urban District of Bologna”, and it's a location where innovation, culture, and community intersect. [63]. The ancient railyard where DumBO is located covers over 40,000 square meters and is made up of six structures and several outdoor areas (Fig. 4.10). It remains the property of a corporation owned entirely by the Italian State Railways, which is in charge of redeveloping and improving railway infrastructures that is no longer operational [64]. But DumBO is considerably more than a temporary multifunctional space. DumBO provides a platform where associations, corporations, and residents may interact and infect each other's ideas, generating fresh and innovative methods to urban development. DumBO is a collaborative example of urban regeneration since it repurposes these places and incorporates collective artistic expressions.

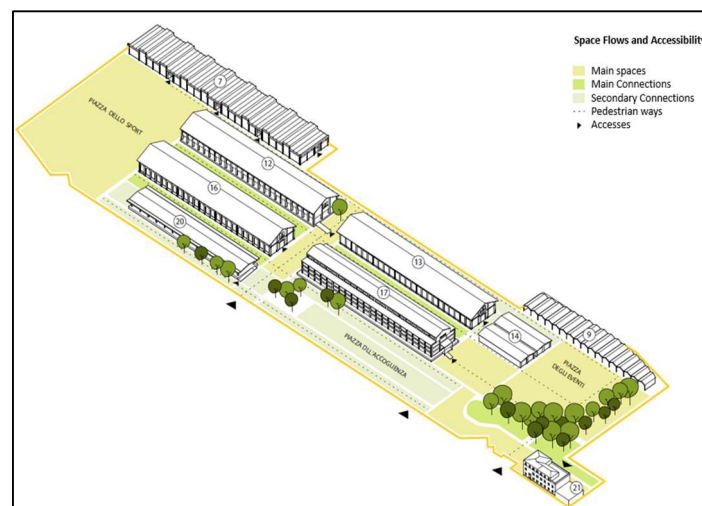


Figure 4-11- Dumbo spaces and Buildings

DumBO space is part of the area Prati-Ravone, that is located in the north-west suburbs of Bologna, between via Zanardi (orange in fig.4.10b) and via Emilia (purple in fig.4.10b). In the following figure the main road axis has been detected. Currently, the district is object of urban transformation, through the construction of a new railway station and a road axis foreseen that connects the district also from the west side, directly with the main suburban road and highways. The IM can be applied to measure the current status of the area in different stages of project till to the urban regeneration will be concluded.



Figure 4-12 b) Public Transport Lines connected the area (bottom)

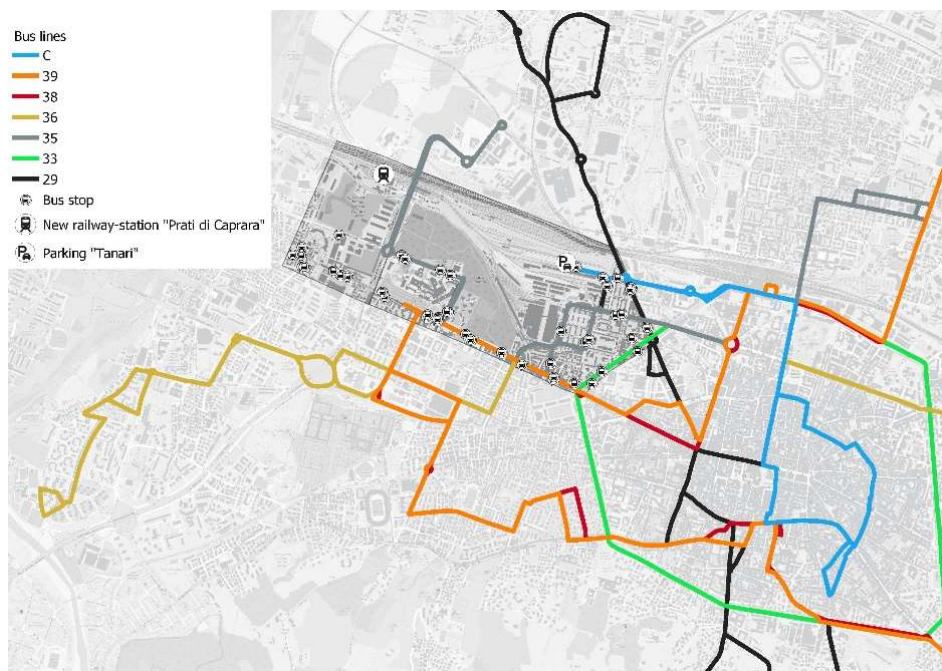


Figure 4-13 a) Main road axes in the Prati-Ravone district(top)

In the western part of the city, road works are planned that substantially modify the current infrastructural grid. In particular, Via Emilia (the purple one in fig. 4.11b) will be affected by the construction of the first tram line, within 2027, that modify its functionality, towards the implementation of Local Public Transport together with the reinsertion of pedestrians and cyclists at the center of mobility policies. The current situation presents a service of bus lines with the following lines underlined by the figure 4.11b. The area is covered by the line 29 that connects the north and south part of the city, as well as for the line 19 that links the western to the eastern part. Furthermore there is a car park, which is configured as a junction point for the modal interchange car/PLT (where shuttle C bring to the city center) and also as a bike interchange, offering convenient prices and services for the users.

Related to the bicycle and pedestrian accessibility, the project area is equipped with cycle path on Via Casarini and Via Tanari and one-way bicycle lanes on both sides of the road (fig. 4.12). The present bicycle paths connect the #1 Samoggia-Imola and #5 Bologna-Trebbio routes. The intervention area it is connected through the bicycle path on via to the bidirectional bicycle path built along the ring roads and allowing to reach important urban polarities. The administration is also committed to transform the city with 30 zones that will increase space sharing in favour of active mobility. Given the state of art in terms of sustainable modes of transport, a series of KPIs were calculated for assessing the actual situation [65]

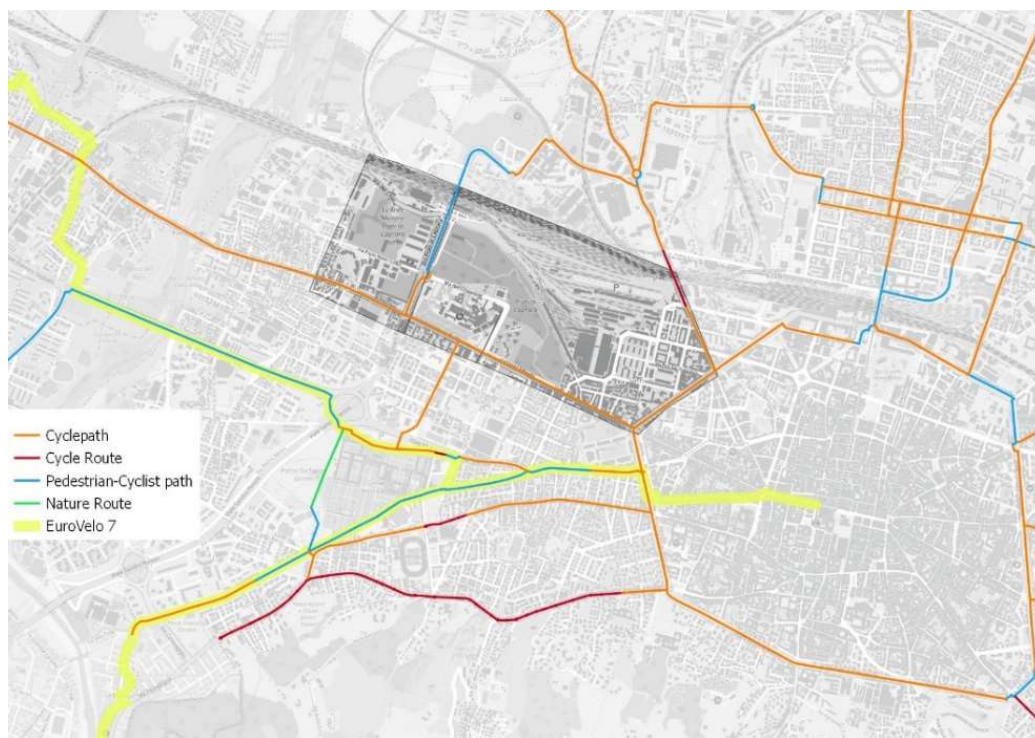


Figure 4-14- Cycle network in the Prati-Ravone area

The analysis is focused on the environmental performance, especially in the impact category of sustainable mobility, that it consists by: studying the proximity and accessibility of an urban center (in order to first reduce the mobility demand following a ‘trias’ approach), the servicing level by active and public transport and the adopted mobility land use in urban environments. In this research, the impact categories related to the sustainable mobility has been developed based on the indicators mentioned in the literature. Starting from the SUMI indicators, selected for their adaptability and flexibility in different cities and levels[66], the following indicators were selected:

- Opportunity for active mobility: this indicator considers the length of the bike lanes (L_{bl}), length of sidewalks (L_{pv}), 30 km/h (L_{z30}) and pedestrian zones (L_{pz}) over the total length of the road network of analysis (L_{rn}). The value from the following ratio is an average of the length of road network adapted to walking and cycling.

$$R_{am} = \frac{L_{pv} + L_{bl} + L_{z30} + L_{pz}}{L_{rn}}$$

- Access to mobility services: Percentage of population served by LPT. The indicator (AccI) value is on a scale from 0 to 10. The level of accessibility takes into account both the distance from the stop and the departures of the service of public transport. The formulation is the ratio between the number of people living in the “I” zone weighted with the dimension of the analyzed area and the number of inhabitants in the urban area. In the formula, “cap” stands for the number of inhabitants, PR_i is the number of people living within the access typology zone i, identified by combination of public transport accessibility level. In conclusion W_i stands for "Wi = Weight to identify if the accessibility to mobility services is appropriate (depending on the combination of PT accessibility level). The weight is differentiated for small (i.e. less than 100,000 inhabitants) or large urban areas (it is = 1 where it is fully appropriate, 0.5 where it isn't fully appropriate, 0 where it isn't appropriate")

$$AccI = \frac{\sum_i PR_i * W_i}{cap}$$

- Multimodal Integration: Index between 0-100 showing the average level of multimodal connection of the analyzed area within an urban transport network. The data for this indicator were collected by studying the network characteristics and facilities of the public transport. The list of all the transport modes in the urban area is predefined and for each zone a percentage is calculated of the number of modes available compared to the total ones. "The list of all the transport modes in the urban area is predefined, and

for each interchange a percentage will be calculated of the number of modes available at the interchange, divided by the total number of modes.

- Mobility Space Usage: Proportion of land use by all city transport modes, including direct (LD, for main and secondary roads) and indirect uses (LI, for sidewalk, parkings etc.). It is calculated from the square meters of direct and indirect mobility space usage per inhabitants (cap).

$$LUM = \frac{\sum_i (LD_i * LI_i)}{cap}$$

The other inspiring example for the mobility evaluation comes from the sustainable urban mobility plan of Bologna (PUMS) [57] and Security Urban Plan (PSSU) [67], focused on the accident prevention, that indicates the following parameters:

- Modal split: Percentage of the usage by inhabitants for the different modes of transport (active mobility, private cars, and public transport).
- Cycle Index: the meters of the cycle path or lanes available for the inhabitants of the analyzed area. The analysis was realized by GIS software.
- Fatality Index: Number Death/1000* inhabitants.
- Injuries Rate: Number Injuries/100* inhabitants.

The pillar which has been analyzed is the one related to “Sustainable Mobility”, which is embedded into the “Environmental Performance” pillar. Specifically the research till now includes several quantitative and qualitative tools such as:

1. Collection of data from the open-dataset: starting from the regional and municipality open data set, the needed data for the calculation of the selected indicators have achieved.
2. Definition of the indicator scale: the calculation of each indicator, is related to a scale of application. It depends from the collected data. This differentiation is useful to understand the challenges
3. Creation of spatial maps for the calculation: in this phase, some indicators need different ways to be measured. This one was realized by using GIS software (Q-GIS), that is useful to create some spatial maps to assess the impact.
4. Definition of the baseline: after the selection and calculation of each indicator, a literature review of the baseline and targets to achieve was realized. Mostly the baseline is defined by European target (as for the case of Opportunity of active mobility) or regional plan (I.e. the Cycle Index). The score from 1 to 5 is given for each indicators

follow the founded targets. It was possible because these indicators show quantitative targets (i.e. m/inhab of cycle path) to achieve or percentage (i.e the access to mobility services).

In the table below, the characteristics of each indicator are defined with, the used methodology. Furthermore, the impact score has been assigned on the base of the available and converting the results on the reference scale 0-5. The highest score has fixed based on the literature or on the European/local target to achieve, for a specific indicators. This procedure allows the creation of a scenario in which all indicators are defined with the best possible result and this can be considered as an optimal scenario, which allows one to observe how the real situation differs from the ideal one. The radar graph (Figure 4.14) is useful to observe how the existing scenario diverges from the ideal situation.

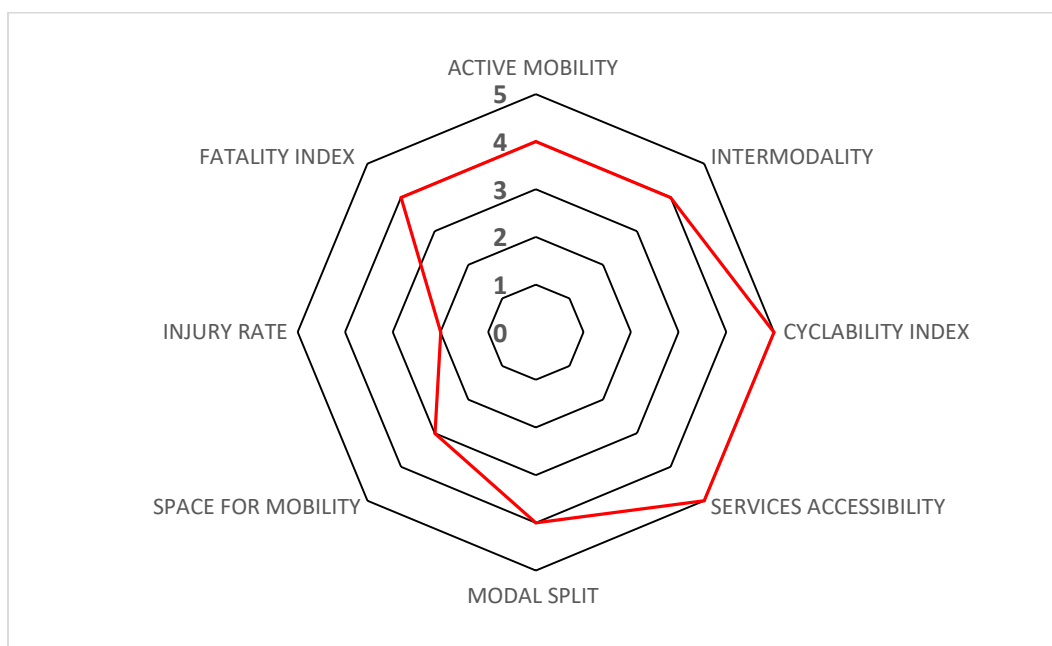


Figure 4-15. Spider Graph about the indicators score

Indeed firstly, the modal split and the incident rates shows that Bologna is on the good way for the European target of the 0 accidents and the modal shift to the sustainable mobility modes. Going more in deepen to the project scale of DUMBO, from the calculated impact scores, shows an excellent starting point for encouraging more sustainable mobility. Indeed, the indicators point out excellence from the point of view of the bicycle network with a 5 points rating for the cycle index. The intermodality indicator collects 4 points rating due to the accessibility of the area (confirmed to the Accessibility Indicator too). The area is well served by bus services and well-connected to stations both in terms of public transport infrastructure and active mobility.

5. Activity 3: Evaluation of active mobility project with VR and BIM approach

5.1 Introduction

Once analyzed the power of the KPis into the planning phase, the research moves on new tools developed in the last years to build, check and evaluate the road infrastructure project in the design phase.

Transport infrastructure networks are currently developing both in terms of technology use and implementation. The growth in transport demand requires any nation to create resilient infrastructures to support this increase in travel. Methodologies are needed to monitor the design phase to minimize waste of resources and emissions, but also to encourage a modal shift towards soft mobility. Policies and actions are being developed across the cities to encourage cycling for both physical and environmental well-being in the urban context. [68][69]. Investments should also be targeted at projects that aim to guarantee the rights of cyclists on the road in addition to those of motorists, encouraging harmony between two different types of users on the move. In this perspective, the construction of cycle paths could help to optimize road use for both categories [70], [71]. The use of building information modelling (BIM) from the design phase of a cycle path can be very useful by streamlining the various steps and preventing possible waste [72], [73], [74].

However, during the project phase, often the results are not clear for the future users or stakeholders. To fill this gap, user experience and perception assessment could help to understand how users perceive and experience public spaces. It includes factors such as aesthetics, safety, accessibility, and overall satisfaction. A human-centric approach considers the experiences, perceptions, and needs of individuals who use or interact with public spaces. It is traditionally conducted through surveys with an on-street questionnaire, which asks people walking and spending time on a street about how they perceive the street. It is a more reliable method but it can be costly and time-consuming. It can also be done through the exploitation of street view imagery or through the use of more personalized videos or images. These types of methods of public space auditing cannot be done for prospective projects not yet constructed, but their methodology can be useful to assess future designs based on 2D drawings or VR setups.

The utilization of VR technology suggests a forward-looking and technologically advanced approach to public space assessment. This can provide a more immersive and interactive experience for participants compared to traditional assessment methods. In the next pages, the research explores both the construction of cycle path using the BIM approach, starting to the definition of this new technology. In addition the Virtual Reality scenarios will be investigated in order to understand the potential of a sustainable mobility projects, experienced in such way. In other words, the next chapters will investigate BIM and VR application in an unexpected project: a sustainable mobility one.

5.1.1 BIM Modelling Approach

Computer advancements have had a significant influence on the processes used to design and generate technical drawings, almost eliminating manual drawing and opening up new form possibilities employing organic shapes and complicated geometries. This led to the next phase, which was the introduction of commercial computer-aided design and drawing software (CAD), which was the primary design program for several years and is still in use today. However, in recent years, the notion of BIM has gained traction. BIM is a digital system for 3D modelling from the physical, performance and functional data of a building [75]. One or more accurate virtual models of a building are created digitally using BIM technology. They assist planners throughout the design process, enabling greater analysis and control than manual methods. Once finished, these computer-generated models contain the precise geometry and data needed to assist with the building's construction and manufacturing. It is profoundly altering design practice and building design, delivery, and operating standards. Building Information Modeling (BIM) is a potential development in the architectural, engineering, and construction (AEC) industries. Below an example of AEC project team (figure 5.1)[76].

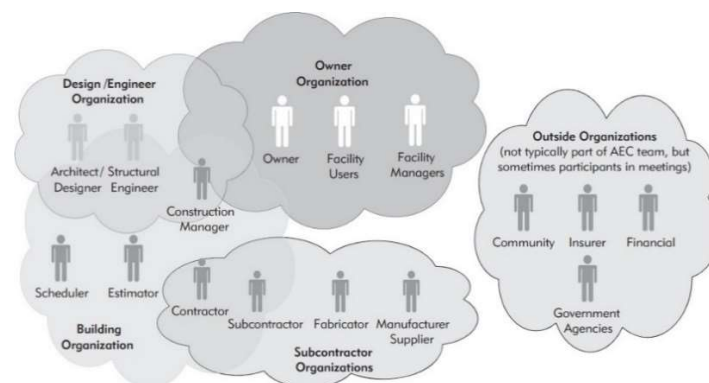


Figure 5-1: AEC project team

The majority of the world's top AEC firms have already abandoned their older, drawing-based CAD systems in favor of BIM for nearly all of their projects. It's crucial to remember that BIM is more than simply a technological shift, it's also a process transition. BIM transforms not only how building drawings and visualizations are created, but also all of the key processes involved in putting a building together. The following are the primary characteristics:

- *Process optimization*: by reducing process times, BIM aims to improve project quality and productivity. It is possible to investigate the efficiency of BIM through a diagram made by the American architect Patrick MacLeamy (figure 5.2). The diagram's curves indicate how concentrating design effort in the initial stages of the design has a favorable impact on costs.

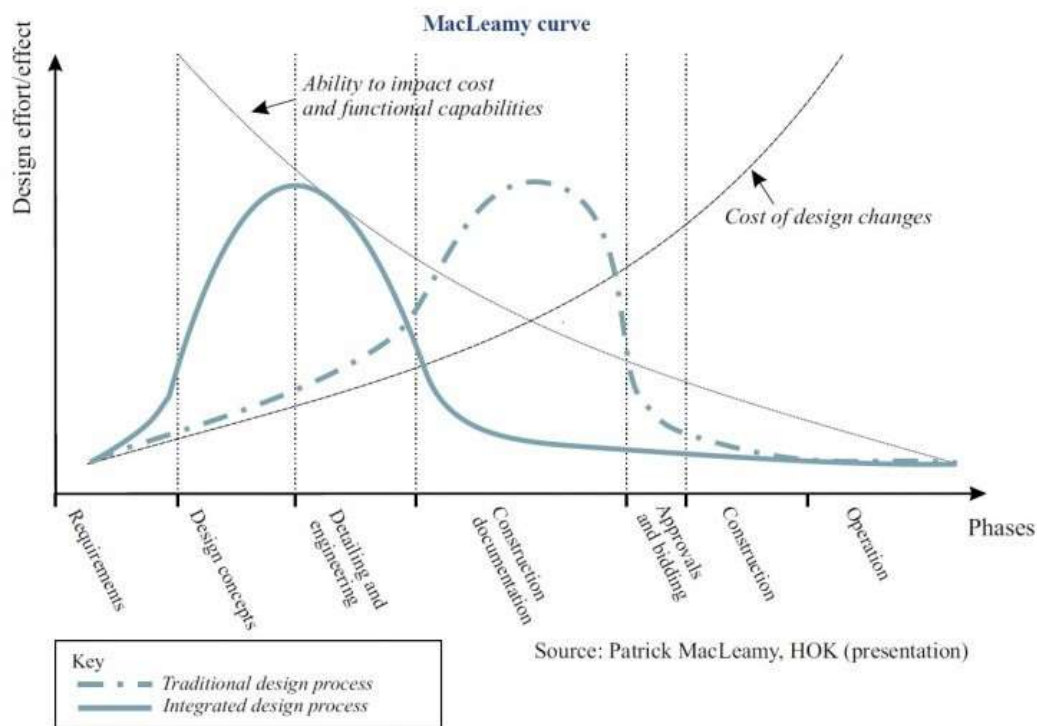


Figure 5-2: MacLeamy curve (2004)

- *Multidisciplinary*: A BIM model permits collaboration between various professional figures participating in the construction process. All of the professionals involved no longer work individually and independently from other, but instead collaborate and make modifications to a single central and dynamic database that corresponds to the BIM model.
- *Error reduction*: Identifying design problems and omissions prior to construction. The 3D model will be free of geometry, alignment, and spatial coordination errors if the

objects utilized in the design are controlled by parametric rules that assure accurate alignment.

- Simulations: BIM models can be used to run simulations or perform accurate material calculations, such as automatically generating lists of the components used in a project or determining the coefficient of natural lighting, energy requirements, air flows, or noise levels.
- *Operational and facility management*: this refers to the control and maintenance of a building and all of its components over the course of its entire life cycle. It is able to sustain track of maintenance, demolition, and replacement actions throughout this phase.
- The interoperability of people involved is placed at the center of the process, creating collaboration and communication among them. In doing so, each professional figure provides all the information on the model to complete it with all the features necessary to outline any problems that may occur in the useful life [77].

Interoperability is the fundamental activity and is mainly articulated in two forms of exchange: the proprietary one is limited to reading the content only to some software and the technical specifications are not in the public domain. The second format is a data system based on the technical specifications in the public domain, without time limits called the Industry Foundation Class (IFC): neutral, open and standard. IFC is an open international standard (ISO 16739-1:2018) developed by buildingSMART [78], [79], [80] that is supported by the industry's leading design software. IFC is a framework that was created to define an extendable collection of consistent data representations for building information for using by AEC software applications. The IFC file format is an object-oriented data structure used to describe building models. Building components are members of classes. These can be discrete objects like walls and windows or abstract concepts like projects and processes. The objects in an IFC model are connected to one another via a complicated network of connections that form a tree hierarchy. Information is kept directly in the IFC structure and is accessible by accessing a basic attribute of an object. Below some examples of components of a building encoded by IFC:

- Identity and semantics (name, machine-readable unique identifier, object type or function);
- Characteristics or attributes (such as material, color, and thermal properties);
- Relationships (including locations, connections, and ownership);
- Objects (like columns or slabs);

- Abstract concepts (performance, costing);
- Processes (installation, operations);
- People (owners, designers, contractors, suppliers).

Operationally, there are two distinct phases: code checking that verifies the adherence between the model and the design requests and the clash detection phase that implements a preventive analysis of geometric conflicts present (and not) in the model. In particular with the introduction of 4D BIM, an organization of the activities related to the schedule of the times of the model is obtained, which allows to extract and visualize the progress of the activities during the life cycle of the project. In this way, BIM helps professionals to reduce trial and error in the construction phase which enhances productivity while diminishing risks associated with time and cost.

5.1.2 Virtual Reality Tools

BIM data opens the possibility to create a realistically referenced virtual three-dimensional model of a building or even an urban space, hence, a virtual reality model. This is where the branch between BIM data and the use of virtual reality is extended. Virtual reality (VR) is a virtual experience that may be both comparable and dissimilar to the actual world. The term 'Virtual Reality' was coined by Jaron Lanier, founder of VPL Research (1989). It includes the potential of simulating events through digital modeling which would be too unsafe or ergonomically impractical to replicate as a real-life prototype. In the engineering and architectural center, developed virtual reality technologies play a pivotal role in analyzing engineering projects prior to their construction and allow for their presentation to customers and stakeholders through virtual environments. Extended reality (XR) is a term covering technologies that enhance or substitute our perception of the world by overlaying and immersing graphics into real-world or resembling virtual environments, often combining the two seamlessly. Extended reality (ER) is built on three foundational components:

- Virtual Reality (VR), also known as computer-simulated reality, wholly immerses users in a virtual world that is computer-generated, providing interactive experiences using tools such as special headsets.
- Augmented Reality (AR) enhances what is found in the real world through the overlay of computer-generated information, contributing with added attributes without a modification of the existing environment. Users thus interact with their surroundings while experiencing essential augmented features.

- Mixed Reality (MR): MR, meshes real and virtual environments, providing a flexible reality where consumers interact with virtually designed objects coined with specific referenced real-world locations.

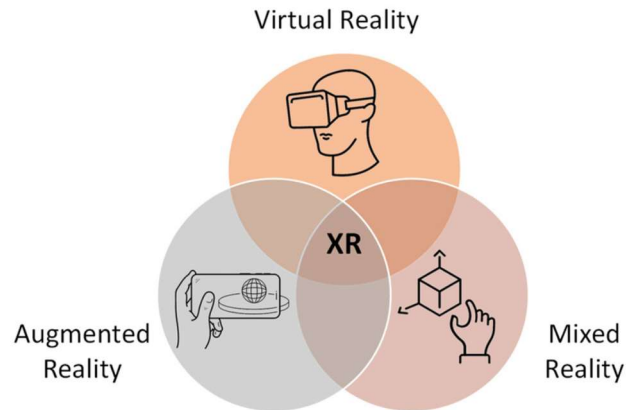


Figure 5-3: Interconnection between different components of extended reality

Extended reality holds considerable importance for the AEC industries. This is because constructed environments go hand in hand with three-dimensional spaces and professionals in the sectors heavily depend on visuals to produce effective communication. To understand where exactly extended reality can be applied within the sectors, it is interesting to look at the following split:

- Design aid: Designers can pre-inspect a prototype of their designs and its effects on the final product before committing to decisions through using extended reality.
- Stakeholder involvement: Enhancing engagements with potential clients and the general public through providing realistic representations of assets. Fostering a stronger comprehension and therefore more pertinent feedback.
- Construction planning: Where VR creates immersive construction simulation and AR allows for the visualization of objects linked to on-site realism.
- Progress tracking: AR enhances the ability to identify the completion of works and areas requiring attention to ensure combating schedule delays.
- Safety in construction: AR and VR Allow for completely avoiding the risks in training for workers through producing simulators and enhances operational efficiency.

The progression of virtual reality and the possibilities that come from it are explicitly related to advancements in its hardware technology and the tools required. The most common virtual reality systems use headsets to encompass all lifelike visualizations, sounds and sensations, prioritizing the perception of an immersive experience, allowing the user to intrinsically feel present within the built environment. Users of virtual reality headsets have the capacity to view

their virtual surroundings from all angles and navigate the area through supporting tools and objects allowing for complete engagement with the surrounding environment. The field of urban studies is no different, as VR presents extreme promise in potentially offering an efficient and realistic alternative to the traditional auditing methods. Public spaces are essential components in a livable urban environment. They contribute by acting as dynamic hubs which encourage community convergence and interaction while also defining the overall character of the city. Due to their criticality, the quality of these spaces extensively influences the wellbeing, social life and the overall urban experience of the residents in the city. Overall, public space auditing is mainly an approach used to evaluate key aspects within open urban areas, such as functionality, design and perceived user experience. In the current moment, a typical public space audit involves on-site inspection, subjective assessments by urban planners, community member surveys and stakeholder surveys. Once audited, the strengths and weaknesses of public spaces becomes coherently visible, and subsequently allows stakeholders to comprehend the state of the space in terms of its accessibility, aesthetics, safety and social encouragement. Over the years, it has been inherently clear, that these traditional tools do present vast limitations. Some of the problems with on-site investigations include:

- Extensive need for resources;
- unwarranted time consumption;
- a struggle in personalizing user perception due to its nature of subjectivity;
- inadequate coherence to the time sensitivity of evolving urban landscapes.

With these limitations, there is a gap for a more innovative approach that allows for a holistic comprehension of public spaces and their dynamic nature to battle the vastly growing diversity and complexity of urban spaces. As mentioned previously, the use of VR technology in the AEC sectors is transforming into a bewildering force in many domains. It's immersiveness leading to unparalleled opportunities for realism in experiences.. Due to its immersive nature, VR can allow for a realistic exploration of public spaces while also limiting the need for resources and time, rather than requiring physical transport to reach spaces, the spaces instead become accessible from the auditors desk, expediting the process and simplifying the repetition of audits in the case of a need for it. Stakeholders become able to navigate the three-dimensional representations of the public spaces, providing realistic and at times real-time dynamics simulations of the environment in question. Thus enabling said stakeholders to perceive the space through the lens of a real-life user of the area, building a deeper comprehension of potential user-space interaction and likely perceptions of the surroundings that could come to

fruition. It can be said, that due to allowing for user immersion in realistic scenarios, VR promotes a simplistic yet holistic exploration of spatial qualities, socio-economic dynamics, and the overall impact of selected designs on the user interactions. When applied in public space auditing, the use of VR technology compliments the built environment by transforming it into an inclusive design. Where it produces a platform that allows for the collaboration of the stakeholders in the design process, in which real-time design alterations based on user feedback is made possible.



Figure 5-4: Example of utilizing VR to immerse users within a designed environment: Lake Doorna Park in Orlando, Florida

For evaluating this VR scenario, in literature is possible to find some research related to the assessment of public spaces, focusing on pedestrian and bicycle levels of service and the integration in virtual reality (VR) scenario for public space auditing [81]. In this way, pedestrian level of service (PLOS) is a crucial metric for evaluating the quality of urban spaces, especially in terms of safety, comfort, and walkability. Various methods are used to assess PLOS, such as flow-based evaluations, pedestrian comfort perceptions, and data collected from sensors tracking pedestrian movement [82]. These evaluations help to quantify the interaction between pedestrians and their surroundings. Factors such as available space, walking direction, and individual physical and psychological aspects contribute to the pedestrian's comfort perception [83]. Comparing 29 PLOS methods [84], it was found that the diversity in approach and the lack of consensus in assessing pedestrian service, make confusion in this topic. In addition, some methods rely on pedestrian opinion, while others focus on flow and capacity measures, showing the multidimensional nature of PLOS assessments.

Moving to the concept of walkability, it refers to how conducive an environment is to walking. It is determined by factors such as safety, accessibility, comfort, and connectivity. High

walkability can lead to social and environmental benefits by reducing traffic, promoting physical activity, and fostering local economies [85]. Pedestrianization, as mentioned in the previous chapter, is one of the main methods to enhance walkability, which includes strategies such as converting streets into pedestrian-only areas or calming traffic to make streets more pedestrian-friendly. Full-time pedestrian streets, part-time pedestrian zones, and traffic-calming streets are examples of different pedestrianization approaches. These strategies aim to increase safety, reduce pollution, and boost social interaction in urban areas. The literature highlights the role of environmental factors, such as street furniture, greenery, and safety measures, in enhancing the walkability of public spaces [86]. These factors contribute to the overall satisfaction of pedestrians, ensuring that the area is conducive to leisure walking and daily commuting.

In this ground, Virtual reality (VR) has emerged as a valuable tool in public space auditing, offering an immersive way to assess urban environments. VR allows stakeholders to visualize and interact with public spaces in a simulated environment, enhancing their understanding of how people would use and perceive these areas. It also offers a unique advantage in assessing prospective designs before they are physically implemented, helping planners make informed decisions [87]. While pedestrian and bicycle levels of service offer quantitative metrics for understanding urban space quality, VR provides an immersive and interactive platform for stakeholders to experience and evaluate these environments.

5.2 Objective and Methods

5.2.1 BIM Modelling Framework

BIM research for transport facilities is on the rise, the focus has been mainly on highways and bridges, limiting its application to minor roads and cycle paths [88], [89] As mentioned above, currently, BIM modelling leads to improvements in all phases of design and is mainly applied to structures and bridges, while only in recent years it is embracing the field of road infrastructures. The latter represents a much more complex world because of the limited availability of libraries of infrastructure components, the difficulties in assigning parameters to the geometries of objects, the specific characteristics of the infrastructures that are not always easy to understand and the inadequate workflows and tools in the architectural field.

Indeed, the digital modelling of road infrastructures starts from the analysis of the territory, in which the model will be realized, and from the evaluation of probable interferences with the

infrastructures or the already existing works. For this reason, in the field of road infrastructure, data is processed in different formats. Often the use of GIS systems is required, typically with point or linear representations [90]. In the field of transport network, there is a “horizontal” concept of BIM, to diversify from “vertical” (referred to as structures). In horizontal BIM, there is a management of information and surfaces that are not always linked to objects. In this way, the ground becomes the fundamental element for design, while in the vertical these products are made in an industrial way, and thus the work has a high impact on the territory and the exchange formats still in maturation. One major differencing factor between a building (vertical) and a transportation (horizontal) structure is the coordinate system that is used in the design, planning and construction. Vertical construction uses the Cartesian coordinate system as a single reference, while horizontal construction uses multiple stations and alignment curves for references.

This difference has been a major barrier to the direct adoption and application of traditional BIM software for transportation [91]. To create an interaction between these two worlds, always having as a background the achievement of sustainable goals, this research investigates the application of the BIM methodology for the construction of a cycle path surrounded by nature in the Puglia Region. In Italy there are different regulation to take into account for realizing a BIM project. Standards are documents that define the characteristics of a product or process based on the state of the art. They encompass the work of all the experts in Italy and around the world who are involved. The main regulation are:

- UNI 11337: Parts 1-3-4-5-6-7;
- Direttiva 2014/24/EU;
- DLgs 50 del 18/04/2016;
- DLgs 56 del 19/04/2017;

The UNI11337 [92] standard is undoubtedly the main reference for BIM design. However, the regulatory structure of this document has no specific reference to infrastructures, but operates in the general field of BIM. The main parts are listed below:

- Part 1: Defines the meaning of "data" and "information" and contains informative documents and models. A distinction is made between informative documents, which include all documents that can be printed, even digitally, and informative models, i.e., 3D models.
- Part 2: Defines models for collecting, organizing, and archiving technical information on construction products and defines the subdivision between LOG1 and LOI2 .

- Part 4: Defines LOD3 by analyzing the informational evolution of documents and the informational interaction with the territorial database (e.g., GIS). LOD is the sum of LOG and LOI;
- Part 5: Defines roles, requirements, and information flows from production to their connection with digitalized construction processes. Additionally, in this specific part, graphic models are coordinated, dividing them into 3 levels, and verification is carried out ;
- Part 6: Defines procedural indications for drafting the Information Specification and constructing its general structure and characteristics.
- Part 7: Defines the knowledge requirements, skills, and competencies of the professional figures involved in information management and modeling: from Project Manager to BIM Figures (BIM Manager, CDE Manager, BIM Coordinator, BIM Specialist).

As seen during the beginning of this paragraph, a road project starts with the geometric design, where the layout is first developed and its plan-altimetric trend determined, then typical sections and intersections are determined. Subsequently, and simultaneously, it is important to determine the structural works that are encountered along the route (hydraulic works, architectural elements, lighting, signage, etc.).

The BIM project of a road layout is based on the technological aspect, in which openBIM processes must support the entities and relationships of the project itself, and on the procedural aspect, in which the objectives determined by the contracting authority must be respected, which also determines the information requirements that the BIM model of the road layout being created must present. As already said, within the road projects, the layout, sections, terrain, structural and architectural elements are closely related to provide necessary project information.

The connection of these elements determines a classic model structure of the IFC scheme that allows the export of the model and allows its study and verification through appropriate software. The evident difference, therefore, between an advanced CAD model and a BIM model lies in the structural difference of the model itself: in the BIM model, a subdivision into subclasses is possible, to which specific properties are assigned [93].

IfcElement		Ipotesi di traduzione nella pratica italiana
IfcBuiltElement	IfcCourse	Strato
	IfcEarthworksFill	Opera in terra in rilevato
	IfcReinforcedSoil	Opera di consolidamento del terreno
	IfcKerb	Cordolo
	IfcPavement	Pavimentazione
	IfcRailing	Elemento di contenimento
	IfcWall	Muro
IfcDistributionFlowElement	IfcSignal	Segnale attivo
IfcElementAssembly	IfcElementAssembly	Assieme (assemblaggio, aggregato)
IfcElementComponent	IfcImpactProtectionDevice	Dispositivo di ritenuta
	IfcSign	Segnaletica verticale
IfcFeatureElement	IfcEarthworksCut	Opera in Trincea
	IfcSurfaceFeature	Elemento superficiale (rif. Segnaletica orizzontale)

Figure 5-5 – IFC classes for road modelling

The IFC structure articulates the model according to a tree scheme, with nodes and leaves that constitute the physical components of the road, as shown in Fig. 5.6. The project, called IfcProject, establishes the main context for the exchange and sharing of information regarding a work. The first level of the structure is constituted by IfcSite, which identifies the area of territory in which the road project is located. In reality, this level is not specific to the infrastructures model alone but is defined for any IFC model. The second level allows determining the type of infrastructures being created by introducing a new subclass: IfcFacility, which can be a building structure (IfcBuilding), a bridge (IfcBridge), a road (IfcRoad), a railway (IfcRailway), a port structure (IfcMarineFacility), a building (IfcBuilding). The third level relates to the work parts, subclasses of IfcFacilityPart. The subclasses are described through two attributes. The first attribute, inherited from IfcFacilityPart and therefore unique for all classes, is the UsageType and is related to the orientation according to which the operator is tracing the breakdown of the infrastructures. The second, instead specific to each class of infrastructure part, concerns the identification of the type of part to be described.

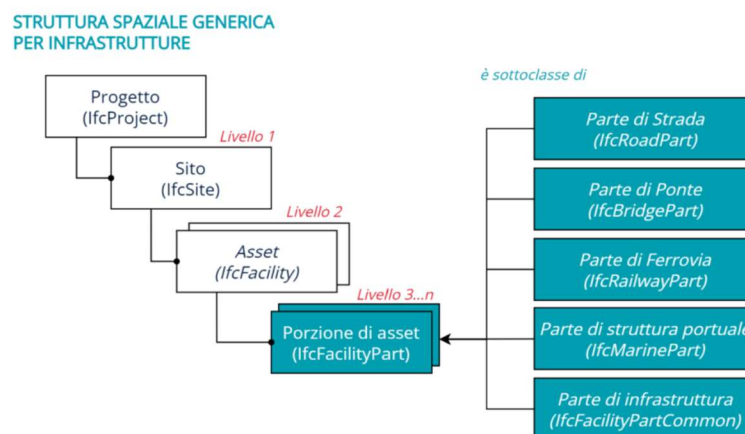


Figure 5-6: Spatial Structure IFC for road infrastructure project

5.2.2 Virtual Reality for Public Space Auditing

In previous sections, a deep dive into the methodologies utilized to ameliorate public space auditing through the use of VR is done, exploring the technological and theoretical foundations and studying the feasibility of the scheme in having a transformative impact on the urban study approach that was developed in this PhD research. In particular, this study may involve collecting data on user interactions and preferences within the virtual environment. Analysis of this data, through algorithms leading to high-level indicators, can contribute to insights into how people respond to different elements of public spaces.

5.2.2.1 Creation of the virtual Scenario

For evaluating this kind of aspect, a project has been taking into account. From the collaboration between the Eiffage group and the University of Gustave Eiffel's Grettia lab, born an incomplete model. It was already been developed but missing several buildings, parcels and lots that had to be added. In this paragraph the methodology for building the scenario was briefly introduced. As previously stated, the problem consisted of 3D city model generation which would later be used for a public space audit to characterize the urban area constituting the district. To ensure the models' use acts as a reflective assessment of the district, several factors had to be considered to promote the required realism and effectiveness:

- Accuracy of terrain and topography;
- layout and placement of buildings;
- Architectural details;
- infrastructures and roads;
- proportion and scale;
- accessibility and navigation;
- interactivity and user experience.

These factors optimize the model by ensuring that it is not only visually appealing, but also highly serving as a premise for the required urban characterization and public auditing. To ensure that these criticalities are addressed, the design of the model is split into three distinct yet intertwined phases:

- a) BIM data: street networks, street furniture, main vegetation and the overall mass plan to induce the utmost precision during the placement of objects (BIM coordinates).

- b) GIS data through Infraworks: to ensure the surrounding context of the area is complete and filling all required BIM gaps through alignment with the context.
- c) TwinMotion: The addition of specific urban facilities inclusive of vegetation, urban dynamics, street furniture, urban competencies and neighborhood niches of all varieties.

Once the three sources of input are merged and the output produced is as a contextually valid, precisely coordinated, realism invoking, a complete version of the Lavallee district as a 3D city model on the VR-compatible TwinMotion was realized. The LaVallée district can be categorized to require a large-scale city model, and thus for the model implementation, the contribution of various architectural firms is required. The current available data is split up into 8 lots, and each lot is comprised of a representative architectural firm who is responsible for the lot's BIM data. The responsibility of these architectural firms lies in converting GIS data which places an emphasis on coordinate locations and city scale into more realistic BIM files of high detail. This is because GIS data solely provides footprints and elevation, which are not enough to completely contribute to an immersive visit later on using virtual reality. To do so, architectural consultants typically use cloud-based technology such as BIM 360. These technologies permit the visualization of the holistic city, its infrastructure and some basic landscape data including trees and vegetation. While the functionality of these models allows for user-interface interaction, they lack realism and require added rendering and editing to improve textures, lighting, and the urban details. Thus, the process begins with the AEC partners of the project. Each company develops the CAD drawings of the buildings, terrain, public spaces, parking spots, road networks, urban furniture such as benches, recreation furniture, and vegetation. All developed drawings are centralized on a BIM 360 cloud platform with their coordinates being tendered as IFC files (Industry foundation classes).

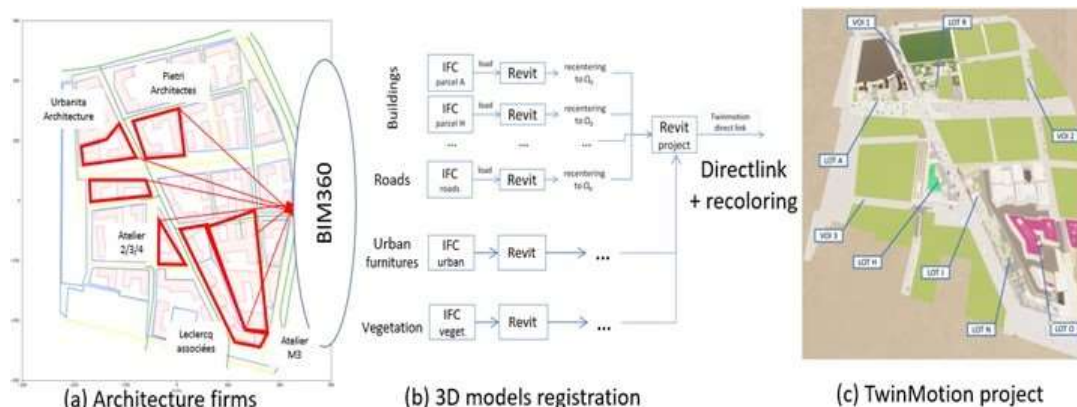


Figure 5-7 – BIM workflow

Once all data is compiled into the BIM 360 platform and it is distributed as industry foundation classes files (IFC), it is ready to be analyzed. In the project, the reference system utilized was the RGF93 CC49 while the Elevation levels use the NGF69 reference system. Using common coordinates between different data sets allows the connection of the digital models. The IFC files given contained comprehensive data on the building's attributes, including the material type of specific portions of the building and the exact location of each individual point on the structure according to the reference frame of the specific file. These location coordinates are the characteristics that had to be examined within their local reference and converted into the RGF93 common reference system, in which one point in the file was to be taken as the reference point to measure all coordinates. Meaning, the origin of each of the points of buildings had to be converted from their own local reference point to the overall project's reference point.

In conclusion, to complete the topography of the area, add-in the missing buildings and align the surrounding context with the district formed by BIM data, the most notable alternative was the Infracore software. The Infracore model builder command allows for the extrapolation of the complete environment of a desired location including its road network, buildings, topography and terrain. This model then allows to create the scenario with OpenStreetMap data available. The area will be limited to less than 200 km squared for the software to be able to process it effectively, otherwise it will be deemed too large. The ETRS89 system is selected to best match the existent BIM data and then the model creation commences. Depending on the size of the area, the model builder processing and preparing time can vary, but typically in a district-scale it takes approximately 5-15 minutes and is not a long wait. When ready, the model is then found in the list provided on the infracore home screen (Fig. 5.8).

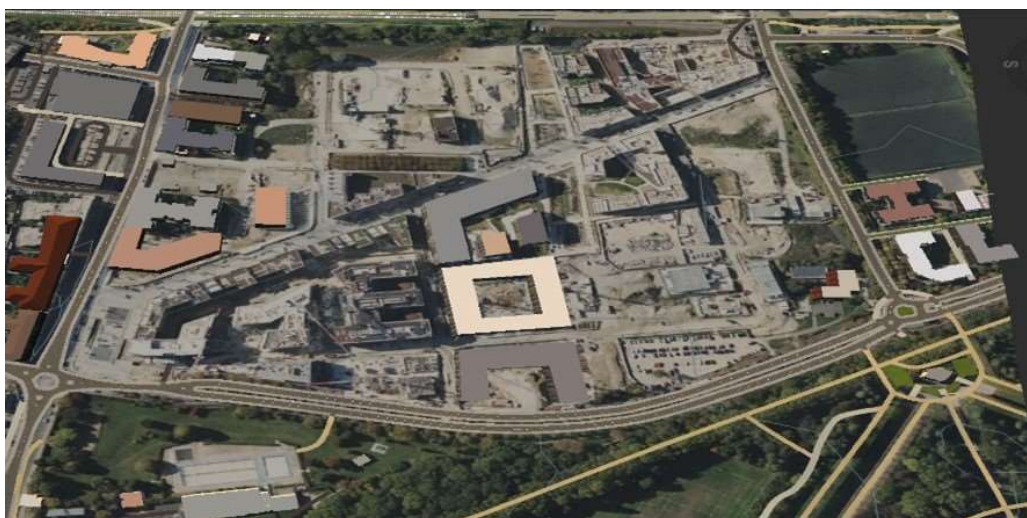


Figure 5-8: Representation of the Context of the District on Infracore

Even though Infracore was considered the best option in terms of time efficiency, precision and data availability, there are still various concerns to be handled after the model's creation. These issues were associated to the outdated OpenStreetMap data, the lack of high-definition model building possibilities and blemishes in capturing the OpenStreetMap images by the software. To solve these issues, certain fixes took place directly on Infracore, while others had to be reserved until after exporting the model into TwinMotion.

The fixes on Infracore included alterations to the road network, terrain leveling, removal of unnecessary buildings and the adjusting of road features. Each of these is simply done by selecting the blemish in mind, and using the software produced index points to alter levels, shapes and directions, allowing for the smoothing of curves in road networks, the leveling of the road and terrain elevations, the fixing of roundabout shape and realism, removal of buildings and building height adjustments. Once these minor, yet vital modifications are made, the model is ready to be used and exported to TwinMotion. To use the model in alignment with the existing TwinMotion model, it should be exported as an .FBX file. Since the whole created model is being used and not a partial polygon, the selection of the "export entire model" tab is critical. Once the file is imported into TwinMotion, it must be manually aligned to the BIM data. After aligning them on the horizontal plane, the elevation of the terrain must also be manually edited as its elevation is not exactly level, ensuring that the context is below the BIM file at all points realistically. Meaning buildings heights are seen as realistic and all additions of the context that need to be visible, are so. Post-integration of the required context into the model, the model now includes high-definition buildings rendered to realism and placed with accuracy on top of coarse contextual data. The rest of the work to be done to finalize this increasingly realistic model is on TwinMotion (Fig. 5.12).



Figure 5-9 - Tram Stop in Twin Motion

5.2.2.2 Creation of an Immersive Virtual Reality for Public Space

The next step is to assess a process used to compare VR public space audits, using dedicated survey. Prior to developing the questionnaire, it is critical to understand which factors would provide an overall sense of understanding of the quality of the urban space and what indicators can be used to draw a statistical comparison using these factors. Through analyzing the comprehensive literature review presented prior and placing the factors used by each methodology at the forefront of the analysis, the following factors were consistently viewed as critical:

- Simplicity of the urban space;
- Functionality and land-use of the urban space;
- Shade and shelter provision;
- Availability of activities and sights to be seen;
- Relaxing atmosphere;
- Sense of safety;
- Presence of sufficient greenery;
- Walkability of the area and its surrounding spaces;
- Bikeability of the area and its surrounding spaces.

While most of the factors are self-explanatory and do not require further investigation, walkability and bikeability are relatively new concepts that are growing contributors to the analysis of public spaces and are commonly found in modern literature works of urban spaces. Walkability is typically defined as the extent to which the built environment supports and encourages the use of walking as a means of transport by inducing pedestrian comfort and safety. Walkability is the possibility to walk through a pedestrian-friendly environment, which is favorable to pedestrians due to its streets, sidewalks and paths being comfortable and interesting [94]. Bikeability on the other hand, is quite a similar concept, but applies to users who choose to utilize the bike. It can be looked at as a measure of how well a space facilitates and accommodates the needs of cyclists. It engulfs essential factors including the availability of bike lanes, independent and shared bike paths, bike racks for parking, and the quality of the overall infrastructure which should promote safe and comfortable day-to-day cycling experiences. A bikeable area is one where it is simple and safe for members of the community to consistently use bicycles for transportation, leisure, and commuting [95].

With the most critical characteristics to optimize urban spaces thoroughly investigated, it becomes possible to select indicators that encompass these factors and reproduce a quantitative figure necessary for sufficient comparisons between the two methodologies of urban space auditing. To portray a clear and comprehensive comparison between different methodologies for public space auditing, a qualitative questionnaire-based survey would only act to provide a surface-level distinction. To investigate an overall comparison between real-videos of the urban spaces and immersive visits of their digital built environments, a quantitative approach would inspire a more holistic statistical analysis of the results. A variety of viable indicators exists within literature that can be used to assess the overall quality and livability of public spaces, Encompassing prime aspects including the use of public transport, the driving experience in the areas, the bicycle level of service etc.

Due to the focus of this experiment being placed primarily on the pedestrian experience in public spaces, and the selected points of view to be analyzed both virtually and in the videos placing participants at a pedestrian level, the indicators utilized must coincide with this and assess the overall pedestrian experience within these areas. Thus, different indicators were chosen for the assessment. The Pedestrian Level of Service (PLOS) was one of the main topics covered during the literature analysis, and presented. It is an extensive number of ways to define and calculate it. To summarize the findings, the pedestrian level of service acts quantifiable measure which is naturally prioritized by raters in the assessment of public spaces and their pedestrian-environment interaction. PLOS in its many forms, can be measured both qualitatively and quantitatively using a multitude of different methods. The indicator is capable of quantifying comfort and safety levels of existing and planned walkways in urban spaces, thus, developing objective and sound evaluations of pedestrian perceptions and responses to walkable environments. PLOS ratings typically produce a number score based on the calculation required of the indicator, and then are converted to a grade score, with being the best result based on method-based conversions. In the following bullet points, the main methods in literature used to estimate PLOS:

- HCM Method: PLOS scores can be determined by considering different flow-related or capacity-related measures. In the HCM method, locations that hasn't a walkway infrastructures but nevertheless were used by pedestrians received an automatic PLOS F value. Pedestrian counts were collected for 3-min volumes, as done in other experiments using HCM and were later converted into 15-min values to use in the HCM method by simple proportionality. With this method, the score can be between 0-23 and

the lower the rating the better. Where 0-5 is equivalent to A, 5-7 is equivalent to B, 7-10 is equivalent to C, 10-15 is equivalent to D and 15-23 is equivalent to E.

- Gainesville PLOS Rating The Gainesville method was developed by Dixon (1996) using a grading point system of 1–21, and evaluates the PLOS of a walkway segment according to the following six categories:
 - Pedestrian facility provided (0–10 points): existence of sidewalks along vehicular lanes (0, 4, and 6 points, for none, one-side, and both-side designs, respectively); sidewalk width (2 points for minimum width of 1.53 m, and 1 point extra for larger design); and off-street/parallel alternative routes (1 point).
 - Conflicts (0–4 points): conflicting with driveways/side streets (1 point); pedestrian signal delay 40 s or less (0.5 point); reduced turn- conflict implementation (0.5 point); crossing width 18.3 m or less (0.5 point); posted speed (0.5 point); and median present (1 point).
 - Amenities (0–2 points): buffer width 1 m or larger (1 point); benches or pedestrian-scale lighting (0.5 point); shade trees (0.5 point).
 - Maintenance (1 to 2 points): major/frequent problems (1 point); minor/- frequent problems (0 points); no problems (2 points).
 - Transportation demand management (TDM)/multimodal(0–1 pts): no support (0 points); support existing, such as a bus stop or connection with intermodal accessibility (1 point).
 - For each sidewalk/walkway location, a total score is obtained by summing the points from each category, and a PLOS rating is assigned through the following conversion: 17-21 is A, 14-17 is B, 11-14 is C, 7-11 is D, 3-7 is E and anything less than 3 is equivalent to an F.
- Trip Quality PLOS rating: The method allows raters to qualitatively rate a walkway from a pedestrian's perspective in regards to pleasantness, safety and comfort using nine measures: Enclosure/definition, complexity of the path network, building articulation, complexity of spaces, transparency, buffer, shade trees, overhangs/awnings/varied roof lines and the physical component/condition. For each of these factors, a score between 1 (very poor) and 5 (excellent) is assessed, afterwards the arithmetic average is taken to obtain a final score on the Pedestrian level of service. The conversions of this method are 4-5 equals A, 3.4-3.9 equals B, 2.8-2.3 equals C, 2.2-2.7 equals D, 1.6-2.1 equals E and 1-1.5 equals F.

All of these methods are capable of producing viable PLOS findings and would be of extreme interest to analyze for the application of this research, though due to the limitation of the prompt of the experiment and the applicability to both a virtual environment and a static video of the real environment. The Trip Quality Method (TQM) was thus chosen. Unfortunately, not all 9 measures analyzed in the TQM PLOS method are relevant to the premise of the experiment, as the experiment is static by nature and thus, does not allow for the sufficient testing of certain factors. As the method has a simplistic arithmetic nature, it is mathematically sound to effectively manipulate the method by extracting the four most relevant characteristics and having our participants rate those on the same scale previously mentioned. Afterwards, calculating their arithmetic average to obtain a required final average score out of 5, which is weighted into a letter grade that is thus considered the Pedestrian Level of Service. Conversion used to obtain final PLOS:

- LOS A = 4.0 to 5.0 = Very Pleasant
- LOS B = 3.4 to 3.9 = Comfortable
- LOS C = 2.8 to 3.3 = Acceptable
- LOS D = 2.2 to 2.7 = Uncomfortable
- LOS E = 1.6 to 2.1 = Unpleasant
- LOS F = 1.1 to 1.5 = Very Unpleasant

The four extracted factors analyzed in the experiment are composed of:

- *Complexity of path network*: The factor emphasizes the importance of the path network being complete and easy to understand for all users. Meaning that while in a static position during the experiment or when viewing the real scenario video, the user is not confused by the path network and does not feel as though it is poorly connected through viewing his surroundings. Thus to quantify this factor in a way that is easily comprehensible for the general participant the questionnaire investigates the simplicity of understanding the configuration of the pedestrian path network in the area.
- *Complexity of spaces*: It is quite similar to the previous factor as it also places emphasis on the importance of completeness and its role in inducing simple comprehension of the functions of the area, but the focus here is on the general public space and not just the path network which has the specific intent of pedestrian mobility. To best assess this factor within the premise of the questionnaire, it investigates the simplicity of understanding the function of the surrounding public spaces in the area.

- *Buffer areas*: Spaces where people can temporarily stop to rest or converse with fellow pedestrians while maintaining a sufficient distance from vehicular traffic and avoiding the interruption of pedestrian flow in sidewalks and public spaces. The buffer zone exemplifies the enhancement of perceived safety and comfort due to its nature in segregating pedestrians from dangerous traffic. Additionally, perceived safety, which goes hand-in-hand with perceived comfort, is proportional to the size of buffer areas, as pedestrians feel safer when they feel further away from traffic. To assess this, all of these elements together in a comprehensive yet simple manner, the question asked was "Rate the availability of buffer areas for pedestrians to wait or converse in the space".
- *Shade and trees*: The presence of shade within the walkway creates an atmosphere of comfort for pedestrians, especially on scorching hot summer days. In addition to immensely protecting users from excessive heat, trees play a pivotal part in adding a green aesthetic to the walkways, thus promoting relaxation and visual pleasantries. This is optimally presented during the questionnaire through the rating about the sufficiency of shade and shelter provided along the area."

The last section of the developed questionnaires studies the feasibility of this method by focusing on the realism of the urban scene and the immersiveness felt by the users during the test. This was done by focusing on specific details of the scene and questioning the realistic feel they evoked within the audience, the following factors of the built environment were front and center:

- Light and Shadows
- Urban details
- Building size and Scale
- The panoramic capability of 360 views
- Wall and roof material

Additionally, to further analyze the realism of the experience, potential sources of error were explored. The presence of shaking within the scene, loss of image and various symptoms of cyber-sickness (such as Nausea, eye strain, headaches, blurred vision and loss of focus) were investigated. The results were then statistically analyzed to understand what improvements could be made to the built environment and the VR experiment as to avoid hindering the reliability of the VR-based public space audit.

5.3 Outcomes

5.3.1 BIM Application on Italian Cycle Route

To foster and investigate the BIM methodology to sustainable mobility projects, it was developed a research where the creation of a cycle infrastructure happened using BIM modelling. In recent years, a national system of tourist cycle routes (SNCT) has been implemented in Italy, a network of cycling routes of tourist interest that extends throughout the nation with variable lengths. The objective of the following case is the project related to the “Realization of the Apulian Aqueduct Tourist Cycle Route (AQP)” [96]. The overall project of the AQP cycle path starts from the sources of the river Sele in Campania that, after crossing the Basilicata near Venosa, enters Apulia in Spinazzola and continues along the Alta Murgia National Park and the Itria Valley, crosses the Salento and ends in Santa Maria di Leuca after a journey of over 500 Km. In this way, the cycle path is transformed from a path to reach places of tourist and cultural interest to the objective of cycling tourism itself. It also becomes an opportunity to network environmental and cultural emergencies together with commercial and hospitality activities in those locations, contributing to the overall growth of the crossed territory. Basically, the project aims to integrate the infrastructures with the environment passed through, develop a network of organic and safe cycles, make constructive choices to reach maximum use and accessibility and achieve complete sustainability in terms of durability, maintenance and life cycle of the works.

The route identified for the project is the Apulian Aqueduct Cycle Route that runs along the hinterland of the province BAT (Barletta-Andria-Trani), for an extension of about 35 km. It focuses on the service road of the main channel of the Apulian aqueduct. The cycle path studied crosses three villages: Spinazzola for an extension of 17.20 km, Minervino delle Murge for an extension of 9.65 km and Andria for an extension of 8.08 km. Most of the route runs along private areas (84% of the total). Mixed sections are limited to municipal roads with reduced traffic (less than 500 vehicles/day) which will be regulated with a speed limit of 30 km/h.

From an operational point of view, the design of a cycle path section involves the modelling of the infrastructures in all its aspects: a study of the route, analysis of interference, modelling of the infrastructure plan and of the longitudinal profile (altimetry), signage design and intersection study. In line with the project guidelines, the cycle project will primarily involve the Apulian aqueduct service track and, secondly, low-traffic roads, converted carriage roads

and newly built sections. The cycle path will have a useful transit width of 3.00 m (1.50 m for each direction of travel) with exceptional and local reductions to 2.50 m at particular point interference, such as manholes or inspection wells or in urban areas where the standard width is not technically feasible or cost-effective.

Consistent with the entire project, the floor will be made of a mixture of loose stabilized limestone adopting a molten grain size to ensure the closure of the mantle and its durability over time. In this way, the hygiene of drinking water transported in the Main Canal, on the service track, will be not compromised. For sections with a slope of more than 3%, mixed soil stabilized with cement will be used to ensure better resistance to surface erosion. In urban or mixed sections on roads with low traffic, the surface will be made of bituminous concrete. The transverse slope will be about 2% to ensure proper water drainage and an adequate coefficient of adhesion. The longitudinal gradients are strongly influenced by the morphology of the land and by the need to maintain the path mainly on the AQP track. Normally, slopes are less than 5%; values of 10% are locally reached for short ramps.

The route of a cycle path is mainly developed in three areas: on the AQP service track, on new paths and on existing low-traffic roads. For each of these situations, a typical section has been defined (Fig. 5.11), and further detailed to consider the multiple situations at the boundary.

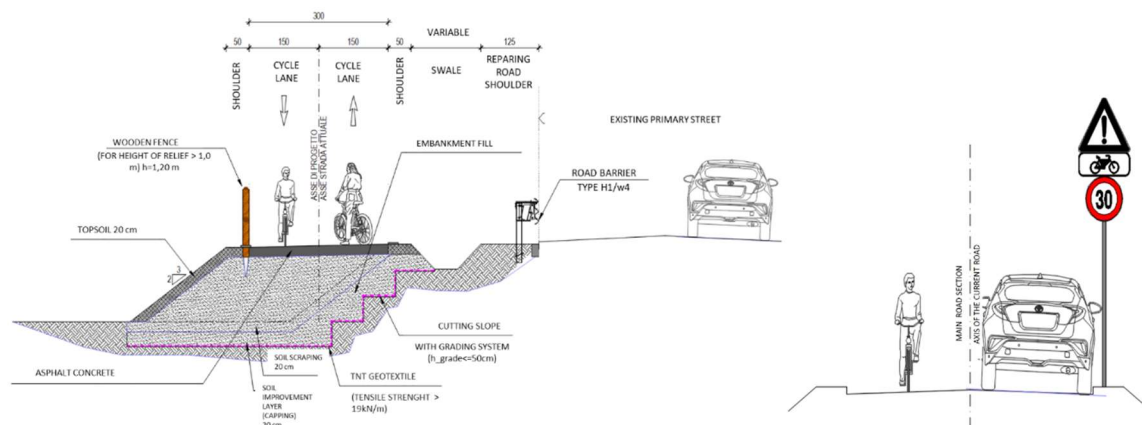


Figure 5-10 Typical section on newly implemented paths alongside existing roads (left) and Typical section for routes mixed with vehicular traffic (right)

Most of the track is located on the current area of the AQP service track, whose sections have heterogeneous bearing capacities. For this reason, two main situations have been distinguished in the design phase: soil with low or good bearing capacity. The first case is typical of sections characterized by silty clay and organic soils, where the service track has the characteristics of a dirt track and turf often invades the track, recognizable by the groove of the vehicle wheels.

In those sections where the longitudinal slope exceeds 3%, the surface layer is replaced by soil stabilized with cement.

The second case is typical of the sections where the service track has kept the original assorted gravel path or is set on rocky (calcareous) soil. The change in altitude of the section matches with the service road of the Main Canal and only locally overlaps the existing carriageways or reduced traffic roads. The average gradients of the sections are usually less than 5%. However, there are steeper ramps locally even more than 10%. The steepest sections are located around the village of Spinazzola. The first kilometer of descent/ascent from Spinazzola towards the Murge and the last 700 m of descent/ascent towards the SP 222 are particularly challenging. In this sense, 7.5% of the planned route does not comply with the requirements of DM n 557/1999 [97] and the Ministerial Directive Protocol 375 of 20 July 2017 [98]. However, since it is an adaptation of existing infrastructures and not new construction, it is considered appropriate to use the analogy with road designs that involve an adaptation of existing locations, whose legislation falls into D.M. n. 2367 of 21 June 2004 [99]. The present project has solved all the intersections of the cycle path with the territorial road network. The solutions were differentiated according to the administrative competence of the road, level of traffic, divided into low and medium/high (TGM over 500 vehicles/day), geometric characteristics (speed limit, width), and road surface of the interfering street. On the basis of these criteria, the following typological interventions have been identified and agreed upon with the operators of the interfering roads. Each of these interventions was developed for the specific situations. Analyzing in detail the most innovative solutions to obtain the maximum protection in the traffic light intersections on the bike path is a sensor system. It can detect the presence of a bicycle or a car, stop traffic and allow access to the main road or its crossing in total safety. The cyclist's priority is guaranteed by the insertion of a short, dedicated lane that allows the cyclist to stop in front of the cars and have a position ahead of the cars when the green is activated, keeping it throughout the crossing. Another innovative design solution N02 has been used in the cases of crossing municipal roads, where bike crossing should be strongly signaled, but a traffic light is not necessary. This is because vehicle flows allow users to find the right time to easily cross the road.

5.3.1.1 BIM Modelling Process

Once the basic elements are found, the engineering design of the tourist cycle route can start. The design is carried out using the "Roads" software released from SIERRASOFT. Firstly, the

bicycle axis has been realized as a basic design element. Consisting of straight and curved lines, the axis has been obtained using a polyline, representing the route the cycle path will follow.

The initial polyline design, equal to 35 km, has been broken into 7 sections to facilitate the modelling of the axis and to differentiate it later according to the specific characteristics of the territory in a certain stretch. This research focuses on the modelling of the third section. Reference elements such as orthophotos or drone surveys are used to obtain the cycling axis with the Roads software. Orthophotos represent a zenithal and georeferenced aerial photograph of a certain zone used for the aero photogrammetric (aerial) restitution of the topographic survey. Compared to traditional topographical surveys, drones allow a survey of a very large area in much less time than the more common procedure. In this case, drone detection is represented by a very large number of triangles, or DTM2 faces, which allow the analysis of the geographical context in which the axis must be modelled, exploiting the information in order to have a faithful 3D reproduction. The digital terrain model extrapolates the level curves, which are essential for calculating volumes.

Having defined the axis of the cycle path from the planimetric point of view, it must also be managed from the elevation point of view. Defining the altimetry of an axis means assigning a reference quota to the graph at the lowest point of the profile and drawing some levels, such as straight segments of different slopes and lengths, reproducing the path of the ground as close as possible. Planimetry and altimetry of the axis are defined, and the generation process is performed. Next, the axis made at first is checked to really resemble the axis that will be modelled. Section by section it must be really in the center line and not encounter any obstacles. The view of the section offers a precise picture of the geographical context, detecting possible earthworks, excavations or surveying, and so on.

Once an axis consistent with all the data collected is established, platforms are defined based on the type sections within the specific modelling environment. Platforms faithfully reproduce the stratigraphy of the ground and represent the roadway, ditches, roadsides, slopes and all those elements necessary for the design. All these features can be parameterized and depend in turn on other elements that, in a sense, represent the geometric key data that, by varying, change all the others related to them. In this project, platforms are multiple according to the division into sections operated at the previous paragraph. Platforms can be differentiated immediately according to the slope of the levels. This difference basically consists of the creation of two types of carriageways:

- Mixed quarry for a slope less than 3%;

- Mixed cement for a slope of more than 3%.

The study of the project sections shows the differences between soil with low and high bearing capacity measured with a specific site test. When the platform is on the ground, in addition to the roadway, there is a sub-base 0.2 m thick. As for the regulations, there is a big difference, both in theoretical and practical terms, in the construction of a bike path on its own headquarter to those made promiscuous.

Separated cycle paths on their own headquarters run parallel to the carriages intended for vehicular traffic and are recognized thanks to physical separations such as curbs or pavements. Cycle paths with optical separation belong to this type: portions of the path indicated only by vertical and horizontal signs, without physical separations and reserved for the transit of bicycles. Cycle paths in promiscuous can be of different types:

- Promiscuous urban cycle–pedestrian path: routes without physical barriers that separate the road intended for vehicular traffic from the cycle path;
- Cycle paths adjacent to the pavement: a rather wide pavement allows two paths, the internal one for pedestrians and the external one for cyclists;
- Cycle–pedestrian routes: usually found in green areas where access to motor vehicles is not allowed, or often also in cycle tourism itineraries.

In the present case of the separate bike path, the analysis of the territory was fundamental to define the platform that more closely reproduced the best type section. In detail, the section will consist of a track width of 1.5 m, with a road pavement thickness of 0.1 m and a foundation thickness of 0.2 m.

Once the insertion of all standard platforms is finished, quantities are calculated for the definition of volumes and amounts of earthwork and ground survey. The calculation of quantities is made by cross-section polylines, each with its own code, and on the basis of the set calculation sequence. Calculating each partial area relative to a given layer, the final area of the layers is calculated as the sum of each single partial area. The line code (which defines the polyline of the reference section for the calculation of the partial area), the processing/characteristic (type of processing that will be performed from the set reference line, depending on whether it is earthwork or survey) the reference code (section code to be compared with the reference line set as “Polyline Code”) and the quantity code (reference code in a certain area calculated by the processing) are inserted within the calculation section. Before proceeding with the modeling of the final project, the last step is to model the signs, both

horizontal and vertical, of the tourist cycle route. Operationally, vertical signage was designed from blocks related to the different signals of the Highway Code (previously created and inserted in the software library). For the horizontal signs, in addition to the insertion of blocks, the function “Smart Polyline” was used to realize, for example, the bicycle crossings. Figure 5.12 shows the realization of the project for Section 3 of the tourist cycle route.

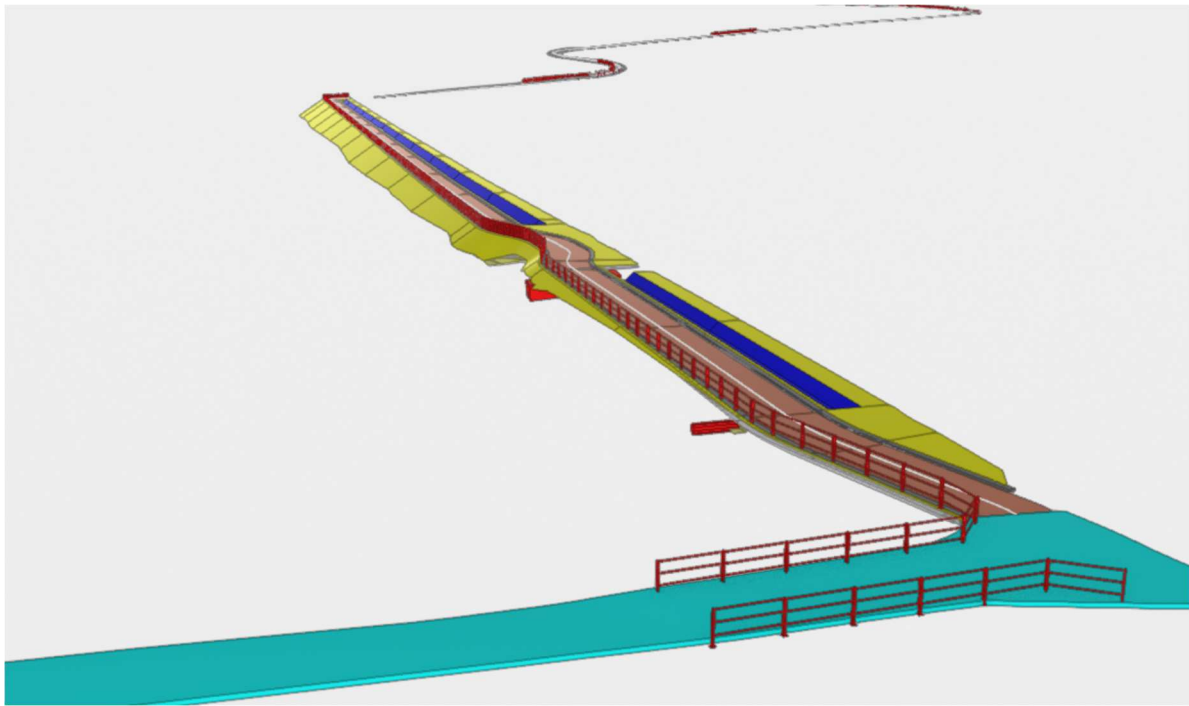


Figure 5-11: Section 3 of the tourist cycle route.

5.3.2 Implementation of Immersive Virtual Environments in 'La Vallee' District

Urban framework planned for the landscape of the La Vallee' district is illustrated in the figure 5.13. The site is exemplary for carrying out pedestrian-based experiments as in its nature is a form of town-planning which is immensely attentive to a pedestrian-city relationship, producing an exemplary living environment in the suburbs of Paris. The map below shows the future district with its overall building footprint, its road network represented with green lines, and the location of various activities including: residential buildings, work offices, education, shopping, leisure, Restaurants and the public transportation stops.

Four urban identities are present within the district: business office districts, an outdoor shopping zone with active surroundings, urban city-like residency near a variety of stores and a green-based surrounding environment producing relaxation and leisure. Thus, the district

represents a real showcase for the city. Beyond being exemplary in its offers of sustainability and housing, the district must offer spaces that evoke a strong enough perception in the audience capable of affirming it as the new city entrance.



Figure 5-12: Location of activities in the LaVallée neighbourhood and the Three Points of View of Interest

As the district is quite large and includes a multitude of areas with diverse land- uses, the experiment could not be carried out on the whole district, as each participant could require up to several hours to analyze the whole district. Thus, specific parts of the district had to be selected for the questionnaire and the over- all experience to be carried out. After analyzing the totality of the constructed area, the 3 scenes were selected because they cover 3 distinct parts of the land mass as each of the scenes is placed in a different portion of the district. Additionally, the scenes considered all have different land uses. One being a public space, another being a shopping street, and the last being a green-based residential space.

The public space was chosen as it constitutes the entry into the district and is the point in which the district is connected to the new tram line of the area. The space contains essential urban footprints such as benches, bike racks and the ability to choose between various modes of transport, as it has plenty of space for pedestrian, cyclists and is surrounded by vehicle-oriented streets and a tram.

The shopping street was chosen as it is the main street in the district. The street stretches all the way from the north of the district to the south of it, connecting to exterior main streets in the process. The street is also the best view point to display the dynamic interaction of residents

and visitors with the area as it constitutes of spaces to walk, bike, shop and sit. Additionally, the street is a connector to the 2 other scenes in the test.

The last scene, the residential space, was chosen due to its completely unique land use in comparison to the other 2 spaces. While the other 2 spaces were more oriented towards visitors of the space, constituting the main street and the entrance to the district; the residential space targets the residents specifically. It is located in an intersection within the district and highly prioritizes greenery and a relaxing aesthetic, giving participants a great outlook on what vegetation in 3D models looks like. These three encompass the points of view that were chosen to be studied through two modalities during the experiment.

This device, available in the University Gustave Eiffel was the HTC VIVE pro 2 virtual reality headset (Fig. 5.14). It had to be accompanied by a high-capacity computer power to display, process and visualize high-detail images with no lag as the headset was tethered to the PCU. Additionally, the headset was equipped with an optimal environmental tracking setting through the positioned cameras and thus captured movement of the user's body and head. It composed by an accelerometer, a video-camera, a gyroscope, an OLED screen with a 110-degree viewing angle and a sublime resolution of 2160x1200 (for its time), along with the aforementioned motion tracking valid within a specified area of 4.5x4.5 meters. Completely immersive 3D spatial sound is also delivered through the integrated headphones pro-actively connected to the Hi-res headset. Lastly, for the visual processing connection required between the PC and the headset, USB and HDMI connection links are presented. Due to the obvious computing capacity required to analyze high-detail pictures, this viewer is linked to external processing units. In addition, there are also two Steam VR Controllers included in the kit, which may be turned into various virtual items within the experiences.



Figure 5-13: HTC Vive Pro Setup and HTC Vive device's components

The experiment took place in a 3x6m office, and was to be carried out from a static seated position (Fig. 5.15). The VR headset was connected to the computer desktop through a USB cable and the headset was connected to the twinmotion. The two scanners were setup accordingly on opposite corners of the room, to try and capture a panoramic view of the whole room, thus, allowing a complete view for the user without a cut-off in specific weak points.

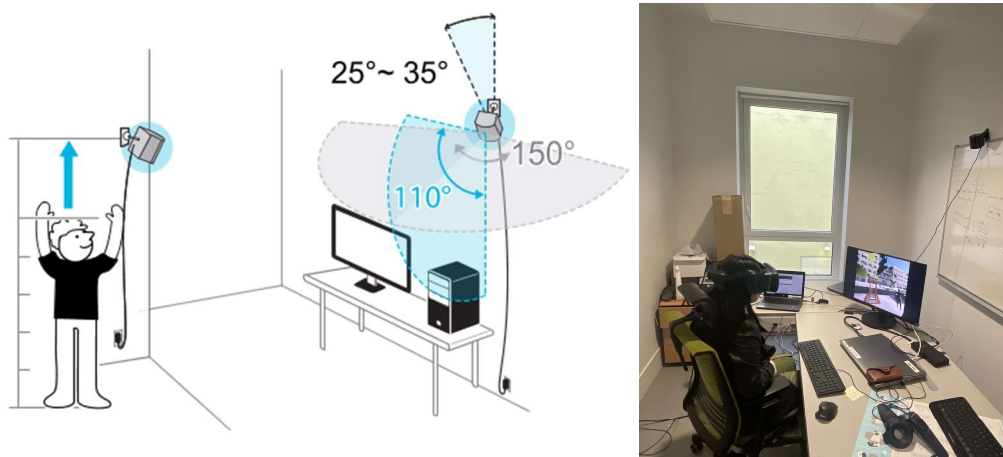


Figure 5-14: Setup Requirement of Camera Scanners(left); Layout of the Experiment with One of the Participant (right)

Once all components of the apparatus were confirmed to be connected and the VR headset was in sync with the TwinMotion file, the experiment was ready to start. The experiment begins following several steps for the 3 different point of view:

1. The participant is brought in, and is seated in the required starting position, the experiment is explained to them and they are asked to read the front page of the questionnaire which summarizes the experience they will be taking part in.
2. After confirming their comprehension of the premise of the experiment, they are required to place the headset on and confirm their visualization of the default headset scene.
3. Once confirmed, they are placed into the first point of view: The public area, and are asked to view the whole scene through panoramic turning from a static position.
4. After viewing the first angle of POV1 for around 1 minute, they are transferred to the others. Once done with the last one, they are asked to remove the headset.
5. After removing the headset, they are asked to complete the set of questions.

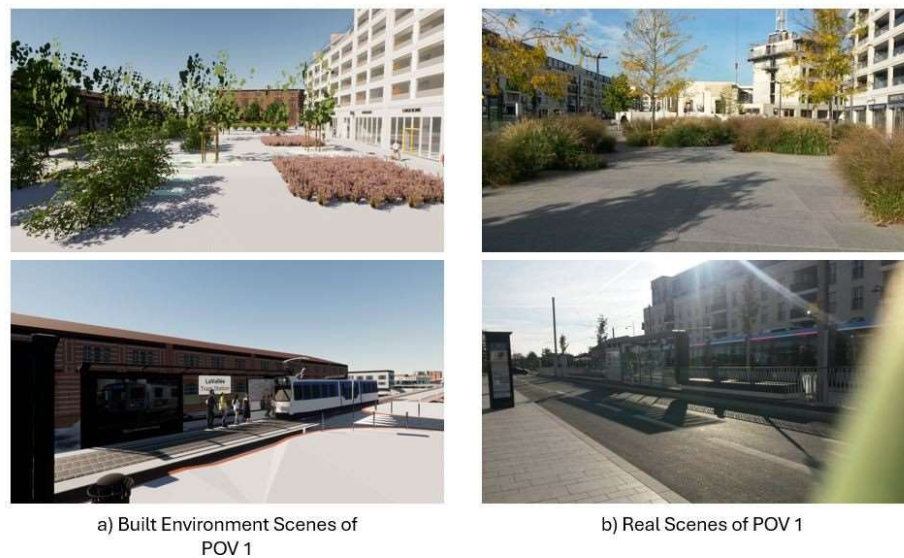


Figure 5-15: The angles of the POV 1 (Public space) in both the immersive experience and the real scenario

This process was repeated for 22 participants. They explored virtual urban landscapes from three distinct viewpoints, providing invaluable insights into the effectiveness of VR in capturing authentic perceptions of public spaces. Combining the survey that comes from literature review with our goals, a meticulous questionnaire, shed light on participant experiences, offering a distinct perspective on the nuanced dynamics of urban environments. The rating of each characteristic in the questionnaire was from 1 to 5. The following question, based mainly on the PLOS method was developed in table 5.1.

Table 5-1: Table one of the Questionnaire

Number	Questions	Rating - Scale
1	How simple is it to understand the pedestrian path in the network area?	1-5
2	How simple is it to understand the function of the surrounding public spaces in the area?	1-5
3	Rate the availability of buffer areas ² for pedestrians to wait or converse in the space:	1-5
4	Rate the sufficiency of shade and shelter provided along the area	1-5
5	Rate the availability of activities to do in the surrounding area:	1-5
6	Rate the availability of things to see in the surrounding area:	1-5
7	Rate the sense of relaxation promoted by the surrounding area:	1-5
8	Rate the sense of safety promoted by the surrounding area:	1-5
9	Rate the sufficiency of pedestrian crossings in the area:	1-5
10	Rate the overall Bikeability ³ of the area:	1-5
11	How likely are people to choose biking as a means of transport in area?	1-5
12	Rate the overall walkability ⁴ of the area:	1-5
13	How likely are you to choose walking as a means of transport in area?	1-5
14	Rate your overall satisfaction with the public spaces available in the area presented:	1-4
15	Rate your overall satisfaction with the green spaces available in the area presented:	1-4
16		
17		

As to emphasize the topics previously discussed related to the realism of the experience, the following questions were developed (Tab. 5.2):

Table 5-2: Questionnaire Section on Realism

Number	Questions	Rating Scale
18	Rate the presence of shaking of the image felt throughout the scene:	1-5
19	Rate the frequency of loss of image that occurred throughout the experience:	1-5
20	How close is the size of the buildings in comparison to the real ones?	1-5
21	How much realism do the urban details give the space?	1-5
24	Overall, how realistic did you find the shown spaces ?	1-5

Additionally, two non-rating-based questions were asked to distinguish which symptoms were most felt and to compare the aspects in terms of their deliverance of realism (nausea, eye strain, headache, blurred vision, loss of focus or none of them).

The PLOS-TQM method accumulates to produce an analysis of user experience relative to the complexity of the path network, the complexity of the place, the presence of buffer area and the shades from trees. The questions from 1 to 4 were asked to participants for each of the POV, in the VR-IV setup and on videos of reality. Afterwards, an arithmetic average of the 4 characteristics was calculated and converted to a letter-grade PLOS. From using this method, the following results are obtained displaying the average result for each of participants both for the VR scenario and for real one (Fig. 5.17).

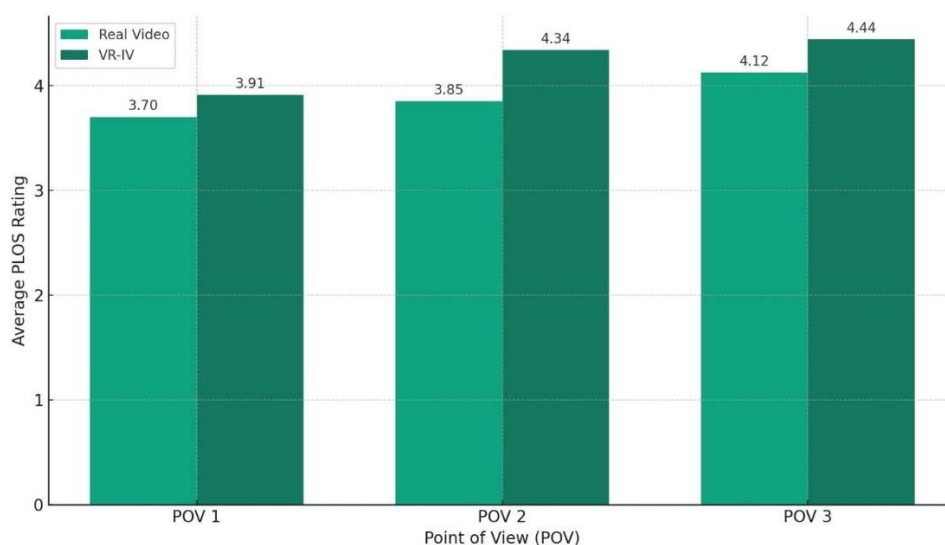


Figure 5-16: Average PLOS Rating for Each POV in both modalities

Despite the consistently higher PLOS ratings observed for immersive VR experience for all three points of view, there is a decently close correspondence with the real video ratings, which

indicates that VR can effectively represent real-world scenarios. The similarity is quite critical in advocating for the use of VR as a reliable tool for public space auditing, insinuating the use of VR can strongly reflect the assessments of real scenarios. This is especially the case in the first and third POVs, even though the immersive visit still garners a greater score in both scenarios, the difference between VR and the real scene is almost insignificant compared to the POV 2, with a 5.5% difference in POV 1 and a 7.37% difference in POV 3.

As both scenes strongly emphasize the necessity of vegetation in public spaces by their diverse greenery, it could suggest that the VR experience is efficiently capable of representing green spaces with appropriate accuracy. The Most Relevant discrepancy for the Points of view is seen in the average PLOS ratings of the second POV: the shopping street. Here, the VR-IV experience induces a significantly higher score with an 12.7% difference displayed. This could imply that specific elements of the shopping street, such as spatial organization or aesthetic appeal, are better captured or appreciated in the VR experience. Moreover, since the area is under progressive development, the area in the videos seemed quite empty, which is typically uncharacteristic of a shopping street like scenario.

Throughout the three points of view, between the 4 characteristics delved into within the indicator, the most significant difference is consistently seen in the buffer areas. As for all three POVs, buffer areas were considered much more sufficient in the VR-IV experience. This discrepancy can once again be attributed to the immersive nature of the VR- IV experience, as spatial recognition and scaling of distances is ironically more realistic in the VR simulation than in the real scenario, as the 3D nature of the VR experience allows you to truly appreciate the distance away from vehicular traffic and the size of the sidewalks (especially since the built environment uses real BIM data-based coordinates and is realistically scaled).

Two of the more important indicators that were not directly analyzed by the modality of the experiment were walkability and bikeability. Thus, to further the scope of the experiment and garner additional insight into the analysis, these indicators will be thoroughly investigated as well. Both of these critical factors were also analyzed within the questionnaire, for both the VR-IV experience and the real videos, thus the average ratings from 1-5 were calculated. To best analyze these results, a box plot was used to display the spread and central tendency of walkability and bikeability scores for the three points of view based on both experiment modalities. They portray a comparison of the variability and median responses between VR and reality assessments in the scores obtained from the questionnaire. Within these box plots the median rating, the interquartile range, and the outliers (individual dots) are on full display.

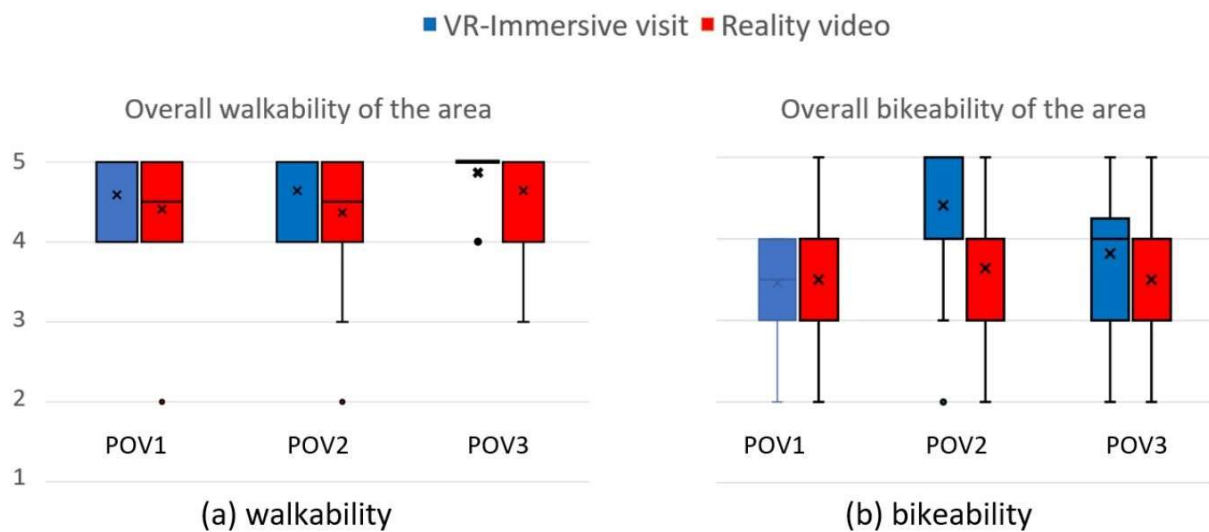


Figure 5-17: Box Plots for walkability and Bikeability

From the box plots, a consistently high median rating for walkability is observed throughout the three POVs for both VR-IV and the videos of reality, which corroborates the data from the tables where averages are around or above 4.3/5. This consistent performance in both modalities suggests that the immersive setup effectively models the necessary elements that produce an environment with immense walkability, some of the critical elements that lead to this participant perception can include clear pedestrian pathways, safety features and distance from vehicular traffic. On the contrary, the third POV shows a slightly higher median and narrower interquartile range in the immersive setup in comparison to the videos, thus, reinforcing the notion garnered from the previous indicators that built environment model may be portraying the necessary pedestrian features even more effectively than the real video, or may be placing emphasis on features that are not as effective in reality. Regardless of this outlier, the consistency of exceptional scores indicates that the VR apparatus is a significant tool in the replication of real-world conditions in the context of walkability.

In terms of the bikeability scores, they are comprehensively lower than walkability both the VR-IV experience and the reality-based videos. This consistent decrease in comparison to walkability in both modalities displays that the VR scores are in fact proportional to those of the real video, which could indicate that the same relative perceptions are being viewed; hence a positive feasibility can be assumed. An interesting point to look into though is the case of POV 2, where the VR-IV score (4.41) peaks significantly higher than the reality video score (3.63). This difference could imply that the built environment emphasizes cycling-friendly features in streets, such as bike lanes or traffic calming measures, which might not be as apparent in the video footage. Unfortunately, the box plots indicate a larger variance in bikeability scores compared to walkability, reflecting a more subjective nature of cycling

infrastructure and safety perceptions. This subjectivity underlines the niche for a more nuanced approach when using VR to assess bikeability, suggesting that there may be room for improvements in how VR displays the biking capacity of an area or that VR might be idealizing the biking conditions and thus could be more suitable in presenting prospective solutions rather than existing environment.

To best assess the use of immersive models as the one present in the study in the long-term for activities such as urban space assessments and stakeholder meeting visual representations, the realism of the model when was significantly emphasized. To exploit the results best, responses scoring 1 and 2 are grouped together to represent an unrealistic interpretation, while responses scoring 4 and 5 are evaluated as a realistic evaluation and 3 is considered a neutral evaluation since all rate-based questions were scored from 1-5.



Figure 5-18 - POV 2: Comparison of the Real scenario vs. the Built Environment

With regards to the scaling of the buildings, the general consensus was that it is quite realistic with 95.5% of the ratings being in the realistic (4-5) range and only 4.5% (1 result) indicating that they found it unrealistic. The outcome of this question indicates that when comparing the buildings in the immersive experience, to those in the real-scene videos, people viewed them to be quite similar in size, thus inducing a sense of realism within the experience. On the other hand, the light and shadows results produce an increase of balance and are not as positively skewed: 45.5% consider them realistic, 45.5% are neutral and 9% consider them unrealistic. Thus, a clear reduction in the perception of realism is found in comparison to the building scale. A potential reason for this is due to the setting set in place for the VR experience, as to reduce the lagging felt in the scene when wearing the device, the graphics visualization of the scene had to be reduced from ultra-definition to medium definition, and one of the factors more prone to the effects of this are the lights and shadows.

In terms of the realism of urban details, they are also considered quite positively skewed. As the majority of participants deemed them realistic (68.2% this time) and not many deemed them unrealistic. Though once again a large chunk of the participant pool (27.3%) deduced a neutral

response. This garners a reasoning which is quite similar to that of the previous questions, as many of the urban details are heavily influenced by the resolution setting set, including vegetation and street furniture, which faced an immense reduction in quality heavily due to the need to allow the CPU to process the frames in time. Out of all the questions related to the premise of realism, this one is arguably the most vital. The question attributes a holistic view on the total experience of navigating spaces through the virtual reality apparatus. Thus, this aids in providing an overall outlook on the realism of the experience and how immersed people felt within their simulated public space audits when analyzing the scenes. The results were overwhelmingly positive with no participant describing the spaces as unrealistic. Only 9.1% of the participants logged in as neutral, illustrating a lack of being swayed to one side or the other as they could possibly have perceived some aspects to be more realistic than others. Reassuringly, a whopping figure of 90.9% of participants perceived the virtual scenes to inspire realism. This immensely portrays that it is possible to reproduce realism using the methods proposed by this study. To best understand which factors can be improved to aid in generating even more realism, a comparison between the different factors displayed in the aforementioned questions can be made. In Fig. 5.21, the ones ranked at 1 are perceived to contribute the most to realism and the ones ranked 5 are perceived to contribute the least, as this question is meant to place these characteristics in an order of realism rather than rate them promoting an internal comparison.

Order the following characteristics according to the realism they give the space: (Rank them from 1-5, 1 being the most realistic)

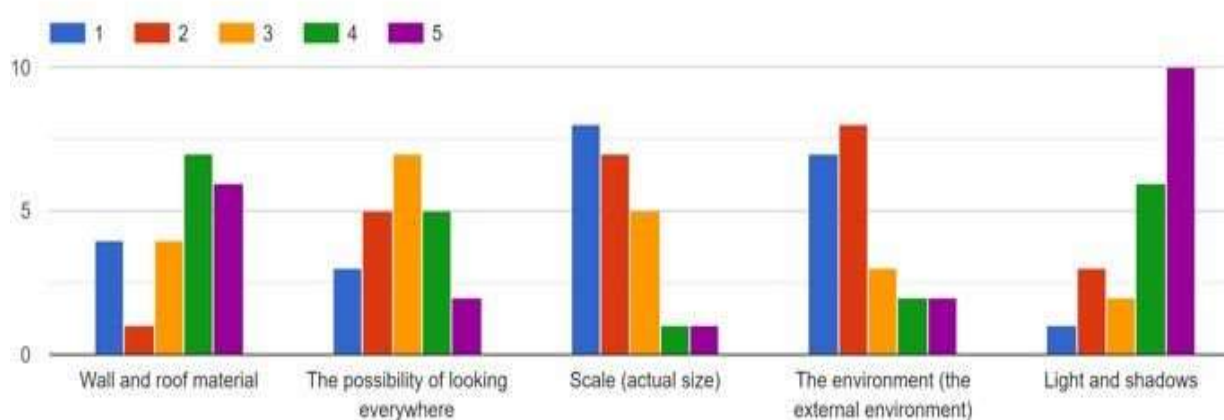


Figure 5-19: Ranking of the Characteristics in Terms of Realism

The characteristics that obtained the most positive results among the bunch are the scaling (actual size) of aspects in the scenario and the external environment (the surroundings, furniture, vegetation, urban details), meaning that participants feel the realism of the immersion

when surrounded by urban details and buildings. On the other hand, as expected, the worst results were achieved by the light and shadows and once again this is directly proportional to the resolution reduction that had to be set. A solution that could be set forth is the utilization of a PC with a higher graphics processing unit for the maintenance of the ultra- quality resolution option and the capacity to process frames fast enough as to not experience major lagging. Therefore, before embarking on the actual experiment with participants, extensive preliminary testing was completed to sort out recurring problems and adverse effects. The outcomes of these preliminary tests indicated several re-occurring issue, such as intermittent image shaking during the tours, brief interruptions due to losses of image, and symptoms including nausea, headaches, eye fatigue, blurred vision, and an overall loss of focus. To further investigate these adversaries, three specific questions were incorporated into the questionnaire. Regarding the occurrence of image loss, the results suggest that this was not a frequent issue, with only a single individual reporting neutrality, while the majority did not experience any image loss. Conversely, the sensation of image instability was noted with greater frequency, with 27.3% of participants noting a feeling of shaking and an additional 27.3% remaining neutral on the matter, indicating its prevalence as a significant concern. Such instability could potentially undermine the immersive experience, as persistent shaking significantly detracts from the realism. The presence of this shaking is indicative of a need for more advanced technology in the software forefront and highlights areas where TwinMotion could enhance its application of STEAMVR. When it comes to the prevalent symptoms felt throughout the experience, typical VR-related symptoms were reported by participants, potentially influencing their perception of realism (Fig. 5.22).

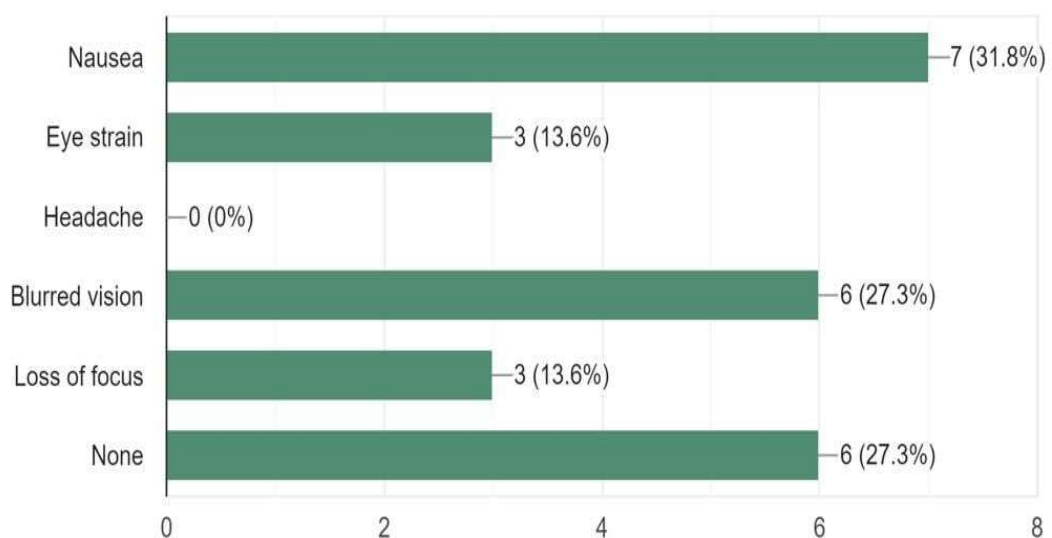


Figure 5-20: Symptoms felt throughout the experience

These symptoms were immense both when glasses were removed during the experiment, as some participants favored the removal of glasses regardless of the headgear's capable accommodation to eye wear, participants noted that vision clarity commonly diminishes when glasses are removed. With some behind the scenes investigation, it was clear that this issue was faced with participants with more severe optical hindrances, and those with acute vision aid requirements were less effected whether or not they wore their glasses. As for Nausea, it can be attributed to the shaking of the images as this is typically when users felt uneasy within the experience.

6. Activity 4: Monitoring of the active mobility in cycle-pedestrian infrastructure

6.1 Introduction

Cycling is a mode of transport which increasing in popularity, particularly in urban areas and in cities where bicycles offer a sustainable and healthy alternative to private cars[100]. This transport mode is recognized as a low-cost, low-emission mode of transport [101] that not only fills gaps in existing transport systems, in last mile transportation as well, but also contributes significantly to public health [102] represented a major shift in the prioritization of cycling within urban transportation systems in Europe.

For the first time, the EU Commission has placed a strong emphasis on cycling and other active modes of transport in a crucial policy document. Local governments, such as in Germany and Italy, have made significant efforts to promote cycling through policy initiatives [103], [104]. However, merely encouraging cycling without enhancing infrastructure poses significant safety risks. However, despite the evident benefits and the issue of cyclist safety is a critical concern in urban transportation planning, particularly as cycling grows in popularity. Cyclist fatalities have fluctuated between 1,800 and 2,100 annually since 2010 . The increment in popularity of cyclability over the past decades, together with insufficient investment in safe cycling infrastructures may partly explain the stagnation in cyclist fatality rates.

Compared to total road fatalities, a smaller proportion of cyclist deaths occurred on road stretches (67% versus 80%), while a higher proportion occurred at junctions (16% versus 9%) [106]. Even the pedestrian crossing records dangerous values of fatalities. In Italy, the fatality index (deaths per 100 accidents) demonstrates higher values especially during twilight hours (between sunset and dawn) compared to the conventionally defined nighttime period (between 22:00 and 06:00). This phenomenon is particularly significant in pedestrian-related accidents, with extra-urban roads showing the most critical conditions during June and September, recording between 10 and 16 fatalities per 100 accidents. In urban areas, pedestrian mortality indices reach their peak during August and September. The data reveals a concerning safety pattern during transitional lighting periods, particularly affecting vulnerable road users such as pedestrians.

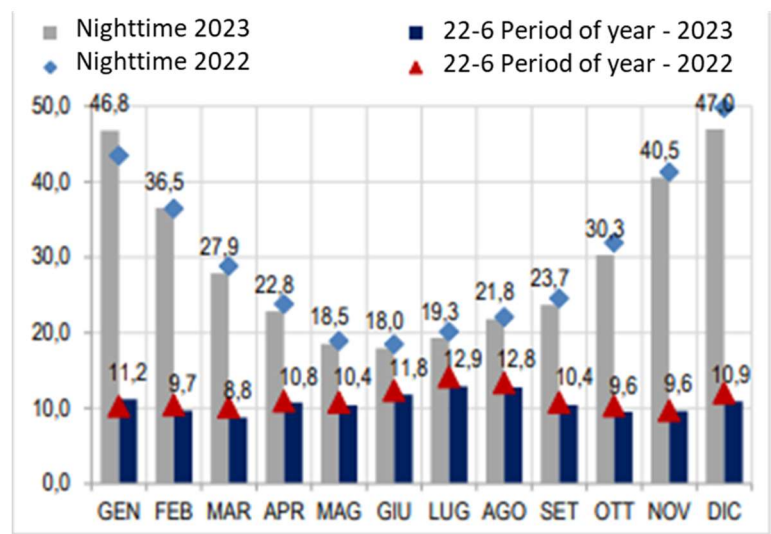


Figure 6-1 Road accidents for the years 2022-2023 analyzed by month and time of day (ACI-ISTAT Report 2023)

These findings suggest that the transition between daylight and darkness presents more significant risks than complete darkness hours, especially in specific seasonal contexts.

This circumstance takes on greater significance when compared with the graph of the number of fatalities by type of user shown in fig. 6.2, from which it can be seen that the pedestrian category is the third largest category in terms of the number of fatalities.

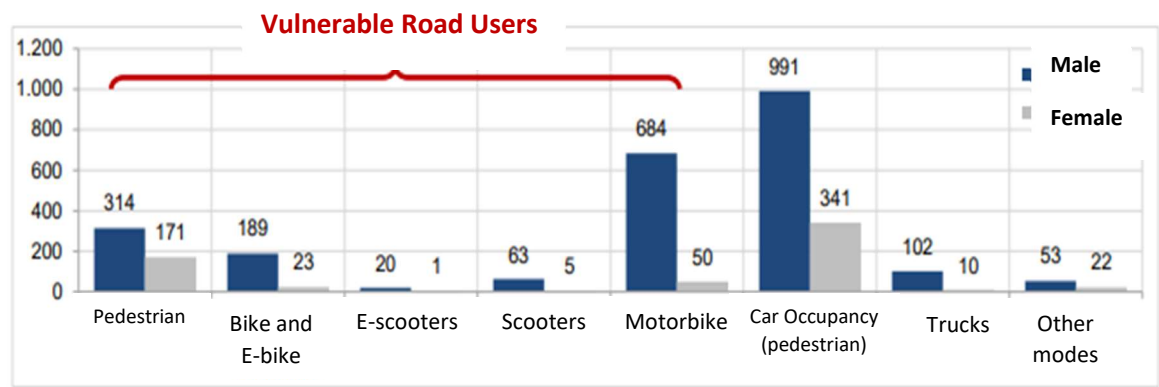


Figure 6-2 - Road Fatalities by Road User Category (ACI-ISTAT Report 2023).

Consequently, in recent years, implementation techniques have evolved towards the research and development of functional elements aimed at enhancing the perceptibility of pedestrian crossings under low-visibility conditions.

6.1.1 Pedestrian Safety in urban environment

Pedestrian safety, especially in urban environments, has gathered significant attention in recent years, with a particular focus on crossing behaviors and the impact of lighting technologies on

nighttime safety. Despite advancements in infrastructure construction and technology, pedestrian safety continues to be a critical challenge in urban planning and traffic management. The data from the Eu project CARE (2022) illustrates a significant disparity in fatality distribution across different road types in the EU27 (Fig. 6.3), with pedestrian deaths predominantly occurring on urban roads (69%) compared to rural roads (24%) and motorways (6%). In contrast, other road users exhibit an inverse pattern, with the majority of fatalities occurring on rural roads (59%), followed by urban roads (31%), and a smaller proportion on motorways (10%).

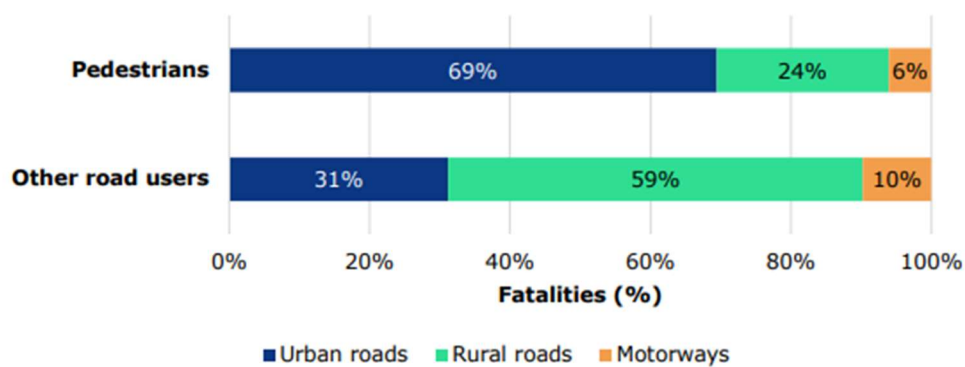


Figure 6-3 – Share of pedestrian fatalities and other road user fatalities by road type in the EU27.
Source: CARE

This stark contrast in fatality patterns emphasizes the particular vulnerability of pedestrians in urban environments, while other road users face greater risks on rural roads. The risk intensified during the winter months, with up to two times more pedestrian deaths occurring compared to the period from March to June. Dark lighting conditions during winter were identified as a contributing factor, reducing pedestrian visibility and leading to more frequent and severe accidents [105].

Italy, too, witnessed a concerning rise in road accidents in 2022, according to a joint report by the National Institute of Statistics and the Italian Automobile Club. The report revealed a 9.9% increase in accident-related deaths, reaching 3,159, and a 9.2% surge in injuries, totaling 223,475 [106]. The examination of pedestrian crossing behaviors, especially during nighttime, reveals a complex web of factors ranging from innovative lighting technologies to social dynamics influencing individual and group decisions. Recent research underscores the effectiveness of technological innovations in mitigating pedestrian safety risks. Integrating advanced technologies and infrastructure modifications presents a comprehensive approach to enhancing pedestrian safety, as evidenced by recent studies. In a study done by Peña-García et al. [107] assessing the impact of public lighting on pedestrian safety and well-being in Granada,

275 pedestrians were surveyed using a five-point scale to correlate their lighting preferences and perceptions with actual illuminance and uniformity measurements across five streets. The findings indicated a general over-illumination compared to recommended levels and revealed that lighting characteristics, including color and brightness, significantly affect pedestrian perceptions of safety and comfort. This research emphasizes the need for carefully designed urban lighting strategies that balance technical specifications with pedestrian preferences to improve urban living conditions [108].

A research done by Fu et al. [109] underscores the success of thermal video sensors in detecting these risks, offering a critical perspective on pedestrian safety and the effectiveness of interventions like LED signage and geometric modifications. These insights present a compelling case for integrating advanced thermal imaging technologies into pedestrian safety strategies, particularly for enhancing nighttime visibility and reducing accident rates. The study's findings highlight a significant increase in pedestrian risk at nighttime at non-signalized crossings, characterized by elevated vehicle speeds and a higher incidence of dangerous conflicts compared to daytime. The research by Czajewski et al. [110] highlights the implementation of automatic detection systems and dynamic signage in Poland, with a particular emphasis on the effectiveness of video detection technology in activating warning signs to substantially reduce accidents. This study underscores the pivotal role of technological innovations in safeguarding pedestrians and enhancing traffic safety strategies. Complementarily, Patella et al.'s (2020) investigation into the impact of LED lighting at pedestrian crossings showcases the considerable benefits of infrastructure modifications. Their findings reveal that LED illuminated crosswalks can decrease vehicle speeds by 19.3% when pedestrians are present, remarkably diminishing the risk of accidents and injuries [111].

The synergy of these studies illustrates the significant potential of combining technological advancements with infrastructural improvements, like in-road LED lighting systems, to create safer pedestrian crossings and promote a holistic approach to traffic safety management. To highlight the importance of psychological elements in road safety education and infrastructure planning, a study exploring the psychological factors influencing pedestrian behavior at crossings, utilized the Theory of Planned Behavior (TPB). The study found that attitudes, subjective norms, and perceived behavioral control significantly predicted intentions to cross roads in risky situations. Specifically, perceived behavioral control was the strongest predictor, suggesting that interventions enhancing pedestrians' sense of control and addressing attitudes towards road crossing safety could effectively promote safer behaviors [112]. Lavalette et al. [113] studies pedestrian accident analysis with a focus on the correlation between urban

planning, behavioral factors, and pedestrian decision-making in crossing environments. Utilizing Ajzen's theory of planned behavior, the research investigates how environmental design influences pedestrian behavior, emphasizing gender and age-related attitude variations. Hamed's study (2001) explores the dynamics between pedestrians and vehicular traffic, focusing on how various factors influence pedestrian crossing behavior and safety. Through observational data and statistical analysis, it uncovers the role of crossing infrastructures, pedestrian group size, and driver behavior influencing pedestrian safety and behavior in pedestrian decision-making at crossings .

Pedestrians' decisions to step down onto the road and cross during the clearance phase are influenced by various factors, including age, engagement in tasks, and social influence. These decisions often result in increased risk due to conflicts with vehicles and the tendency to cross at speeds lower than required for safety [114]. The study by Gorrini et al. [115] critically examines pedestrian crossing behavior in social groups at non-signalized intersections, revealing a structured crossing process divided into approaching, appraising, and crossing phases. A key finding is the emergence of a leader-follower dynamic within dyads, indicating the influence of social interactions on crossing decisions. Despite this, no significant differences were found in the safety gaps accepted by single pedestrians and dyads [116].

Therefore, when building pedestrian crossings, designers are creating furnishing components of the road platform using approaches that take advantage of various operating principles and technology to induce vehicle drivers into acting in a way that will keep pedestrians safe. The simplest and least expensive technique is to create horizontal markings using the principle of perspective in such a way that the optical illusion of raised crossing strips induces the driver of the vehicle to slow down when approaching the crossing itself. However, this method poses two criticalities: a short-term one related to the driver's perception of an obstruction on the road, which may cause them to brake suddenly and endanger other cars; the other long-term one related to the driver's habit of this optical illusion, which lessens their perception of the likely future obstruction. Another form of economic crossing relates to the stripes or, more generally, the photo-luminescent signage. An ongoing project that is being carried out in several countries throughout the world, including Europe, involves using a specific paint that can illuminate even in the absence of light sources or other materials. In this case, the paint is strontium aluminate, which is combined with bitumen to create a bright path, as shown in figure 6.4.



Figure 6-4: Strips with photo-luminescent paint

When this synthetic material is recharged by the sun during the day, it can emit light for ten hours. High visibility pigments are used in the paint, which absorbs and stores solar or automotive headlight light before restoring it at night. This type of system is resistant to moisture, UV radiation, and heavy traffic, such as trucks. Unlike the previous cases, the existing lighting system is replaced by an external one. A single LED strip, as seen in figure 6.5, or light signals are placed at the ends of the pedestrian crossing as part of an LED strip system or smart pedestrian signal technology.



Figure 6-5: a) System with LED strips (left) and b) Smart pedestrian signal (right)

These asphalt-fixed LED lights are directly connected to the pedestrian crossing traffic signal on either side of them, and they change colors with it. Unlike the pre-programmed traffic lights now in operation, the signals use a sensor-based ground system that can indicate when pedestrians are waiting to cross and automatically modify the remaining signal time. Its main objective is to prevent accidents that occur when pedestrians use their cellphones making them distracted and failing to pay attention to the road. Reducing the amount of time that pedestrians must wait to cross the road helps to keep traffic moving in addition to preventing accidents in

the unlikely case that a pedestrian becomes distracted close to an intersection. Another lighting system called "Line of Sight" was designed by the Mettle Studio design team. Its electrical strips use people detecting technology to identify when a pedestrian is about to cross the road. To prevent accidents, the crosswalks' front stripes will light red to alert vehicles that someone is approaching, as seen in Figure 6.8.



Figure 6-6: Crossing with line-of-sight system

High-definition cameras and position sensors are used by the command-and-control unit to detect traffic components, compute direction and speed, and instruct the individual LED elements to turn on. Since it is possible to create a considerable number of messages for both vehicle drivers and pedestrians, the use of LED elements on the entire road platform expands the potential of the pedestrian crossing. Since, as mentioned before, a significant number of accidents occur during nighttime with the pedestrian being the major affected part in these accidents, a search for functional components that enhance pedestrian crossing perception in low light conditions has led to an evolution in construction strategies. Technological research at this time is focused on building pedestrian crossings equipped with lighting systems that draw attention to the pedestrians utilizing the crossing itself from passing vehicles. There are primarily three categories of possible configurations that can be defined:

- A smart pedestrian: is made possible by installing colored lights transversely to the axis of the pedestrian crossing and connecting it to the intersection's traffic light system in such a way that both the pedestrian and the driver have an additional indication of the status of the traffic lights.
- Smart zebra: neutral lights are installed along the pedestrian crossing's longitudinal axis to improve visibility for passing cars.

- APL: installation of a lighting system made up of two poles positioned at either end of the pedestrian crossing so that, through the help of specially designed asymmetrical optics, a beam of light is focused only on the crossing, improving the visibility of pedestrians for passing cars, as seen in figure 6.7.



Figure 6-7: Night configuration of pedestrian crossings: smart zebra (left) and b) night configuration of pedestrian crossings (right)

After reviewing some of the innovations in pedestrian crossing construction, it is important to pay attention to how technology development and the regulatory framework interact. Additionally, specializing businesses must keep up their continuous technical research and experimentation with cutting-edge technologies, while legislators must assess the manufacturing technique's efficacy and, if needed, incorporate it into the overall regulatory framework.

6.1.2 Cyclist Safety in urban environment

Cyclists are often forced to share roads with motor vehicles, which increases the likelihood of accidents [117], particularly in high-traffic areas. Apart from the number of fatalities, sometimes cycling is perceived as unsafe and stressful, largely due to the risks posed by motor vehicles, high traffic speeds, and poorly designed or inadequately maintained cycling infrastructures [118], [119]. These perceptions of danger and discomfort deter potential cyclists, reducing the effectiveness of cycling promotion strategies in urban areas. The consensus is that where cycling is perceived as “safer”, interest in cycling will increase [120]. Research indicates that cyclists, especially women and older individuals, express strong preferences for infrastructure that separates them from motor traffic, emphasizing the importance of creating dedicated cycling lanes to reduce stress, improve safety and enhance equity [121], [122]. Without substantial improvements to cycling infrastructures, increasing the number of cyclists alone will encounter the underlying safety issues.

In addition to the dangers posed by motor traffic, pavement conditions are a significant factor in determining cyclists' safety and comfort. Well-maintained cycle paths and cycle lanes will help promote cycling, as this impacts the safety [123], [124], accessibility and riding comfort [125]. Studies have shown that pavement issues, such as potholes, debris, and uneven surfaces, are key stressors for cyclists, influencing both their perception of safety and their behavior on the road [126]. This suggests that the road surface condition affects the willingness to cycle [127], [128], [129], [130]. Despite being essential for cyclists' comfort, maintenance of these facilities is often inconsistent, and the infrastructure suffers from a lack of proper assessment. Addressing these deficiencies is crucial, particularly as the demand for cycling continues to rise in urban areas.

For instance, quantitative studies using GPS data and surveys have provided valuable insights into cyclists' route preferences, helping to identify the infrastructural characteristics that make routes more attractive [131]. However, these studies often fail to explain the deeper motivations behind cyclists' route choices or how specific infrastructural factors affect their perception of safety. This gap in the literature underscores the need for more qualitative research that explores how cyclists perceive and evaluate existing infrastructures. Understanding these perceptions is essential for creating cycling routes that are not only functionally effective but also perceived as safe by users. To address this gap, there is growing interest in developing tools that combine real-time feedback on both infrastructural and behavioral factors. Such a tool for infrastructural monitoring could be integrated directly into bicycles, providing continuous data on the condition of cycling infrastructures and offering insights into how cyclists respond to various road conditions and traffic interactions [132], [133]. This would allow for a more accurate assessment of the actual safety of cycling sections, as opposed to relying solely on perceived safety. Cyclists encounter various external stimuli while undertake a cycle ride experience (i.e. motor vehicles, pedestrians, potholes, and other potential safety hazards) and mobile eye tracking devices are powerful tools for capturing cyclists' vision during naturalistic cycling experiments. Mobile eye tracking provides insight into which environmental features cyclists focus on while riding.

Cyclists' perceptions of safety and comfort (PSC) significantly impact travel satisfaction and are crucial for evaluating low-stress cycling facilities [134]. Traditional methods of measuring PSC, such as stated preference (SP) and revealed preference (RP) surveys, are prone to biases and limitations in data resolution [135]. For this evaluation, eye tracking offers an objective, high-resolution alternative for assessing cyclists' stress levels in real-time. Eye tracking devices provide data on what cyclists focus on, which can be correlated with biomarkers such as

galvanic skin response and heart rate to measure emotions like stress. Visual cues often trigger emotional responses, and observing how individuals look at objects in their surroundings helps interpret these emotions [136], [137]. Understanding the different types of oculomotor events and their functions is essential for interpreting eye-tracking data. Duchowski (2017) identifies five distinct types of eye movements. Three of these are gaze-orienting movements: saccades (rapid eye movements targeting specific visual stimuli), smooth pursuit (which follows a moving target) and vergence, (detects depth when focusing on distant objects). The remaining two are gaze-stabilizing movements: the vestibulo-ocular reflex (VOR), which stabilizes gaze during head rotation, and optokinetic nystagmus (OKN), which maintains gaze in a moving scene. Other relevant events include fixation, blinking, and pupil dilation. Fixations occur when the eyes are stationary over an object of interest, blinks protect the eyes from external stimuli, and pupil dilation responds to changes in light and emotional stimuli. In cycling behaviour studies, oculomotor events are often used as indicators of cognition, attention, and alertness. According to Duchowski [138], fixation, saccades, and smooth pursuit are the only eye movements that can infer overt visual attention. Fixation-based metrics, such as fixation count and duration, provide insights into cognitive processing and engagement. Variability in fixation metrics correlates with workload, stress, and emotional states [139]. Changes in pupil size reflect arousal levels and intensity of attention [140], while blink duration and eye openness can reveal cognitive load and attention, particularly useful for detecting driver fatigue.

Cyclists travel at intermediate speeds between pedestrians and vehicles, which gives them a wider horizontal field of view than drivers but narrower than pedestrians [141]. Unlike drivers, whose vertical view is limited by a windshield, cyclists have an unrestricted vertical field of view, which is essential for monitoring road quality [142]. Cyclists also share the road with vehicles, requiring heightened attention to traffic and hazards [143], and they must maintain balance, which is supported by vision. As such, research on other road users' visual behaviour cannot be directly applied to cyclists, necessitating a targeted review of eye-tracking applications in cycling studies. Mobile eye tracking in naturalistic cycling experiments is a relatively new method, with the first study conducted in Belgium in 2013 [144]. Over the past decade, more studies have employed diverse samples and research objectives. Selecting and interpreting oculomotor metrics is critical for understanding cyclist behaviour and perception. Due to the complexity of oculomotor events, a variety of metrics have been used in cycling studies. Mahanama et al.[145] provide a comprehensive review of the application of eye movement measures across disciplines such as neuroscience, human-computer interaction, and psychology.

6.2 Objective and Methods

6.2.1 Analysis of innovative pedestrian crossing

Previously, the literature review synthesizes key findings from various studies to better understand the connection between technology, human behavior, and urban environments, enhancing pedestrian safety. The review highlights the critical role of technological advancements and infrastructural improvements, the impact of behavioral factors on pedestrian safety, and the potential of machine learning models in shaping future safety interventions.

Moving forward, it is imperative to continue exploring the connection between technology, urban planning, and pedestrian behaviors to improve urban safety and foster environments where pedestrians can navigate safely. For encouraging this, a new configuration of a pedestrian crossing in Bologna was analyzed. The aim was to understand if the system architecture installed in the case study, makes safer the crossing. The pedestrian crossing chosen for the experimental system is located in Via Andrea Costa, in the Porto-Saragozza. This two-way road conveys the vehicles in the direction of the city avenues, allowing both the flow towards the city center of Bologna and, in the opposite direction, towards the nearest suburb. In its current dual-strip configuration, the pedestrian crossing serves both pedestrians coming from and those heading to the bus stop on the pedestrian safety island as well as those exchanging between the two existing platforms (Figure 6.8).



Figure 6-8 – Urban context of the experimental pedestrian crosswalk (source: Google Maps).

Therefore, three different signaling technologies have been installed on this pedestrian crossing, which is a part of a larger experimental study being carried out by the Metropolitan City and Road Department of Bologna University, on lighting systems to protect pedestrians. Pedestrian crossings are distinguished by the presence of a few signaling systems that are controlled by pedestrian detection sensors or twilight switches, as described below (fig. 6.9).

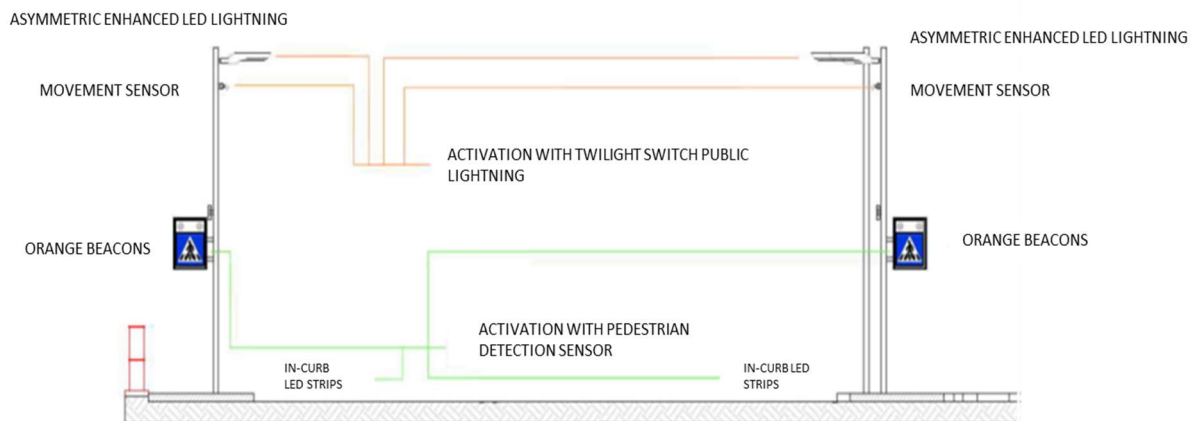


Figure 6-9: Overview of installed systems

The "Look at me" system consists of a flexible LED tube system of the Flexi-led line type, which allows the element to adapt to fit the desired shape and is installed on the two ends of the approach curbs to the pedestrian crossing (Fig. 6.11).

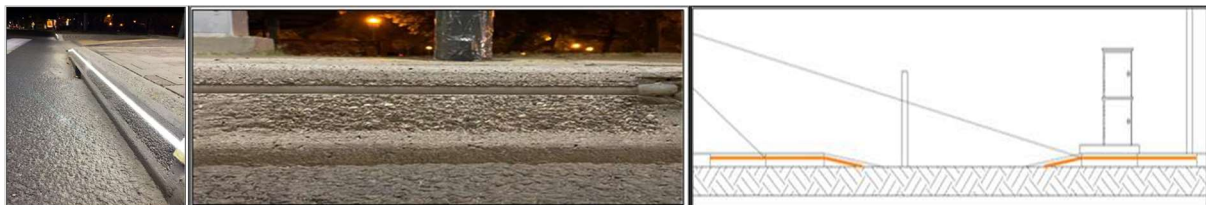


Figure 6-10: View of the activated "Look at me" system (left) particular installation of "look at me" system (centre) and Installation outline of "look at me" system (right)

The "Sicurlux" system uses a highly reflective film that shows the pedestrian crossing symbol on both sides of a backlit panel with LEDs. Two pairs of highly brightness amber flashing LEDs are also set on the same panel.

The Sicurlux system consists of a steel pole that is positioned on both sides of the pedestrian crossing. A die-cast aluminum illumination body with a white light LED system is mounted atop the pole, six meters above the carriageway platform. To enhance the view of the pedestrian and the crossing, asymmetrical optics are focused on the crossing zebra pattern.



Figure 6-11: Sicurlux implant (left) and Sicurlux plant (right)

The video surveillance system consists of two video-cameras with a metal and optical structure, a viewing angle of about 70° that enables you to take color videos even in low light, and a device network switch that connects them to a DVR video recorder. All systems receive their power supply from the existing 220 V single-phase voltage of the public lighting line. Additionally, since the public lighting line is controlled by a twilight switch that activates power only during the night, a 12/24V battery with a corresponding battery charger has been installed. This setup ensures the power supply for the Sicurlux system and associated presence detection systems during periods when the public lighting is inactive.

As a result of the preceding information, the Sicurlux system, in conjunction with presence detectors, operates continuously, while the other systems only operate when the public lighting line is switched on during specific hours. During light conditions, as depicted in Figure 6.14, solely the Sicurlux system remains powered and in standby mode. In the event of detecting a pedestrian, it triggers the activation of the flashing amber LEDs positioned on the top of the backlit panels.

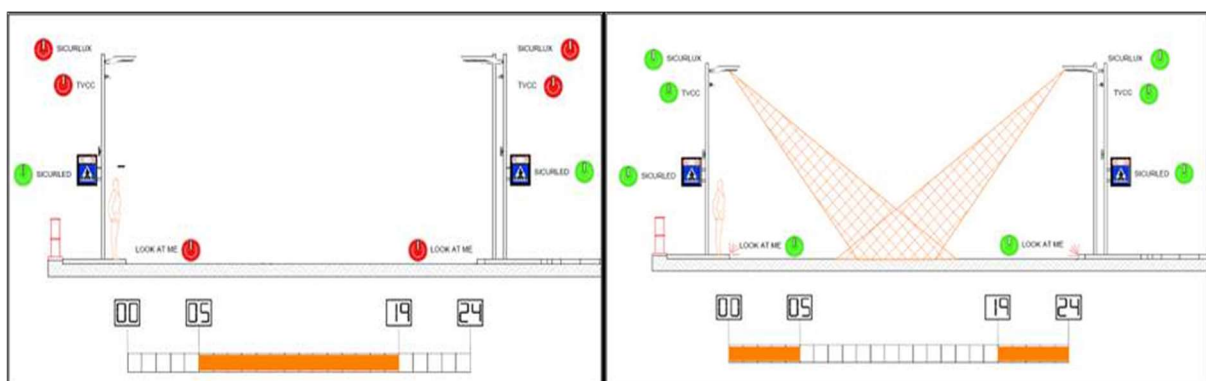


Figure 6-12: Operative System during the day

In low-light conditions, as illustrated in Figure 6.13, all systems are powered, with some in standby mode and others activated, typically between the hours of 18:00 to 6:00. Specifically,

the video surveillance system is activated, concurrently with the activation of the Sicurlux system during the video recording phase. Based on the outlined operating principle, vehicles approaching the pedestrian crossing perceive the crossing itself via the light beam emitted by the Sicurlux system and the illumination from the backlit panels displaying the pedestrian crossing symbol. When pedestrians are utilizing the crossing, vehicles detect the flashing LEDs of both the Sicurled system and the Look at me system in addition to these visual cues. In conclusion, it was set seven different combination of these devices (Table 6-1).

Condition 0 served as the control scenario, incorporating a single conventional streetlight without supplementary experimental illumination components. This baseline illumination remained operational continuously, independent of pedestrian presence, and established the foundational parameters for subsequent experimental configurations. In Condition 1, orange beacons were integrated with the standard street lighting infrastructure. This configuration implemented specialized illumination via LED projectors, activated exclusively through pedestrian detection sensors. Condition 2 augmented the orange beacons system with enhanced LED lighting, incorporating an orange flashing illumination mechanism for the vertical pedestrian crossing signal. Conditions 3 and 4 built upon Condition 1's framework with the addition of in-curb LED strips. Condition 3 utilized Fixed LED strips with constant luminous output, while Condition 4 implemented Flashing LED strips. Conditions 5 and 6 expanded upon Condition 2's design by incorporating Fixed LED strips and Flashing LED strips systems respectively.

Table 6-2 – On-off status of the crossing systems in the seven conditions

Condition	Standard road Lightning	Orange beacons	Enhanced led lightning	In curb led strips fixed	In curb led strips flashing
0	On	Off	Off	Off	Off
1	On	On	Off	Off	Off
2	On	On	On	Off	Off
3	On	On	Off	On	Off
4	On	On	Off	On	Off
5	On	On	On	On	Off
6	On	On	On	Off	On

6.2.1.1 Video Analysis of pedestrian behavior

The DVR video recorder possesses a collective storage capacity capable of retaining approximately 7 days' worth of recording for each camera. Consequently, it was necessary to schedule the data download to occur every four consecutive calendar days. Upon installation of the system, a specialized network was established. Within this network, the cameras situated at

the pedestrian crossing, along with the switch device and the DVR video recorder, were configured. After the video download, the "Smart Player" software, provided by the manufacturer of the video surveillance system, is utilized for data processing and analysis. The video surveillance system receives signals from two cameras. These cameras provide a view of the horizontal zebra stripes of the crossing and the section of the road platform approaching the crossing itself. The captured video is in high resolution, formatted as 1920 x 1080 pixels in color, with a viewing angle of approximately 70°. With regard to Figure 6.14, these cameras captures both sections A and B of the pedestrian crossing, along with the portion of the road platform occupied by vehicles facing the ring roads.

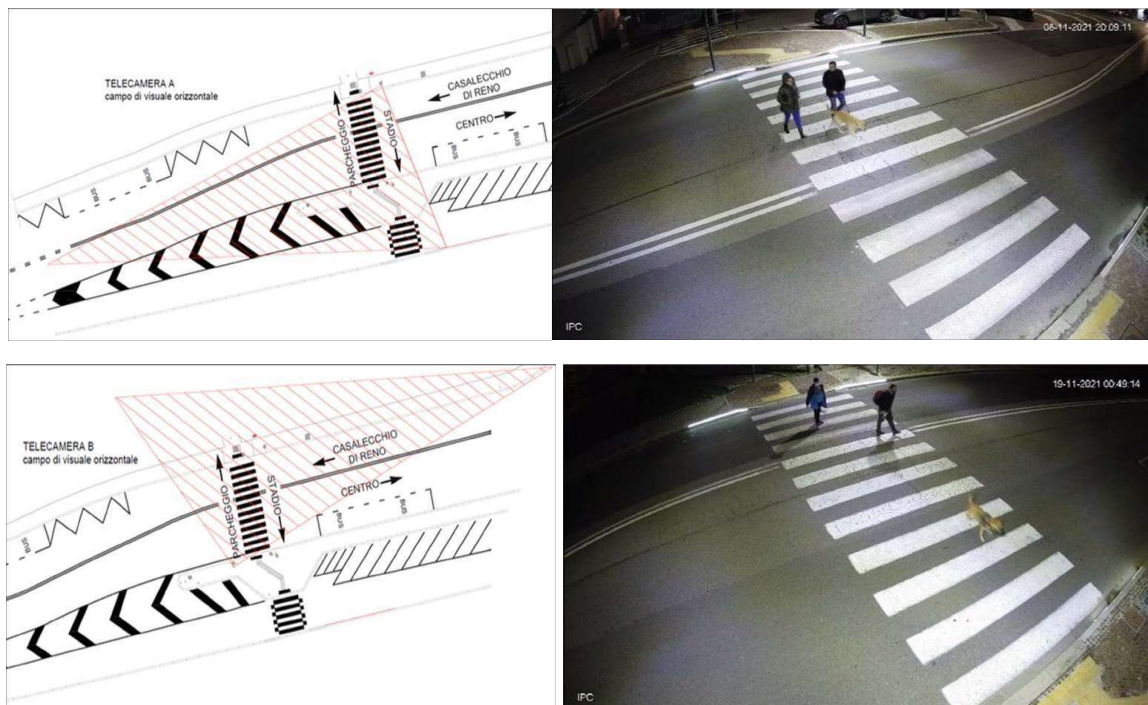


Figure 6-13: Visual planimetry of the roof (left) and frame extracted from the video recording (right) for camera A (top) and B (bottom)

Based on these evaluations, a list of parameters to be assessed was created, included not only the general component, but also the lighting system component, the crossing user component, and the vehicle component. Only the significant crossings for a total of 521 events were considered when performing the video analysis. In detail, the following data was collected:

1. *General Parameters*: Date of the crossing, Time of crossing, Unique progressive number of the list referring to the observation period;
2. *User Parameters*: Direction of crossing in both direction, type of users.
3. *System Parameters*: Failure to activate the system, Correct/incorrect approach of the user to the crossing.

Examining the videos to determine why the innovative lighting system did not perform, it was found that there are two types of reasons why the system does not function properly: incorrect approach of the pedestrian crossing and pedestrian detection sensor put on a lighting pole equipped with the "Sicurlux" technology malfunctions, failing to detect the passage of a pedestrian crossing. Despite encountering these irregular cases, we were able to gather a subset of viable instances that proved useful for our research objectives.

In addition, as part of a collaboration between the University of Bologna and the University of Gustave Eiffel, these videos were analyzed to study the pedestrian crossing pattern. The period of analysis was on the months of October and July of 2021 only, for configuration 5 and configuration 6. In terms of types of pedestrians our focus was placed on individual pedestrians and dyads (a group that consists of two pedestrians together). To identify the differences between the Individuals and dyads, a dataset was compiled by manually reviewing videos and extracting relevant data points for analysis. The data that was collected includes:

- Qualitative data: if the pedestrian anticipates the vehicle passing, If the pedestrian checks traffic or not before crossing, the pedestrian is distracted by technology (using their phone, listening to music, etc.) or in the case of dyads also distracted by conversating between the two pedestrians (turning their heads from the road to the other person), If the pedestrian steps down onto the road while waiting for a gap between vehicles to cross.
- Quantitative data: Timestamp of the start of the video, Timestamp of the pedestrian arriving to the crosswalk, Timestamp of the pedestrian starting to cross, timestamp of the pedestrian finishing crossing.

To further analyze the videos of October, the Intelligent Transport Systems (ITS) research team of CEREMA (Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning), has joined the study for limited time to conduct these works together with our department of Bologna. They were able to extract the trajectories of pedestrians and vehicles using YOLO in both its 7th and 8th versions to get the best detection and tracking [146] YOLO, which stands for "You Only Look Once," is a popular series of deep learning models for object detection tasks. Unlike traditional object detection systems that apply a two-step process, YOLO frames object detection as a single regression problem, directly predicting bounding boxes and class probabilities from full images in one evaluation.

This approach allows YOLO to achieve high speeds and real-time performance, making it highly effective for applications that require fast processing times, such as video surveillance and various real-time monitoring systems. For each video they would use an object detector to get for each object (pedestrian or vehicle) what is called a bounding box which is a rectangular frame that identifies and locates objects within an image, defined by coordinates and dimensions, it marks the position and size of an object, pairing this spatial information with a class label to specify the object's type (e.g., vehicle, pedestrian) and a confidence score that indicates the model's certainty in its detection. They then link all the detected objects together by the tracking algorithm since the detection originally is frame by frame. After this it is transformed into a 2D view appearing like a top view of the crossing giving the trajectories. The crossing area is represented by a line that goes through the center of the crossing, and the distances of the objects would be measured to this line from the centroid of the bounding box.

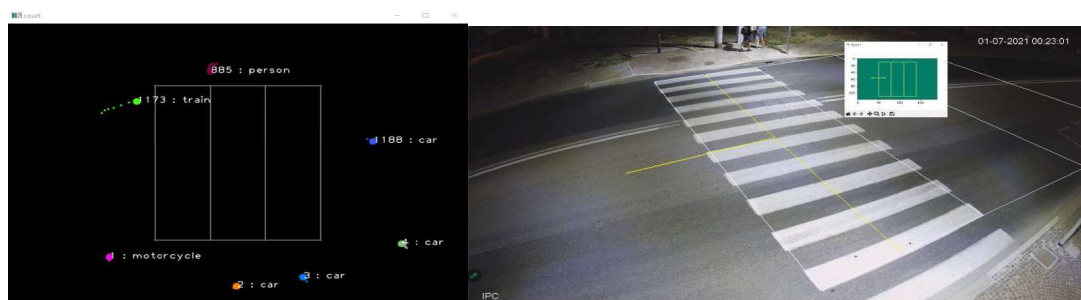


Figure 6-14: 2D view of the items trajectories (left) and Crossing area representation (right)

Computing distances using the middle line as reference could present a lot of error since the indicator want to get uses the intersection point between the trajectories of the pedestrian and the vehicle, which is different for each pedestrian and vehicle and is not constant as the middle line. In addition, due to distortions in the videos, there is an error of around 20 centimeters. The indicator that we obtained from CEREMA is the post-encroachment time (PET) which is a traffic flow measurement used in the field of road safety and traffic engineering to assess the interaction and potential conflict between road users at intersections or other points of potential conflict. PET is defined as the time interval between the moment one vehicle (or pedestrian) has passed a certain point and the moment another vehicle arrives at the same point, assuming their paths intersect or nearly intersect. A shorter PET indicates a higher potential risk of collision, as it implies that the vehicles or road users come into conflict within a smaller time window.

6.2.1.2 Speed Analysis of cars approaching the crossing

The measurements, for a total of 521 events, were extracted from the videos produced by the cameras and used to examine the speeds. The videos are recorded at a frame rate of 15 fps, which corresponds to the frequency of frames per second. Using the formula:

$$t = (1 \text{ second}) / (15 \text{ frames per second}) = 0,06667 \text{ seconds}$$

As a result, each frame is stored every 7 hundredths of a second. The number of frames (n) that a vehicle "takes" to get from point A to point B (Figure 6.15) is then counted, which is equivalent to the fixed distance of 20 meters.

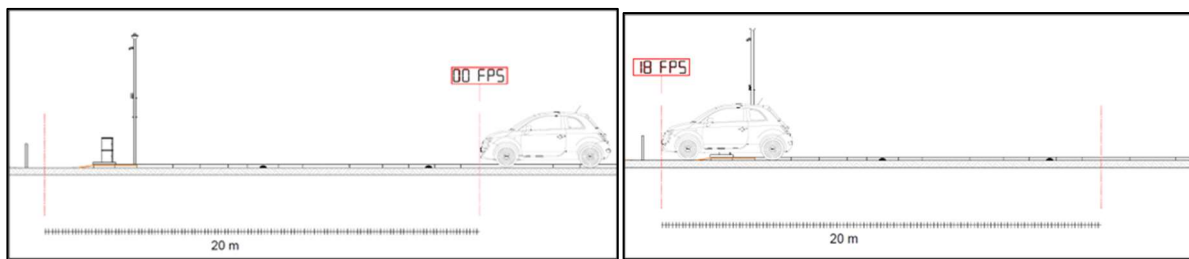


Figure 6-15: Detection technique for speed estimation: Reference section entry area (left), Output area reference section with number of frames counted (right)

The number of frames (n) is calculated using the following formula: $n \cdot t = T$. The time T required for the vehicle to get from point A to point B is calculated. Finally, using the instantaneous speed formula, we can calculate the vehicle speed:

$$v = \frac{d}{t} = \frac{\text{reference section (= 20 meters)}}{n \times i} \quad (E.1)$$

Where “i” is the time interval between frames = 0.0667 sec. For the evaluation of the travel time of the reference route by the vehicles, it was necessary to conduct an approximation process as a difference was detected between the resolution of the installed cameras and the sampling rate of the videos converted to .dav format by the software of the smart player display manufacturer.

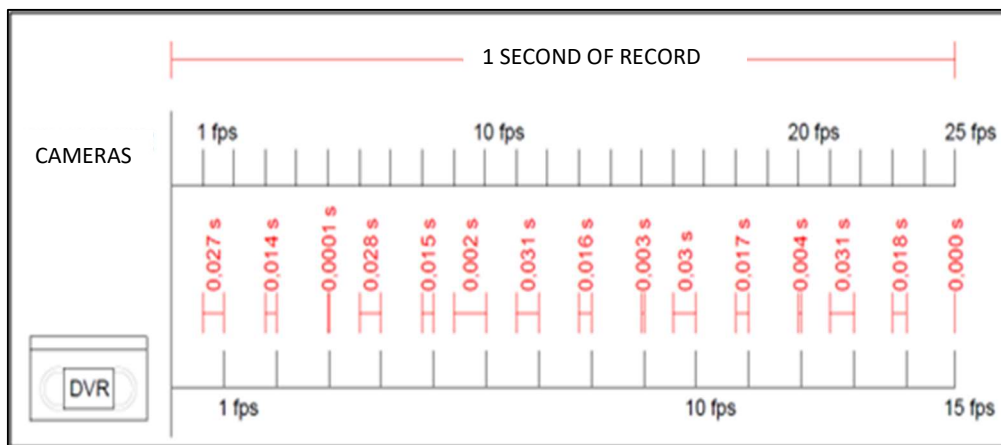


Figure 6-16: Time lag between the different sampling rates of the devices: graphical representation (up) and an example (b).

Specifically, with reference to fig. 6.16 it is observed that the cameras have a sampling rate of 25 frames per second, corresponding to a time interval between each frame equal to 0.04 s, while the movie converted and extrapolated in .dav format by the manufacturer's software has a sampling rate of 15 frames per second, corresponding to a time interval between each frame equal to 0.067 s. These different sampling rates have consequently the creation of a variable time lag between frames according to a sequence that repeats itself with a series of different time intervals contained within a time cycle equal to 1 second. For this reason, it appears that the estimate speed made based on the images extrapolated from the film is characterized by a systematic error due to differences in sampling frequencies and, therefore, it is necessary to conduct assessments of the order of magnitude of that error. Taking as a reference Fig. 6.17, it emerges the inaccurate correspondence between the integers of the frames of the sampling rates of the devices. As a result, during the analysis of the movie, the frame number is detected according to the sample rate of the DVR video recorder, but because the camera has a higher sampling rate than the DVR VCR, it is not possible to pinpoint the exact time interval between the two whole numbers of the frames.

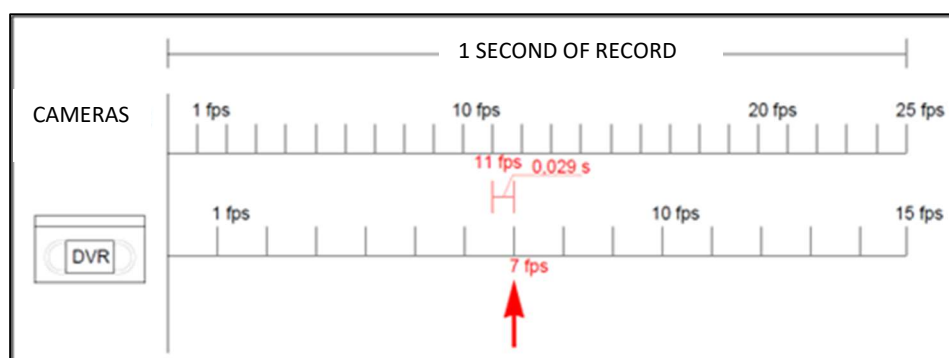


Figure 6-17: Example of error detection between different sampling rates.

Assuming that, it is noted that in the camera frequency scale, the number of full frames closest is equal to 11 fps with the addition of a time interval equal to 0.029 seconds. However, since it is not possible to establish the exact centesimal time interval, it is admitted that the uncertainty about the speed estimate is equal to 0.029 seconds, corresponding to the case in which the vehicle took exactly 11 frames to travel the reference route. Numerically, applying the velocity formula to both sampling frequency scales yields:

$$7 [fps]_{frequency \frac{1}{15}} \times 0,067 [s] = 0,047 [s] \quad (E.2)$$

$$11 [fps]_{frequency \frac{1}{25}} \times 0,04 [s] = 0,044 [s] \quad (E.3)$$

Equations E.2 and E.3 show a time lag of 0.003 seconds, which is equivalent to saying that, due to the uncertainty about the estimation of the centesimal range, it is accepted that the vehicle took a time interval between 0.047 and 0.044 seconds corresponding to the following speeds to travel the reference route:

$$v_{1/15} = \frac{d}{t} = \frac{20 [m]}{0,047 [s]} = 42,86 \frac{[m]}{[s]} = 154,29 \frac{[km]}{[h]} \quad (E.4)$$

$$v_{1/25} = \frac{d}{t} = \frac{20 [m]}{0,044 [s]} = 45,45 \frac{[m]}{[s]} = 163,64 \frac{[km]}{[h]} \quad (E.5)$$

Since equations E.4 and E.5 show a maximum speed difference of 9.35 km/h, corresponding to a percentage error of 5.71 %, the speed difference was calculated for all frames with a sampling rate of 1/15 up to 85 frames per second. The results is represented graphically in Fig. 6.18 both in terms of percentage and numerical values of estimated speed.



Figure 6-18: Graphical representation of the speeds according to the two different sampling rates:

It is observed that the difference between the estimated speeds has a cyclic trend with variable amplitude depending on the number of frames and, specifically, the lower number of frames counted the greater difference between the speeds. In numerical terms, the maximum amplitude

value of difference between the speeds is equal to 9.35 km/h at the counted value equal to 7 frames and gradually decreases to values close to zero at the counted value equal to 85 frames per second. It emerges that due to the difference between the sampling rates an error is made that, regardless of the number of frames counted in the movie, potentially underestimates the real speed of the vehicle by a percentage value between 0 and 5.71 %. Therefore, in order to evaluate the reliability of the analyzes carried out, all the estimated speeds have been counted and divided into categories. The estimated speeds are contained within categories with a margin of error of less than 1.5 %, corresponding to numerical values depending on the speed not exceeding 2.00 km/h, while there is only one category, corresponding to the range 100÷110 km/h, with a margin of error of just over 4 %, corresponding to a numerical value of 4.50 km/h.

In the last phase, the methods involve the calculation of the stopping distance in emergency conditions. It can be assessed taking into account three main contribution:

1. Phase of perception, decision and reaction: the vehicle maintains its initial speed v_i unchanged along a space equal to:

$$x_r = v_i * t_r \quad (E.6)$$

Where: v_i = the initial speed and t_r = the reaction time

2. Transient braking phase: the vehicle reduces its speed with variable deceleration until the stabilized braking force is reached, covering a space equal to:

$$x_a = v_i * t_a + \frac{1}{2} * k * -d_f * g * t_a^2 = v_i * t_a + \frac{1}{2} * a_a * t_a^2 \quad (E.7)$$

Where:

- v_i is the initial speed
- t_a is the transient time function of the type of braking system
- a_a is the negative acceleration of braking in the transient phase

3. Stabilized braking phase: the vehicle has reached the stabilized braking force and reduces its speed by reducing its speed with constant negative acceleration, covering a space equal to:

$$x_s = \frac{v_s^2}{2 * d_f * g} \quad (E.8)$$

Where:

- v_s is the speed reached by the vehicle at the end of the transitional phase
- d_f is the braking coefficient of 0.8
- g is the acceleration of gravity

From the sum of following terms, a vehicle with an initial driving speed of v_i stops, following an emergency braking event, has a total breaking distance of:

$$x = v_i * t_r + \left(v_i * t_a - \frac{k * d_f * g * t_a^2}{2} \right) + \frac{(v_i - k * d_f * g * t_a)^2}{2 * d_f * g} \quad (E.9)$$

in the time corresponding to:

$$t = t_r + t_a * (1 - k) + \frac{v_i}{d_f * g} \quad (E.10)$$

Fig. 6.19 shows the stopping distances in emergency conditions together with the total time used to stop the gear obtained by inserting different speed values into the equations E.9 and E.10.

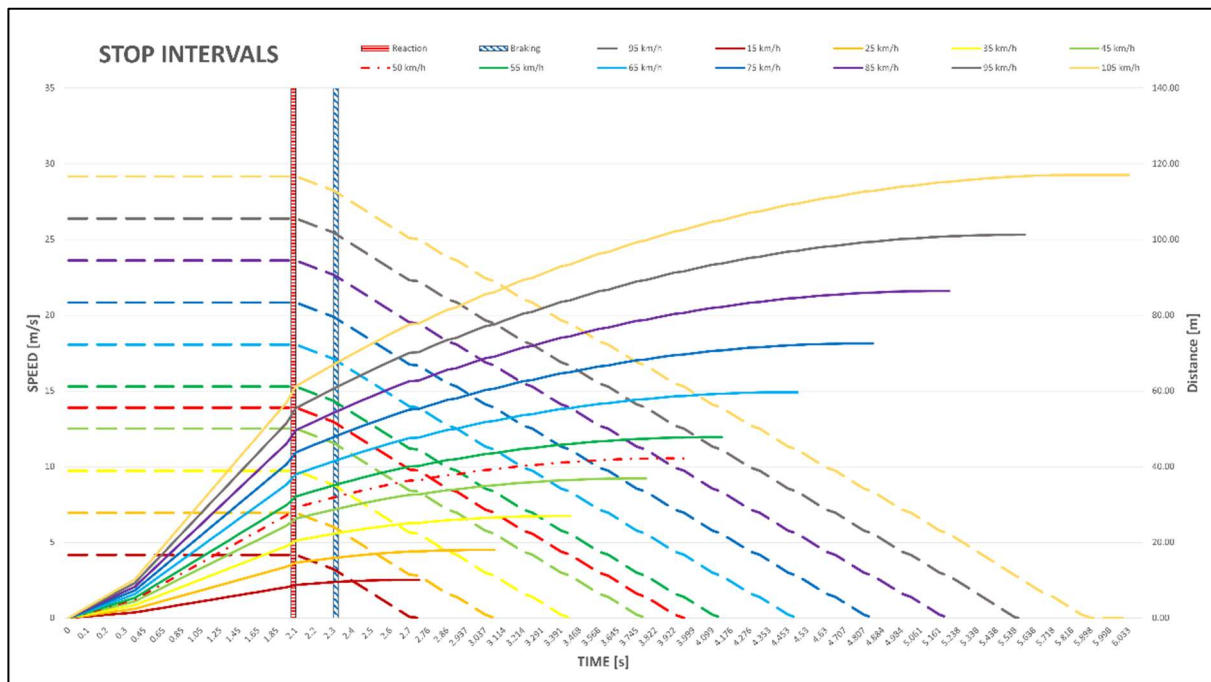


Figure 6-19: Stop distance diagram for different speeds.

It is apparent from the observation of that figure that a vehicle which is travelling at a speed of 50 km/h, corresponding to the speed limit for that section of road, needs a distance of 42.72 m in order to stop its journey under emergency braking conditions. The D.M. 6792/2001 [147], used for the design of newly built roads, prescribes that the safety distance for stopping is satisfied on the entire route; in the case under study this value is equal to 54.47 m and is satisfied for both lanes. Comparing the values obtained according to Ministerial Decree 6792/2001 with those obtained from dynamic evaluations on vehicles in emergency braking conditions, we find a greater distance available for braking equal to 11.75 m, corresponding to 21.57% more than the distance calculated according to ministerial regulations.

6.2.2 Evaluation of Cycle Infrastructure

To establish the safety of the cycle infrastructures from the human and infrastructural point of view, different sensors and devices were used to instrument a bicycle in order to collect exact data about bicycle dynamics, gaze fixations, speed, as well as information that allows to study the behavior of the cyclists, their reaction to the different cycle section during their journey and their interaction with other road users such as: pedestrians, vehicles and other cyclists. This paragraph would explain the methodology used to assess the inner safety of different typology of cycle path. The bicycle instrumentation and processing of the output signals were explained.

6.2.2.1 Alma Instrumented Bike

The study has selected the "Alma" bicycle from the University of Bologna for its flexibility and suitability for urban commuting. As part of the AlmaBike project [148], these bicycles are custom-designed for students and promote cycling within university campuses. The Alma bike features a unisex "city bike" design with a sporty look, making it adaptable to various riding conditions. It prioritizes reliability, practicality, ease of maintenance, durability, and lightweight construction. With 28-inch wheels made from durable materials, the bike weighs only 14 kg, ensuring easy handling without sacrificing durability. The "Alma" bicycle is chosen to be equipped with sensors, enhancing its utility for research purposes. A schematic of the instrumented bicycle is included in Figure 6.20.



Figure 6-20: Alma Instrumented Bike with all the applied sensors

The tools are composed by 4 individual sensors. These sensors were chosen based on the type of data they measured, and the researchers' interests. A list of sensors, general functions, and data acquisition gateway (DAG) with software to collect data are provided in Table 6.3.

Table 6-3. Alma bicycle sensors array

Sensor Name	Component (s)	Function	Picture	DAG & Application
A) Garmin EDGE® 130 PLUS	- GPS - Speed - Distance/Time - Route Mapping	To provide GPS navigation, performance tracking, and connectivity with other sensors		Garmin Connect app
B2) Garmin Speed Sensor	- Speed Sensor - Batteries - Magnet - Mounting Hardware	To measure the longitudinal speed and distance of bicycle		Garmin Connect app
B1) Garmin Cadence Sensor	- Speed Sensor - Batteries - Magnet - Mounting Hardware	To measure the cadence of pedaling		Garmin Connect app
C) Avisaro 4.0 Data Logger	- IMU - WLAN - Data Logger - External Power Source	To measure the motion bicycle tracking including 3 axis acceleration / 3 axis gyro, and to provide GPS		- PC Avisaro Companion Software - USB Memory Stick

The Edge 130 Plus device from Garmin is a feature-packed cycling computer designed to enhance the cycling experience. Equipped with different systems, it offers real-time position detection, ensuring accurate navigation in different environments. Furthermore, it integrates a barometric altimeter to measure altitude which is essential for tracking elevation changes during participants' ride. Thanks to its accelerometer, the device measures dynamic movement data. Furthermore, its internal memory facilitates integration with other Garmin devices, such as speed and cadence sensors, enabling data logging and analysis. Data acquisition takes place within the device itself. The Edge 130 Plus device offered easy accessibility since it is mounted on the handlebar. The Edge 130 Plus device from Garmin is integrated with the Garmin Connect application. The Garmin Connect application is a powerful companion that synchronizes the participants' data ride with the smartphone or computer.

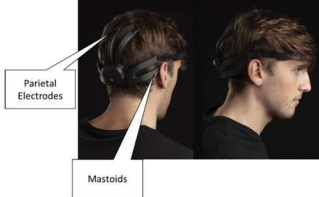
The Speed Sensor from Garmin offers a wireless solution for tracking longitudinal velocity and distance without the need for magnets or exposed parts. This sensor, mounted on the hub of the rear wheel, provided continuous and accurate data throughout the experimental ride. One of its key features is self-calibration, achieved via Bluetooth connectivity with the Edge 130 Plus device. This ensured optimal accuracy and reliability in speed and distance measurements. The data were synchronized through Garmin connect application. The Cadence Sensor from Garmin is designed to accurately measure pedal strokes per minute (cadence) during the real road experiments. This sensor provides real-time cadence data without the need for additional magnets or exposed parts. It was fastened to the left-side crank arm. One of its key features is self-calibration, achieved via Bluetooth connectivity with the Edge 130 Plus device. The cadence data were synchronized through Garmin connect application.

Avisaro 4.0 Data Logger served as the primary data logging solution for the experiment. It is equipped with a 6 Degrees of Freedom (6 DOF) Inertial Measurement Unit (IMU) unit comprising 3-axis acceleration and 3-axis gyro sensors, along with a built-in GPS Satellite Receiver. Moreover, it includes a slot for USB memory to collect and stores data. This sensor was positioned on the rear seat of the bicycle to measure the accelerations of the rear part of the bicycle. The IMU sampling rate was configured to 100 Hz, ensuring high-frequency data acquisition. The measurement range for the accelerometer and gyroscope were set to $\pm 2g$ and 250 DPS respectively, enabling accurate measurement of acceleration and rotational speed. Furthermore, the GPS receiver, integrated within the data logger, eliminates the need for an external antenna. It possesses a position accuracy of 2.5 meters in circular error probability (CEP) and operates at a sampling rate of 1 Hz. This provide reliable location data (add reference). Power is supplied to this sensor by using the same K2 power bank from PowerOak.

6.2.2.2 Cyclist Behavior Assessment

For assessing the behavior of the cyclist, two devices has been wearing by the users. It was decided to track the user experience of the participant, studying their fixation and workload during the ride (Tab 6.4).

Table 6-4: Device for investigating the cyclist behaviour

Sensor Name	Component	Function	Picture	• DAG & Application
Tobii Pro-Glasses 3 Mobile Eye-Tracker	• Eye Tacking • Scene Camera • Four eye Cameras • Battery	To measure and analyze gaze behavior		• Tobii Pro Lab • SD card
Mindtooth EEG System	• EEG analysis • Stress, Workload and Vigilance metrics	To measure the workload level in real time, in order to evaluate the user's experience		• Mindtooth Software

The Tobii Pro Glasses 3 is an eye tracking equipment, capable of continuously detecting the driver's gaze while driving (Fig. 6.21). The eye tracking system is integrated with glasses, so as to be easily wearable and discreet, with a minimal design, so as to go almost unnoticed in research contexts in a naturalistic environment.



Figure 6-21 – Tobii Mobil Eye Tracker

The data is monitored via software application and recorded on SD-card. The sampling of the signal must reach up to 50Hz. Wireless data transmission occurs via WiFi protocol, to avoid interference with the EEG system. In output, you have a pointer in the direction where the participant is looking. Visual attention to advertising signs was assessed by eye movement recording. Eye movements are highly correlated with the path of visual attention and therefore the probability to attract fixations could be an indirect measure of a roadside advertisement salience. Several studies have found that horizontal eye movements are dominant over vertical movements and that when the driver is not looking straight ahead the eyes non looking at the focus of expansion so can transmit driving-relevant information, as seen in the introduction.

The Mindtooth EEG system is equipment that allowed us to analyze the Human Factor using EEG technology (Fig. 6.22). The Mindtooth system, by analyzing users' brain activity, is able to measure the workload level in real time, in order to evaluate the user's progress, from a cognitive point of view, in learning to drive. Furthermore, Mindtooth itself is able to measure levels of attention and vigilance, to detect any moments in which this falls below a certain safety level, and in this case to send instant messages on the simulator screen to recall the user attention. Thanks to this new device the future towards greater road safety and intelligent driving systems. The mindtooth system providing real time indicators of cognitive or emotional states by processing cerebral signals, providing affordable cross-application indicators based on scientifically proven algorithms, using a wearable, comfortable and easy device to fit EEG headset, equipped with gel-free sensors.

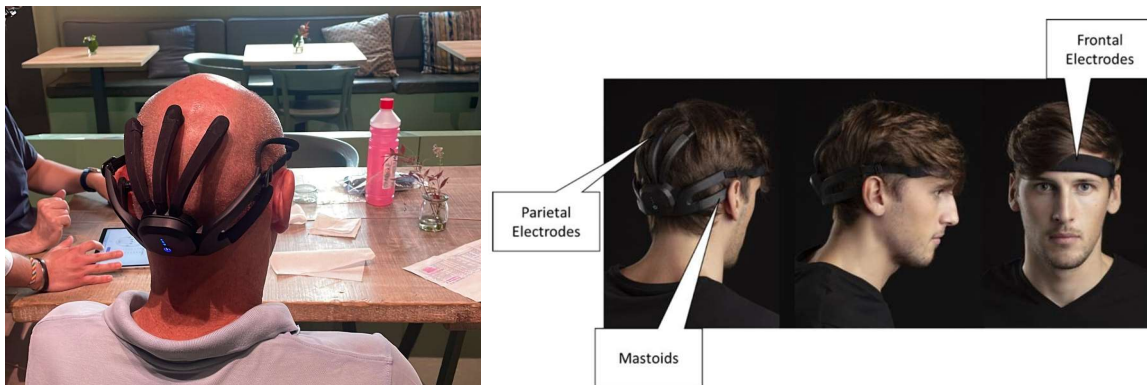


Figure 6-22– Mindtooth EEG System (right) and its calibration during the study (left)

The electroencephalographic headset is equipment for measuring the driver's neural activity. The electroencephalogram (EEG) is a diagnostic test which, through some electrodes positioned on the skin scalp, measures brain electrical activity, reproducing it on a screen in the form of a series of waves. The technique consists in measuring the extracellular current flow generated by the sum of the activities by high number of neurons. EEG can exploit the propagation of these voltage signals to measure Electrical potentials as a method of approximating brain activity: Comfort, ergonomics and ease of use depend on the type of EEG sensors and system design.

In the EEG system there are sensors with electrodes passive and removable sponge sensors, so they can be immersed separately in the relevant solution saline. Depending on the system design, the sensors are integrated into a structure (“headset”), easily wearable independently by the participant, and covers the anterior-frontal and parietal positions of the scalp. The EEG amplifier has integrated batteries and can be separated from the headset to be recharged separately. The amplifier has a resolution of 24 bits and signal sampling up to 250Hz. Data

transfer in wireless mode it occurs via Bluetooth. The data collected by the EEG sensors is transmitted to a device that processes it in real time. Mindtooth software analyses EEG signals using advanced artificial intelligence and machine learning algorithms. The analysis makes it possible to extract useful information regarding the user's mental and physiological state, such as attention levels, stress, fatigue and other cognitive and emotional conditions.

6.3 Outcomes

6.3.1 Analysis of the innovative lightning crossing

6.3.1.1 Research on Pedestrian Crossing Pattern

Data were carefully gathered on a total of 166 pedestrians for both months October and July consisting of individual and dyads. These months were selected for testing the configuration 5 and 6. Specifically, 104 pedestrians were observed as individuals, navigating their crossing solo, while the remaining 62 were observed in dyads, showcasing a different dynamic in terms of movement and interaction with their surroundings. The data collection was conducted over two distinct periods: July and October, to capture any potential variations in pedestrian behavior that could be attributed to seasonal changes, or changes in the innovative lighting system. In July, a total of 53 pedestrians were observed, of which 32 were individuals and 21 were dyads. This part of the data provided initial insights into the summer pedestrian patterns, where individual movement might be more common due to the vacation season, and dyads movements could represent a variety of social interactions, from tourism to local leisure activities. The data collection for October involved a larger sample of 113 pedestrians, with 72 observed as individuals and 41 as dyads. The increase in dyads observations compared to July could indicate a change in social behavior patterns, potentially influenced by the season's change, the restart of academic and professional routines, etc. This approach provides a comprehensive dataset that is capable of supporting detailed analyses on pedestrian behavior, offering insights into how people navigate crossing areas both as individuals and in dyads, across different seasons, taking into account seasonal shifts that may influence pedestrian dynamics. In this study on pedestrian crossing, the duration between the moment a pedestrian arrives at the sidewalk and the moment they begin crossing, was evaluated. This parameter, defined as the waiting time, was crucial for distinguishing between pedestrians who immediately proceed to cross and those who deliberate before making a move. To make this distinction, a threshold of 2 seconds was established. Pedestrians who embarked on crossing within 2 seconds of arrival were considered

as not waiting, the rising that this short period was spent assessing traffic conditions or accounted for by the pedestrian's reaction time to their surroundings. The reason behind selecting the 2 second threshold comes from psychological studies suggesting that the average human reaction time to visual information is approximately 1.5 seconds [149]. This threshold allows us to assume that any duration beyond this reaction time indicates a conscious decision to wait, possibly due to perceived traffic risks or the need for a safer gap in the flow of vehicles. This methodological decision aids in categorizing pedestrian behavior more accurately, offering insights into their risk assessment and decision-making processes at crossings. For the month of July, from the video recordings of 53 pedestrians, only 31 chose to wait before crossing. As shown in figure 6.23, this group consisted of 16 individuals with mean waiting time of 5.75 seconds and 15 dyads with mean waiting time of 3.7 seconds. While for the month of October, it was recorded 53 pedestrians who waited before crossing, 32 of them were individual pedestrians with mean waiting time of 3.46 seconds and 21 were dyads with mean waiting time of 3.52 seconds. The mean waiting time for individuals in July is longer than the mean waiting time for dyads. On the other hand, the mean waiting times in October are more closely spaced, this shows that there is less differences in the waiting behaviors of individuals and dyads in October as opposed to July. When comparing July and October, there is a noticeable decrease in waiting time for individuals from 5.75 seconds to 3.46 seconds. This suggests an improvement in the efficiency of the crossing or a change in pedestrian behavior over time. For dyads, the mean waiting time also decreases but only slightly from 3.7 seconds to 3.52 seconds. The relatively stable waiting time for dyads might indicate that their crossing behavior is less affected by the factors that influenced the change in individuals' waiting time.

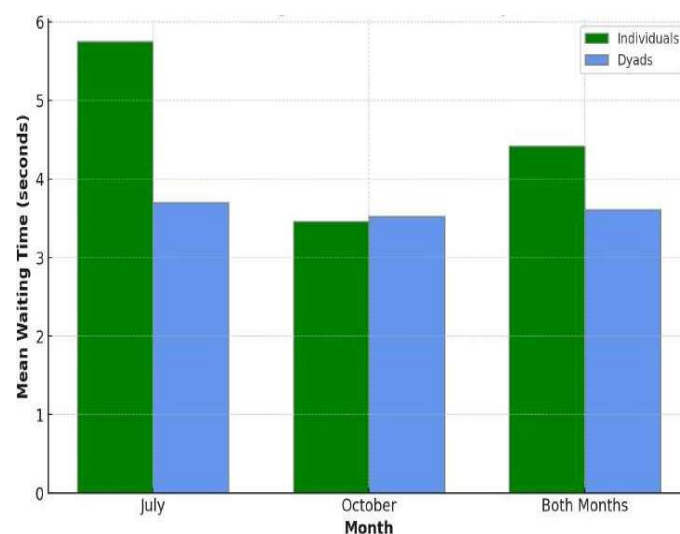


Figure 6-23: Mean waiting time for pedestrian by month

Subsequently, when combining the two months together it calculates a total mean waiting time for individual pedestrians for both months equal to 4.42 seconds and a total mean waiting time for dyads equal to 3.61 seconds. This shows that, on average, individuals wait longer than dyads. This might be due to individuals being more cautious or having different crossing habits than dyads.

For the waiting time spent by individuals and dyads during the month of July, a two-sample t-test assuming unequal variances was assessed. With using the alpha level equal to 0.05 which is often chosen because it is a good balance between avoiding type I errors (false positives) and type II errors (false negatives). The two-tailed p-value (0.116) exceeds the common alpha level of 0.05, indicating that the difference in means between the individuals and dyads groups is not statistically significant. For the month of October, the difference between the means of the individuals and dyads groups is not statistically significant, as the two-tailed p-value (0.781) is above the conventional threshold of 0.05. The test does not provide sufficient evidence to reject the null hypothesis of equal means between the two groups. While separate t-tests for July and October show no statistically significant difference in the mean waiting times, it is not wise to assume that these patterns will hold when data from both months are combined. It is important to consider that the lack of significant difference in each month does not automatically guarantee an insignificance over the combined period. However if the monthly results show a steady trend and the conditions did not change significantly over the course of the two months, it could be logical to assume that the combined analysis would also reveal no significant differences in waiting times. Therefore, over the period of these two months combined, there appears to be no statistically significant difference in the mean waiting times between individuals and dyads. Using the timestamps found on the videos when the pedestrian starts crossing and when they reach the other side of the road, it was possible to calculate the crossing time for each pedestrian. In July, dyads had a slightly longer mean crossing time compared to individuals, as dyads had a mean crossing time equal to 10.9 Seconds while Individuals had a mean crossing time of 9.93 seconds. This could suggest that navigating or coordinating movements as a pair takes more time than moving individually. Similar to July, the mean crossing times during October also show that dyads took longer on average to cross than individuals. Individuals spent an average of 8.81 seconds to cross, while dyads' mean crossing time was 9.78 seconds. The combined mean crossing times of both months July and October for individuals equaled to 9.07 seconds and for dyads it equaled to 10.34 seconds, showing that, on average, individuals cross faster than dyads. The bar chart in figure 6.24 provides a more

detailed look at the exact mean crossing times for both individuals and dyads in July, October, and the total combined average.

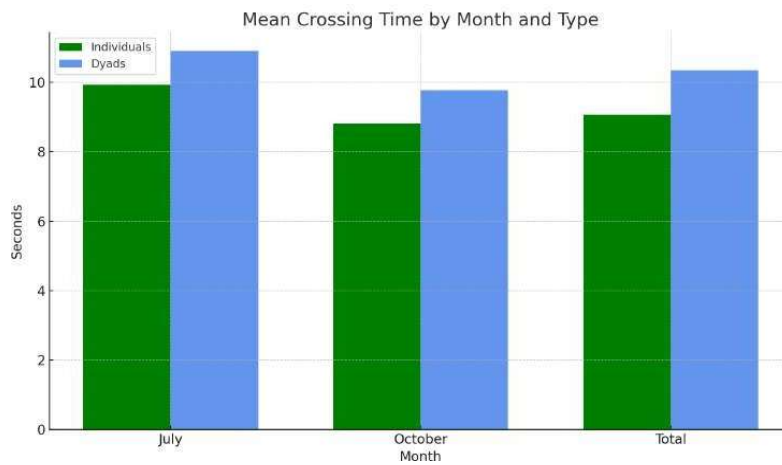


Figure 6-24: Mean crossing time

Utilizing the t-test to analyze the crossing times for the month of July, there is a statistically significant ($p\text{-value}=0,029$) difference in mean crossing times between individuals and dyads, with dyads having a higher mean. In addition, there is a statistically significant difference in mean crossing times between individuals and dyads for October, with dyads having a higher mean. The results are consistent across both months, reinforcing the finding that the mean crossing times for dyads are significantly higher than those for individuals in this sample. As expected, when combining the samples of two months together, the t-test will give a two-tailed $p\text{-value}$ smaller than 0.05 showing that there is a statistically significant difference between the individuals and dyads. An additional Logistical Regression Analysis has been conducted to illustrate the relationship between the crossing time and the probability of pedestrians being part of a dyad.

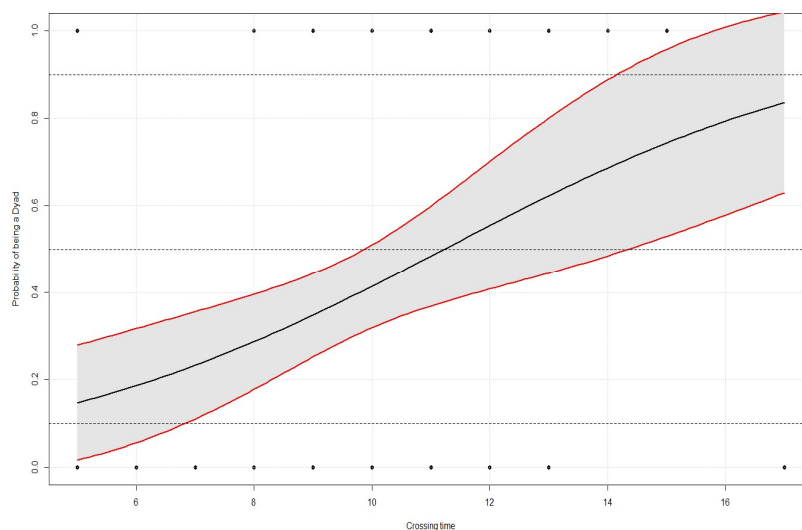


Figure 6-25: Logistical Regression Analysis

The logistic regression plot (Fig. 6.28) depicts the probability of pedestrians being part of a dyad based on the crossing time. The red lines represent the confidence interval around the prediction, indicating the range within which the true probability lies with a certain level of confidence. The graph suggests a positive correlation between crossing time and the likelihood of being in a dyad, meaning that as the crossing time increases, so does the probability of pedestrians crossing together, to be exact, for every additional second in the crossing time, there is an increase of 32% of the probability of being a dyad.

Post-Encroachment Time (PET) is a critical parameter in the field of road safety, serving as a valuable indicator of potential conflicts between road users, including vehicles, cyclists, and pedestrians. This measure, defined as the time interval between the departure of one road user from a specific area and the arrival of another, is key in assessing the severity and likelihood of collisions at intersections, roundabouts, and other points of interaction on the road network. For the PET values of October obtained, crossings with PET less than 5 seconds were considered as conflicts, and those with PET less than 1.5 seconds were considered as dangerous conflicts [150]. Only the October conflicts were analyzed due to the consistence number of the sample. Which leads to have a total of 52 conflicts involving pedestrians. Among these conflicts, 35 were caused by individual pedestrians, who presented a mean Post Encroachment Time (PET) of 3.16 seconds. This indicates a relatively narrow window between the individual's crossing path and the approach of a vehicle, underscoring the precarious nature of these encounters. On the other hand, the remaining 17 conflicts involved dyads, pairs of pedestrians, with a mean PET of 3.27 seconds. However, the t-test results for the post encroachment time between individuals and dyads do not show a statistically significant difference. The p-values are well above the typical threshold used to denote significance (0.05), indicating that any observed difference in mean PET between individuals and dyads is likely due to chance.

6.3.1.2 Results from driver-pedestrian interaction

Commencing with conventional street illumination parameters, the research phase encompassed the implementation of 7 distinct illumination configurations [151]. Subsequently, the second phase involved a five-month continuous monitoring period utilizing video surveillance methodology, which facilitated the third phase's analysis of vehicular velocity and braking distances. The fourth phase employed statistical evaluation methods to compare the efficacy of the 7 configurations, determining their relative significance in ensuring pedestrian safety at nocturnal street crossings.

The video surveillance analysis facilitated the quantification of vehicle-pedestrian interaction occurrences, categorizing them into three distinct behavioral patterns: deceleration, complete cessation of movement, or absence of interaction (indicating non-compliance with pedestrian right-of-way). Furthermore, as previously established, the methodology enabled the calculation of corresponding approach velocities. The empirical evidence indicates that Condition 1 (incorporating orange beacons) and Condition 5 (utilizing flashing LED strips) yielded mean vehicular velocities of 28.24 km/h and 20.37 km/h respectively, which are deemed conducive to pedestrian safety at crossing points. A notable reduction in vehicular speed was observed across all experimental conditions when compared to Condition 0 (baseline condition with conventional street illumination), which lacked any supplementary crossing elements. Velocity differentials were documented for each condition implementation. The statistical analysis revealed minimal speed variance across conditions, as evidenced by the standard deviations, with no outliers detected. Notably, Condition 0 exhibited particularly low standard deviation values, suggesting that in the absence of enhanced illumination systems, motorists maintained remarkably consistent speeds approximating 42 km/h. Additionally, a supplementary velocity range differentiation was implemented to establish risk levels, across the different condition. Below are the percentages of events involving vehicles with speed ranges analyzed for each condition (Figure 6.26).

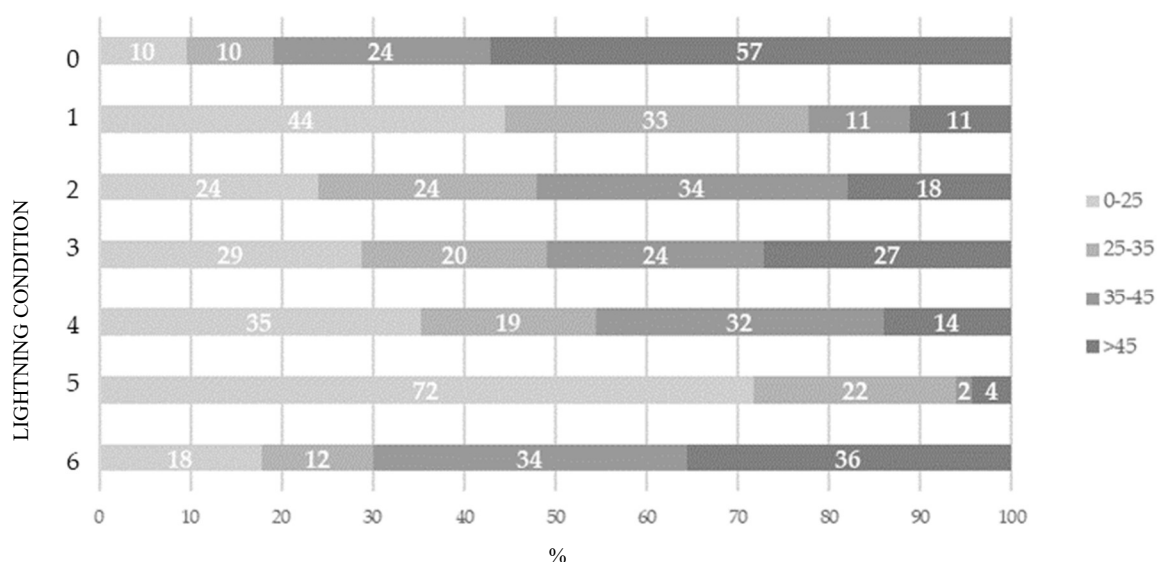


Figure 6-26 - Distribution of speed across the seven condition.

From the braking distance calculation, given by the formula (E.7), it is possible to define three speed classes within the driver of a vehicle is able to perform complete stop, slow down manoeuvres or no manoeuvres to stop the vehicle and let cross the pedestrian. With regard to

speed, it can be said that for speeds up to 25 km/h a driver is able to perceive a user at a pedestrian crossing, assess any emergency manoeuvres to be made and stop the vehicle safely within the available space. For speeds between 25 km/h and 35 km/h, the driver can only perceive the pedestrian crossing, assess the emergency manoeuvre to be carried out and activate the emergency braking without completing the transitional braking phase. Finally, for speeds above 35 km/h, the driver of the vehicle is not able to perceive the user crossing the road and implement the emergency manoeuvre since the required journey time is less than the psychophysical reaction time set at 2.10 seconds. Although condition 1 has the same percentage of events, within in the range 35-45 km/h, equal to condition 5.

To assess the difference between the different condition, a one-way ANOVA was run with the seven configurations with speed as independent variable. This test statistically confirms that significant changes were found between conditions, especially between condition 0 and others. Condition 5 is distinct from a number of other conditions in an important manner. The addition of the dedicated enhanced LED lighting and the fixed-in-curb LED device shows that the difference between conditions 0 and 5 was significant in terms of speed. This suggests that the use of all the smart instrumentation has real effectiveness in decreasing speed. Figure 6.27 delineates the interaction typologies which, as elucidated in section 4, encompass: deceleration maneuvers, complete stopping procedures, and 'Non-Yielding' scenarios, where pedestrians are unable to execute crossing maneuvers.

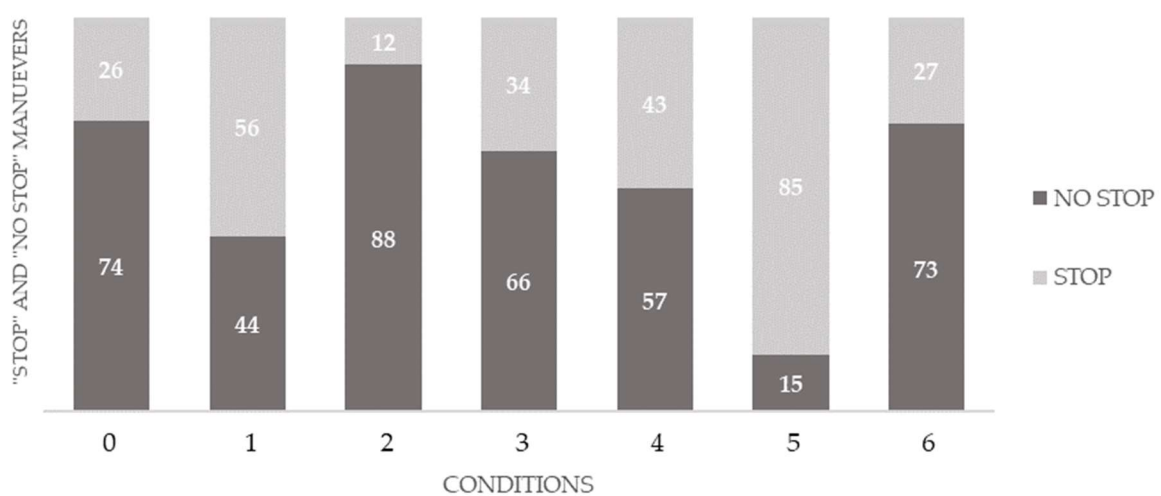


Figure 6-27 - Percentage distribution of driver responses when approaching crosswalks with active pedestrian presence

Upon examination of the cumulative value of the studied interactions (deceleration and stopping), it is noteworthy that configuration 6 accounts for 67% of appropriate interactions. This significant finding suggests that configuration 5, characterized by the integration of SICURLUX, fixed LOOKATME, and SICURLED systems, demonstrates superior efficacy in terms of road safety parameters. In conclusion, the pedestrian crossing on Andrea Costa Street is situated in a zone characterized by multiple attractors, including: a stadium facility, a supermarket, and various commercial establishments (beauty services, restaurants, automotive repair shops, etc.). Consequently, it is essential to evaluate both the vulnerable road users who predominantly utilize this crossing and the patterns of vehicle-user interactions that manifest. For the crossing configurations that demonstrated superior effectiveness (condition 1 and 5), an analysis was conducted to determine the user typology accessing the crossing. The findings reveal a substantial percentage of pedestrian usage in both condition 1 (94%) and condition 5 (98%), while cyclist presence remained minimal (5% and 2% respectively).

6.3.2 Cycle Infrastructure Monitoring: Florence Case Study

The investigation encompassed a sample of 20 participants who were instructed to ride a predetermined route spanning approximately 1.2 km. This methodology enabled the assessment of variations in kinematic parameters and behavioral responses across different urban environments and cycling segments. The experimental protocol was implemented in Florence, incorporating both training and experimental segments. To facilitate participant adaptation to road conditions, training sections were strategically positioned in the first part of track and interspersed between test segments. The route has been divided into four sections (Fig. 6.28).

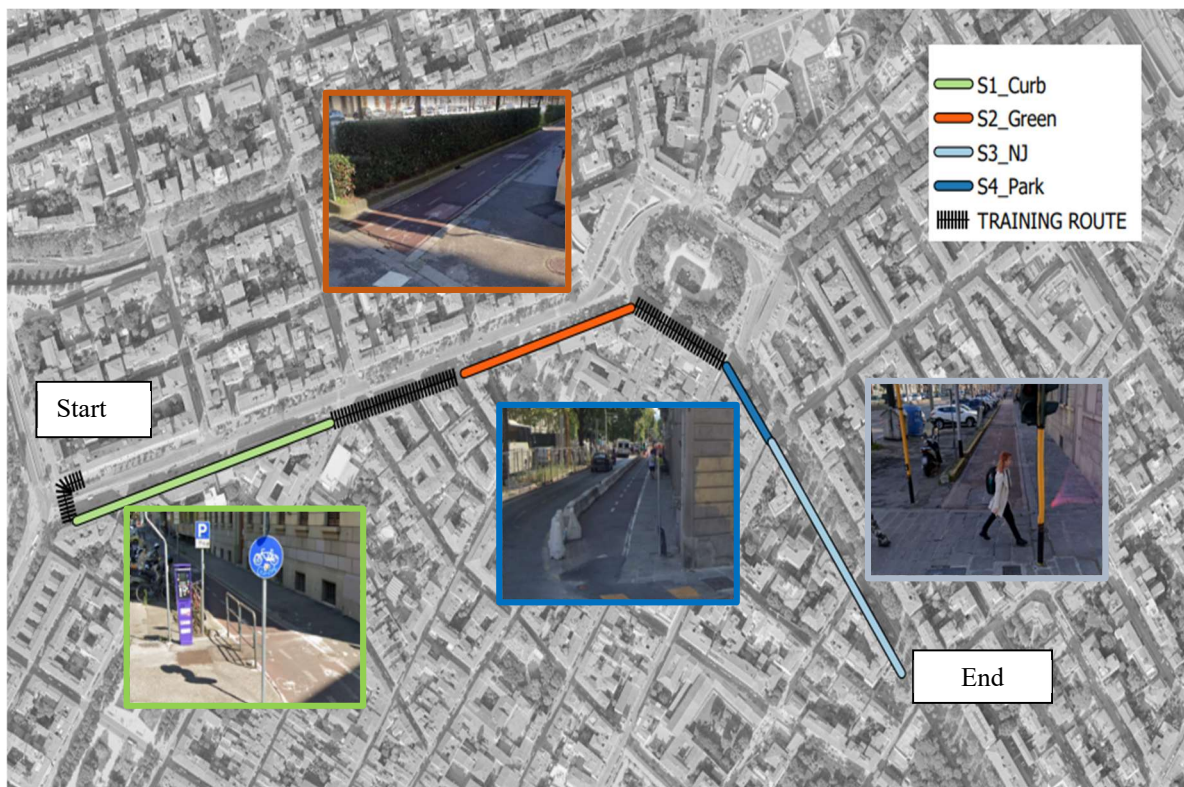


Figure 6-28 - Cycling routes subdivision into S1_Curb, S2_Green, S3_NJ, S4_Park (source: Google Earth©)

The experimental route comprised four sections with varying infrastructural characteristics. The initial segment, designated as S1_curb (300 meters), featured a dedicated red cycling facility with physical segregation elements: a kerb separating it from the pedestrian pathway and a secondary road in other side. The subsequent segment, S2_Green (200 meters), incorporated similar protective elements but utilized urban vegetation as the street-side barrier. S3_NJ (100 meters) was distinguished by its elevation continuity with the primary carriageway, employing New Jersey barriers as segregation elements. The final segment, S4_Park (300 meters), consisted of a protected red cycling facility with curb separation from the adjacent pedestrian

infrastructure. The physiological monitoring equipment demonstrated high acceptability, with 90% of subjects reporting no discomfort during usage. Table 6.5 summarizes the main characteristics of the different sections and defines the type of cycle path separation according to M.D. n. 557 del 30/11/1999 art. 4 and Regional Guidelines n. 10/2017.

Table 6-5 – Cycle paths characteristics and type of separation element

Section ID	Section	Separation Element with the carriageway (left)	Length [m]
S1_Curb	1	Curbs	300
S2_Green	2	Vegetation	200
S3_NJ	3	New Jersey Barriers	100
S4_Park	4	Curbs + Parkings	300

All participants rode the same bicycle for an equal cycling conditions and the experiment lasted for approximately 10-15 minutes. Questionnaires were administered at the end of the session, specifically asking participants to target two main different information. The first one aims to collect demographic and personal data (e.g., age, gender, driving experience, comfort during the ride). The second one wants to collect cognitive load during the test. For this reason, a NASA Task Load Index was used to profile users and their perceptions. In addition, a declaration of the perceived safety was asked of each one.

Firstly, the demographic composition of the study population comprised 71% male and 29% female participants, with age distribution ranging from 31 to 60 years (31-40 years: 43%; 41-50 years: 38%; 51-60 years: 19%). The study employed a single-blind protocol, with participants unaware of the specific research objectives. Analysis of participants' cycling patterns, through surveys, revealed distinct usage categories. The predominant group (62%) exhibited limited cycling frequency, categorized as rare users. Daily cyclists constituted 33% of the sample, while bi-weekly riders represented a minimal fraction (5%). Regarding typical journey lengths, the majority (60%) regularly undertook trips exceeding 5 kilometers. Equal proportions (20%) reported typical journeys of 3-5 kilometers and 1-3 kilometers respectively. Notably, no participants reported routinely cycling distances below 1 kilometer, suggesting a preference for extended journeys among the cycling population studied.

NASA Task Load Index (TLX) was used to reveal that cognitive and temporal demands were the predominant workload factors, each exceeding 25% of the maximum score. Other dimensions, including performance metrics, exertion levels, and frustration indices, exhibited

moderate values, suggesting a cognitively demanding yet manageable experimental environment. Safety perception assessment, conducted using a five-point Likert scale (1 representing optimal safety; 5 indicating perceived danger), demonstrated that segments S1_Curb, S2_Green, and S4_Park were perceived as predominantly secure by 90% of participants. In contrast, S3_NJ elicited heightened danger perception among subjects.

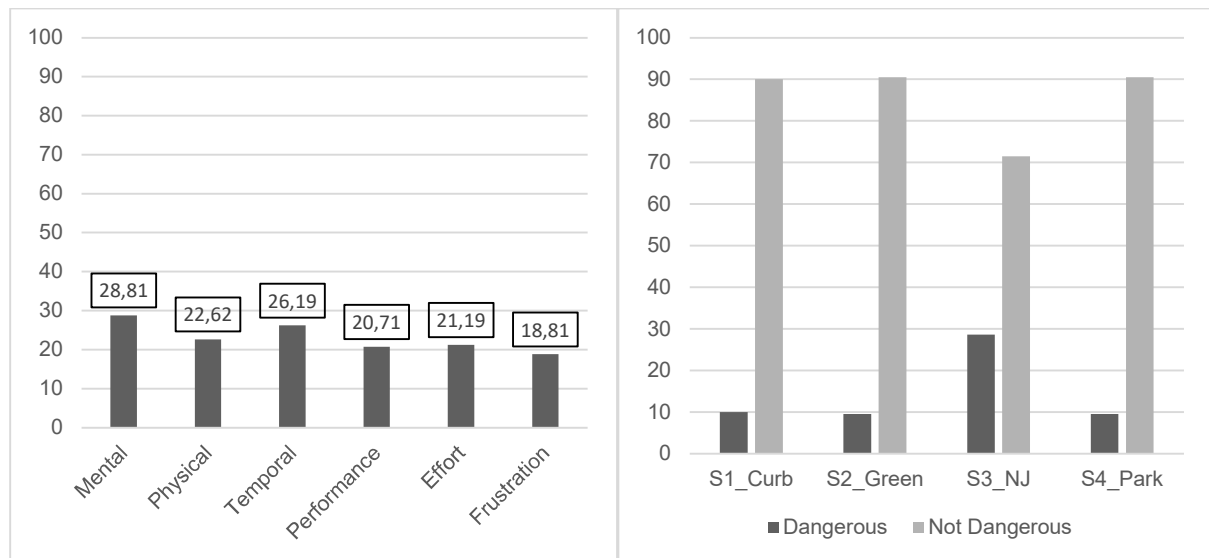


Figure 6-29 a) Nasa TLX results and b) Declared Safety perception in the section

Test Results

Subsequent kinematic analysis, utilizing data from Garmin devices processed through Geographic Information System (GIS) software, revealed notable velocity variations across segments. Peak velocities were recorded in section S2_Green, where lateral road visibility was minimal due the presence of vegetation. Conversely, the New Jersey barrier-protected section (S3_NJ) exhibited the lowest velocity measurements (Fig. 6.29). Table 6.6 defines the main characteristics of the different sections along the tested route. In the analysis of the speed data, the stops and the zero were deleted from the calculation.

Table 6-6 – Descriptive Statistics for speed of the sections

Section ID	Average Speed (km/h)	Standard Deviation	Minimum Speed (km/h)	Maximum Speed (km/h)
S1_Curb	14,94	1,78	12,12	18,62
S2_Green	15,58	1,50	12,88	18,98
S3_NJ	12,02	1,35	8,71	14,49
S4_Park	12,94	1,19	10,13	15,40

The average speed of sections S2_Green, separate cycle path (18,62 km/h), and S3_NJ protected cycle path (12,02 km/h) are respectively the highest and the lowest. A decrease in speed is evident in the shift to the protected cycle section. Standard deviations show low variability of speed data between different configurations.

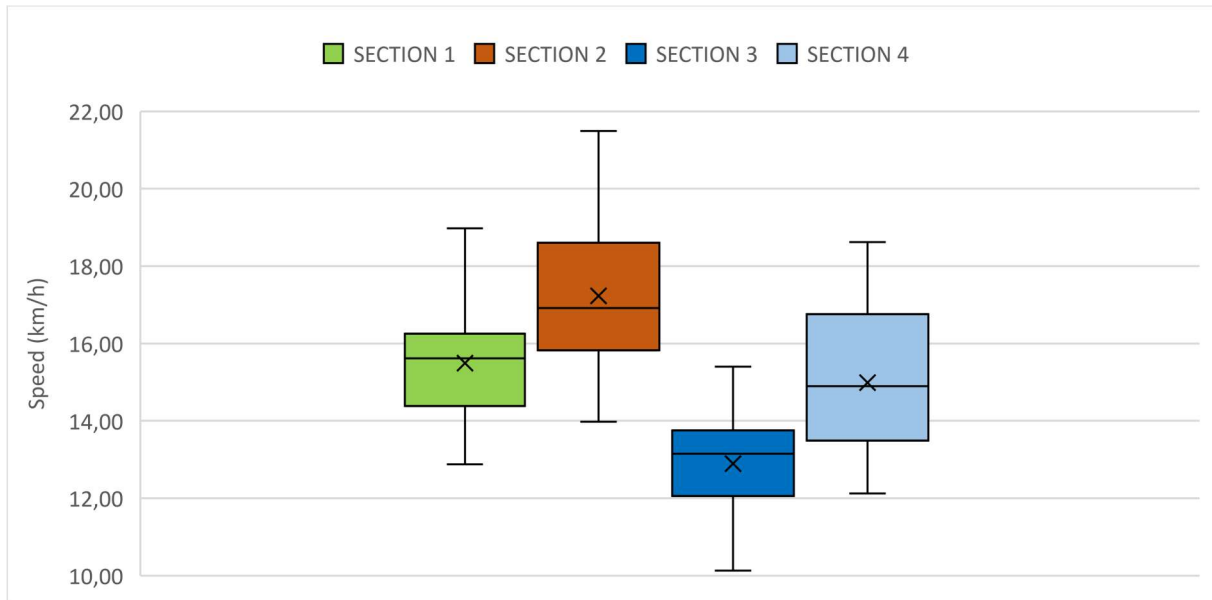


Figure 6-30 – Speed Box Plot

Moving to the gaze data that were extracted from the video using Tobii Pro Lab software. All the records were evaluated maintaining a gaze sample percentage over the threshold equal to 85%. Videos with gaze cursor were coded frame by frame to assign gaze location to one of following areas of interest (AOI): road, side, focus of expansion and front direction (Fig.6.31).

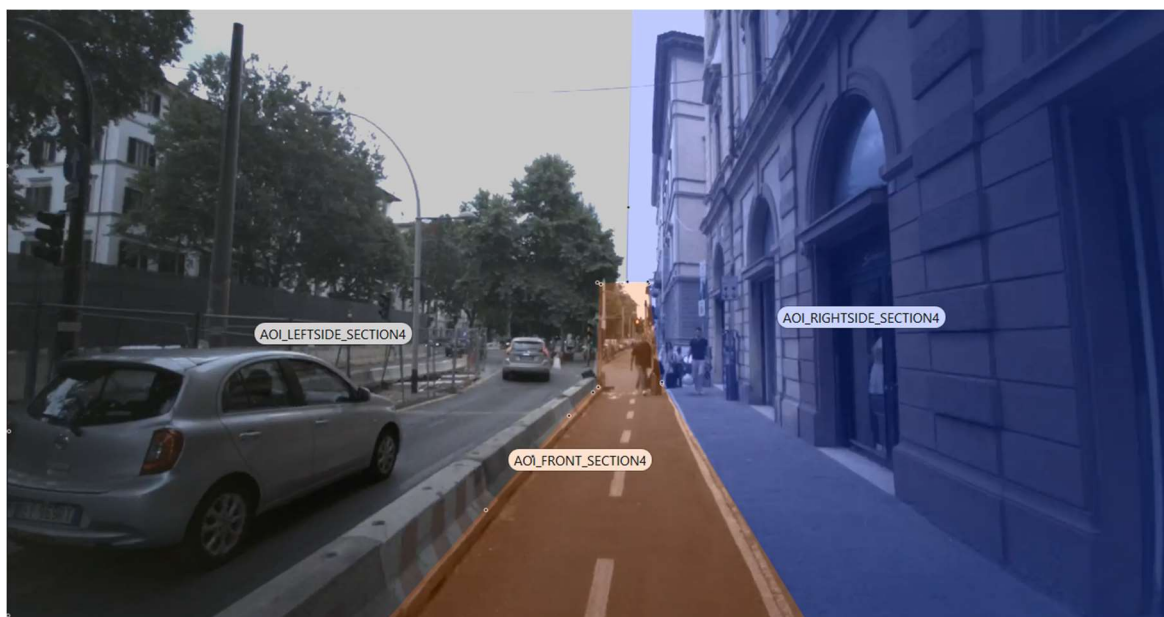


Figure 6-31 – AOI analysis from Tobii Mobile Eye tracker

For each area, the duration and the number of fixation were extracted (Fig. 6.32-6.33) in order to understand possible relation with the cycle kinematic parameters. Due to the different length of the cycle section, the percentage of these two-gaze data was analyzed.

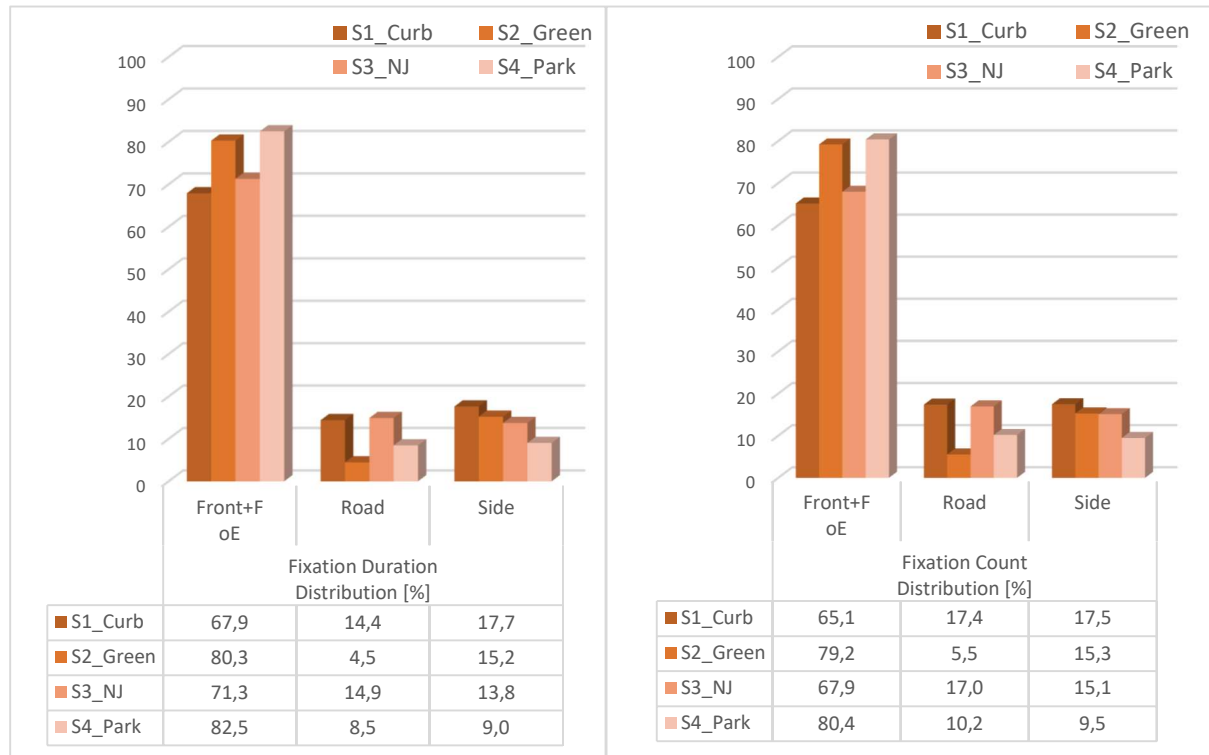


Figure 6-32 – Fixation Count Distribution

Figure 6-33 – Fixation Duration Distribution

The most fixed AOI is the front one both in term of distribution and counts. Analyzing the AOIs in the sides, the section S1_Curb and S4_Park record the most fixation and duration. In particular section S1_Curb, it records the higher number of distraction than the front direction. In detail, the road is more perceived in section 4 than in the others, the sidewalk captures more fixation in section S1_Curb. In addition the section S2_green records the lowest value of fixation in the road direction, due to presence of vegetation.

Moving to the accelerometer data, a MATLAB code was realized to perform an algorithm that read the accelerometer data and synchronize them with GPS records. Subsequently, the root mean square (RMS) value per second was calculated. For the RMS calculation, the following equation was used where N acceleration value and x_i is the values for vertical acceleration:

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \quad (\text{EQ. 8})$$

In addition, the classification of these values according to Table 6.7 ,adopted from ISO 2631-1[152] was carried out. This clause concerns the estimation of the effect of vibration on the comfort of persons in normal health who exposed to whole-body periodic, random and transient

vibration during travel, at work or during leisure activities [153]. For realizing it, vertical accelerations for each section were calculated using the output from the sensors, converting them in m/s^2 , filtrated for noise, and categorized between the different ISO classes.

Table 6-7 - Comfort perceptions for different vibration levels

Acceptable Values of Vibration Magnitude for Comfort (RMS m/s^2)	Likely User's Reaction	Category
$< \pm 0,315$	Not Uncomfortable	A
$\pm 0,315 \div \pm 0,63$	A little uncomfortable	B
$\pm 0,5 \div \pm 1$	Fairly uncomfortable	C
$\pm 0,8 \div \pm 1,6$	Uncomfortable	D
$\pm 1,25 \div \pm 2,5$	Very Uncomfortable	E
$> \pm 2,5$	Extremely Uncomfortable	F

Dividing the data according to the aforementioned regulation yields the percentage distribution for each section. Section S1_curb has a relatively higher proportion of points (40%) classified under lower comfort, Class D), whereas Section S4_parks demonstrates a more balanced distribution among classes C, D, and E. In another hand, section S3_NJ show the most comfortable path with 74% of vibration values with low level of discomfort (Fig. 6.34). In the end, the results suggest differing pavement conditions or maintenance standards that influence the overall comfort experienced by cyclists.

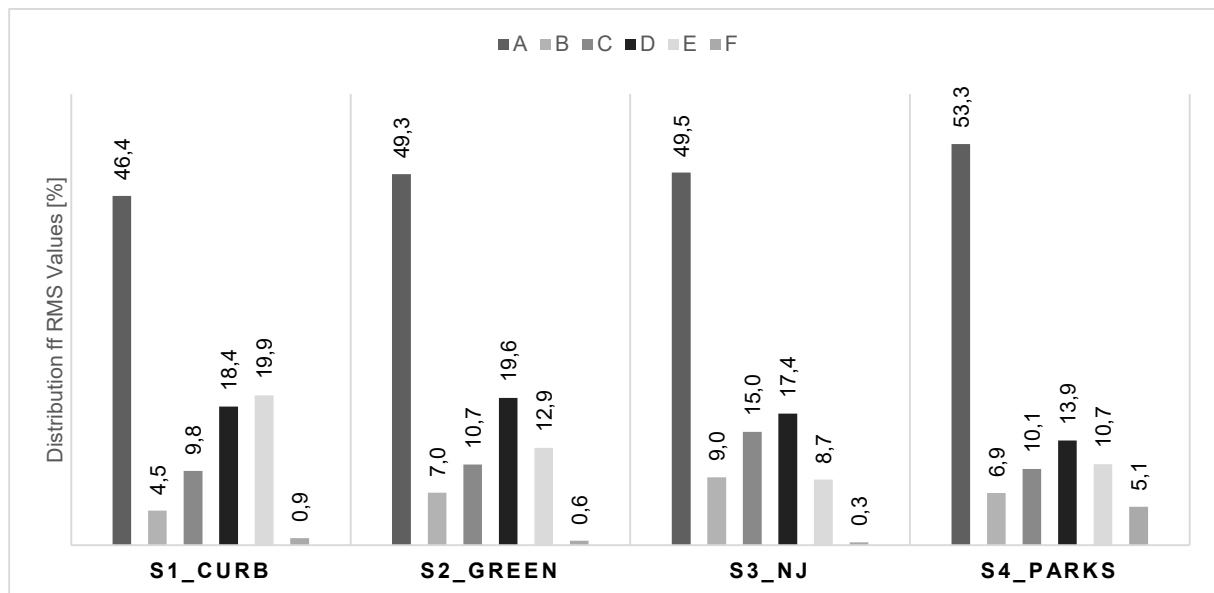


Figure 6-34 - Distribution of RMS into ISO classes for the different sections

Cognitive measurements obtained through Mindtooth's EEG sensors reveal distinct patterns across different road sections, with particular emphasis on stress, mental workload, and alertness levels (Fig. 6.36). The analysis indicates that all sections show similar stress values, which reflects the physiological and psychological responses to perceived environmental

challenges. In addition, the graph shown in the figure below was used to understand the output data from the device.

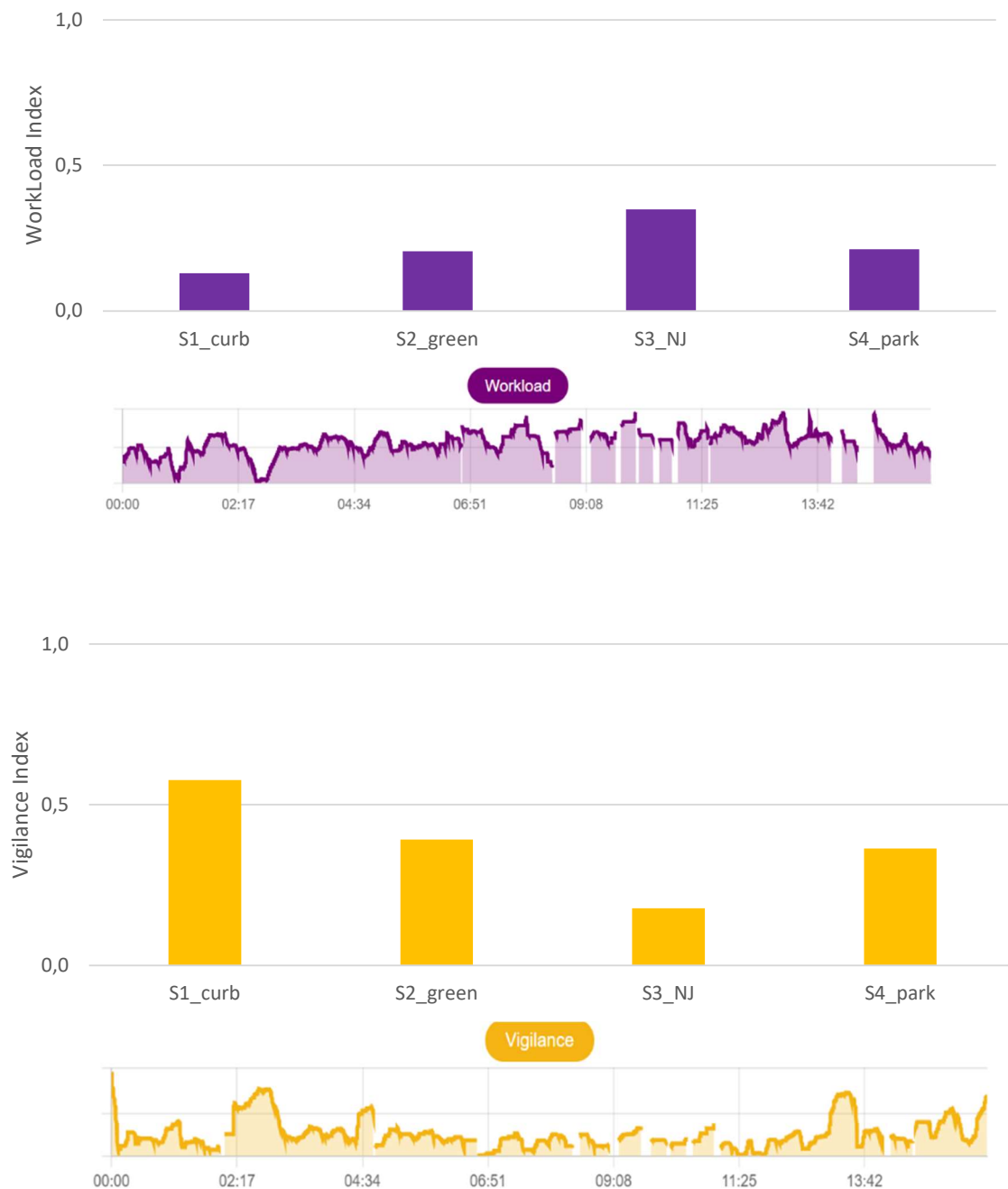




Figure 6-35 Cognitive metrics elaboration

The workload index shows that S1_Curb, S2_Green, and S3_NJ have relatively elevated levels, with S3_NJ exhibiting the highest workload. This outcome supports earlier findings, as S3_NJ's that indicates increased cognitive resource allocation, presumably due to proximity of vehicular traffic. The vigilance index reveals a different distribution, with the highest levels observed in S1_Curb and S2_Green, followed by S4_Park, while S3_NJ registers a marked decrease in vigilance. This pattern implies that although participants were aware of potential risks in S3_NJ, the continuous vigilance observed in S1_Curb and S2_Green may not have been as sustained. It is plausible that environmental factors such as physical barriers and consistent lane separations in S1_Curb and S2_Green contributed to an increased attentiveness, promoting a state of vigilance that was not as effectively supported in S3_NJ due to its design. The stress index remains relatively stable across all sections, with only a slight increase in S3_NJ, aligning with the section's heightened danger perception.

In conclusion, the EEG data analysis reveals significant correlations between environmental conditions and cognitive demands, particularly in sections with complex infrastructural configurations. The findings underscore how temporary bicycle infrastructures and close vehicle proximity may substantially impact cyclists' cognitive functioning, potentially affecting their safety and performance. The comprehensive EEG assessment through Mindtooth provides valuable insights into the relationship between infrastructure characteristics and cyclists' cognitive responses, particularly regarding stress reactions, attentional resources, and mental processing demands. These observations suggest that infrastructure design significantly influences cyclists' cognitive load and stress levels, with temporary or suboptimal conditions requiring increased mental resources for safe navigation.

Statistical Analysis

Differences from the variables, especially speed and fixation across the different section, were investigated using ANOVA test with significance level set at $p \leq 0,05$. In addition, the linear correlation between all the factors and speed has been outlined. First of all, the normality test of Shapiro Wilk and the Levene test for the variance similarity assessed that the speed values are quite normally distribute for each section. It can be confirmed by the statistical tests, the speed values are distributed according to a normal distribution ($p > 0,05$) and have comparable variances ($p > 0,05$). Subsequently, a one-way ANOVA was performed in order to understand if there are some statistical difference between the mean values of velocity from the different sections (Tab 6.8).

Table 6-8 - Single-way ANOVA between the speed sections.

ANOVA	Sum of squares	df	Mean Square	F	Sig.
Between Groups	319,908	4	79,977	30,655	,000
Within groups	247,851	95	2,609		
Total	567,760	99			

Results of the ANOVA showed a significant difference between the speed of the four sections ($F(4,95) = 30,655$, $p < 0,001$). So, the null hypothesis that the difference between the average values is equal to zero would be rejected. For investigating further, the correlation between the different cycle sections, in terms of speed, a Turkey post hoc analysis (Table 6.9) was carried out.

Table 6-9 - Turkey post hoc

(I) Sections	(J) Sections	Mean differences (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
S1_Curb	S2_green	-1,379	0,511	0,061	-2,799	0,041
	S3_NJ	2,638*	0,511	0,000	1,218	4,059
	S4_Park	0,637	0,511	0,724	-0,783	2,057
S2_green	S1_Curb	1,379	0,511	0,061	-0,041	2,799

(I) Sections	(J) Sections	Mean differences (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
	S3_NJ	4,017*	0,511	0,000	2,597	5,438
	S4_Park	2,016*	0,511	0,001	0,596	3,436
S3_NJ	S1_Curb	-2,638*	0,511	0,000	-4,059	-1,218
	S2_green	-4,017*	0,511	0,000	-5,438	-2,597
	S4_Park	-2,001*	0,511	0,002	-3,422	-0,581
S4_Park	S1_Curb	-0,637	0,511	0,724	-2,057	0,783
	S2_green	-2,016*	0,511	0,001	-3,436	-0,596
	S3_NJ	2,001*	0,511	0,002	0,581	3,422

*p<0,005

The section S2_green (M=15,58, SD=1,50), where the mean speed is the highest, showed relevant differences with almost all the other ones, not for section S1_curb (M=14,94, SD=1,78) probably due to the similarity of the geometric characteristics. Indeed, the section S4_ (M=12,94, SD=1,19), the slowest in the test, show significant differences between all the speed sections. It suggests that the difference in the mean value of speed changes according to several factors, such as road elements, users or fixations. They may influence speed differently across these sections. To understand if the velocity is influenced by different factors along the cycle route, different elements was observed and extracted from the video recordings:

- Fixations in terms of duration and count of the cyclist gaze;
- Vertical acceleration calculated from the back rear;
- Number of the cyclist (both in the same and opposite direction);
- Vehicle flow of nearby roadway and interference with them along the route.

So a further investigation on what influences the speed of the cyclist, has been outlined below. Studying the linear correlation between speed and the other factors, using Pearson's correlation matrix, it was possible to obtain the results in the table 6.10.

Table 6-10 – Pearson Correlation

Speed Correlation	Duration of Fix.			Fixation Count			Vert. Acc.	N° of Opp. Cyclist	N° of Encount. Cyclist	Vehicle Interference	Vehicle Flow
	Front	Road	Side	Front	Road	Side					
Pearson Correlation	,469**	,022	,222*	,322**	,107	,102	,256*	,299**	,167	,058	-,003
Sig. (2-code)	,000	,831	,026	,001	,289	,313	,010	,002	,097	,566	,979

*p<0,005 and p**p<0,001

The correlation analysis reveals that speed is significantly associated with the duration of fixations in the front area ($r = 0.469$, $p < 0.001$), the number of front fixations ($r = 0.322$, $p < 0.01$), vertical acceleration ($r = 0.256$, $p < 0.05$), and the number of cyclists encountered ($r = 0.299$, $p < 0.01$). These results suggest that an attention on the front area might give the possibility to increase the speed. Probably the positive correlation with the encountered cyclist is due to the willing of overpassing.

In addition, taking into consideration the fixation in the lateral direction during the ride, ANOVA for the percentage of fixation in the three different AOI was applied. It is possible to emphasize that the quickest section S2_green show the largest number of lateral fixation and duration on the sidewalk, due also to the presence of vegetation in the other side, that closes the sight. On the other hand, the slowest one, S3_NJ, has more fixation oriented to the roadway, probably due to the presence of high vehicular flow. A single way ANOVA was performed to find statistical evidence based on the different cycle sections. Results of the ANOVA (Tab. 6.11) showed a significant difference between the road ($F(4,95) = 8,463$, $p < 0.001$) fixations in the four sections. There were no significant differences between sections for the duration of sidewalk and frontal fixations, suggesting that the duration of fixations on the lateral and frontal area is similar between all sections considered.

Table 6-11 – Single-way ANOVA between the fixation on different sections.

ANOVA		Sum of squares	df	Mean Square	F	Sig.
Frontal Direction	Between Groups	3124,160	4	781,040	3,978	,005
	Within groups	18652,750	95	196,345		
Road Direction	Between Groups	2429,600	4	607,400	8,463	,000

	Within groups	6818,400	95	71,773		
Sidewalk Direction	Between Groups	882,700	4	220,675	1,873	,121
	Within groups	11190,050	95	117,790		

For investigating further the correlation between the different duration of the fixation on road, a Turkey post hoc analysis (Tab. 8) was carried out.

Table 6-12 – Turkey post hoc of Duration of Fixation on Road

	(I) Sections	(J) Sections	Mean differences (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Lower Bound
Duration of Fixation on Road	S1_Curb	S2_green	10,700*	2,679	,001	3,25	18,15
		S3_NJ	,250	2,679	1,000	-7,20	7,70
		S4_Park	7,500*	2,679	,048	,05	14,95
	S2_green	S1_Curb	-10,700*	2,679	,001	-18,15	-3,25
		S3_NJ	-10,450*	2,679	,002	-17,90	-3,00
		S4_Park	-3,200	2,679	,755	-10,65	4,25
	S3_NJ	S1_Curb	-,250	2,679	1,000	-7,70	7,20
		S2_green	10,450*	2,679	,002	3,00	17,90
		S4_Park	7,250	2,679	,060	-,20	14,70
	S4_Park	S1_Curb	-7,500*	2,679	,048	-14,95	-,05
		S2_green	3,200	2,679	,755	-4,25	10,65
		S3_NJ	-7,250	2,679	,060	-14,70	,20
*.p<0,005							

Table 6.12 shows that section S2_green has significant differences from section S1_curb and S3_NJ, with a lower percentage duration of fixations on the road with differences of approximately 10 percentage units, respectively ($p \leq 0.002$). This indicates that in sections S2_green, and S4_parks, participants tend to fixate less on the road than in section S3_NJ, which is similar to the visual behavior associated with section S1_curb. These findings suggest

that road configurations where vehicular traffic is within users' visual field (sections S1_curb and S3_NJ) appear to influence both visual perception and speed choice behaviors.

In conclusion, the analysis of the empirical data reveals several significant patterns regarding cycling behavior and visual attention across different infrastructure sections. The speed analysis demonstrates significant variations in cycling speeds. The separate cycle path (S2_green) exhibiting the highest mean velocity (18.62 km/h), while the protected cycle path with barrier (S3_NJ) recorded the lowest one (12.02 km/h). The decrease in speed during transitions to cycle sections suggests a potential correlation between infrastructure type and user behavior. The relatively low standard deviations across configurations indicate consistent speed patterns among participants. For assessing it, eye-tracking data, were analyzed. Through Tobii Pro Lab software, sight data maintained robust reliability with gaze sample percentages (>85%). Analysis of AOI reveals a predominant forward-facing gaze pattern across all sections. However, Sections S1_curb, S2_green and S3_NJ demonstrated significantly higher lateral fixation frequencies and durations. Of particular interest, Section S1_curb exhibited the highest rate of visual attention deviation from the forward direction, with increased fixations on sidewalk features due probably to the high pedestrian flow. Section S3_NJ showed elevated road-focused attention compared to other segments (vehicles flow nearby), while Section S2_green reduced road fixation patterns appear attributable to the presence of green elements between cycle path and road. To analyze the relationship between all the recorded variables, the ANOVA and correlation analysis between factors were carried out. Statistical analysis suggests that speed variations are influenced by multiple factors, including infrastructure elements, user characteristics, and visual attention patterns. A positive correlation emerged between forward-focused attention and increased speeds, potentially indicating a relationship between perceived environmental safety and cycling behavior. The consistency in fixation durations between lateral and frontal areas across all sections suggests a uniform visual scanning pattern regardless of infrastructure type. The research suggests that the composition of the cycling environment significantly influences cyclists' visual scanning patterns. Specifically, in segments where vehicular flows are in close proximity to the cycle path—and thus within the cyclist's field of vision—there is a noticeable increase in attentional focus toward that side and a concurrent reduction in speed. Analyzing the correlation between traffic flow visibility and speed adaptation reveals a substantial perceptual-behavioral relationship in these cycling segments. These findings contribute to understand of how infrastructure design elements influence cycling behavior and perceived safety, with potential implications for urban bicycle infrastructure design and safety enhancement strategies.

7. Conclusion

This doctoral thesis underscores the evolving role of sustainable mobility as a pivotal element in the landscape of urban development and policy, highlighting its impact on environmental, social, and economic dimensions. This research offers an in-depth investigation into methodologies, technologies, and policies that have been developed to address the multifaceted challenges of sustainable urban mobility. At its core, this work provides a cohesive framework for understanding the complex, interlinked components of sustainable urban mobility. Throughout this study, the importance of coordinated efforts in policy, infrastructure design, technology, and public engagement becomes evident, with each component reinforcing the overarching goal of creating safer, more accessible, and environmentally sustainable urban spaces. Starting from the macro-scale, this research acknowledges the broader implications of sustainable urban mobility on global sustainability targets. The alignment of this study with the United Nations Sustainable Development Goals (SDGs), particularly those focused on sustainable cities and climate action, reinforces the potential of sustainable mobility as a transformative force. The reduction of emissions through low-carbon transportation modes, such as electric and non-motorized options, is critical in meeting SDG 11, which emphasizes inclusive, safe, and sustainable urban development. Furthermore, by advocating for energy-efficient transportation systems, this research supports SDG 13, which calls for urgent action to combat climate change. In this context, the sustainable mobility wants to give its contribution to achieve them. Indeed, micromobility has emerged as a significant component of last-mile transportation solutions, bridging gaps within traditional public transit networks. However, as demonstrated by this thesis, micromobility also presents unique safety challenges and requires careful policy and infrastructure adjustments to mitigate risks associated with mixed traffic environments. Findings reveal that e-scooter users favor cycle paths and dedicated lanes over sidewalks, especially when shared with pedestrians, as they prioritize spaces that allow higher speeds and minimize interactions with vulnerable users. Interestingly, the study shows no significant gender-based differences in speed, and both private and shared e-scooters exhibit similar patterns of road use, emphasizing that infrastructure design and regulatory frameworks must cater to general safety rather than user-specific characteristics. Insights from these findings propose that micro-mobility, when appropriately regulated, can effectively bridge gaps in urban transport networks, offering sustainable last-mile connectivity and reducing the burden on congested public transit systems. Future research directions suggest enhanced data collection, possibly through app-based surveys and video monitoring, to further refine e-scooter integration strategies.

The thesis proceeds to analyze the role of tactical urbanism within the City as a Commons framework, where collaborative, low-cost and temporary urban interventions facilitate safer, more inclusive public spaces. This research finds that participatory processes, exemplified by Bologna's experience as collaborative city planning, are essential in bridging policy and practice. The integration of video analysis technologies in urban design evaluation allows for precise, data-driven assessments of interventions, supporting continuous monitoring and refinement. For instance, the study of vehicular flows near pedestrian crossings in Bologna demonstrates how tactical interventions can significantly improve pedestrian safety by reducing vehicular speeds. This research highlights that tactical urbanism, with its agile and experimental approach, not only fosters civic engagement but also serves as a viable model for other cities aiming to promote sustainable mobility and urban safety. The analysis reinforces that participatory methodologies enhance project legitimacy and efficacy, a valuable insight for policymakers aiming to replicate similar projects in other urban contexts. Further, the thesis examines the application of the Impact Model (IM), which emerged as a vital tool for evaluating sustainable mobility projects within the European CrAFt project. The IM allows for multi-scalar analysis, capturing the transformation of urban spaces from granular, project-level details to broad, city-wide impacts. The DumBO case study in Bologna exemplifies how urban regeneration projects can utilize the IM framework to quantify improvements in mobility infrastructures, accessibility, and environmental quality. By combining local and regional indicators with European benchmarks, the IM provides a replicable methodology for assessing sustainable urban initiatives across diverse contexts. Findings from DumBO reveal that improved bicycle network connectivity and intermodal transport options significantly enhance urban accessibility, supporting Bologna's progression towards its ambitious sustainability goals. This structured and holistic evaluation model underscores the utility of adaptable indicators for continuous project monitoring and refinement, guiding cities toward achieving measurable sustainability outcomes.

In addition to these strategies to improve sustainable mobility in urban scale, this thesis explores how innovative technologies, including Virtual Reality (VR) and Building Information Modeling (BIM), can enhance sustainable mobility infrastructures. VR enables planners to simulate and evaluate various infrastructure configurations in a cost-effective, low-risk environment, offering insights that can refine design choices before physical implementation. In the French case study, using professional BIM software, a 3D model was created, with three points of view (POVs) assessed through VR-immersive (VR-IV) visits on an HTC Vive headset and one-minute real videos. Participants evaluated walkability and cyclability, with results showing consistent assessments between VR-IV and video formats, though VR-IV tended to

overestimate quality. This discrepancy highlights the need for improved photorealism in VR. Limitations include methodological constraints, such as the fixed order of video and VR-IV presentations, and the study's focus on young, able-bodied participants. Future work suggests expanding participant diversity, incorporating additional sensory modalities (e.g., auditory), and comparing VR-IV with onsite evaluations after the district is built to validate VR's utility for public auditing. Overall, VR's potential to simulate urban environments marks a significant advancement in mobility planning, providing planners with a user-centered perspective on infrastructural adaptations. BIM, on the other hand, facilitates integrated project planning by aligning physical infrastructure needs with sustainability goals, ultimately contributing to efficient resource allocation and long-term resilience of urban mobility networks. BIM's benefits are especially notable in projects that integrate environmental, cultural, and commercial interests, as seen in the Puglia tourist cycle path project. The study examines the entire BIM design process, demonstrating how it enables precise modeling of terrain, sections, and structural features, enhancing the infrastructure's alignment with environmental goals. Using the I-BIM approach, realistic virtual simulations were generated, allowing designers to compare various scenarios based on feasibility, cost, and environmental impact. In addition, BIM's ability to simulate construction phases and improve team collaboration marks it as a valuable tool for future sustainable infrastructure development, especially as urban mobility planning shifts towards active transport solutions like cycle paths.

The thesis also presents a forward-looking perspective on monitoring active mobility infrastructures, emphasizing the need for dynamic evaluation methods that can adapt to the rapidly changing urban landscape. To fill this gap, several sensors were installed in a bicycle for monitoring the cyclist behavior and kinematic characteristics. Data on speed, acceleration, and eye fixations revealed that infrastructure types impact cyclist behavior: for instance, a separate cycle path allowed the highest speeds, while paths with nearby vehicular flow prompted slower speeds and more lateral fixations. Eye-tracking analysis confirmed predominant forward gaze across sections, though lateral fixations increased with pedestrian or vehicle presence. ANOVA and correlation analyses underscored that both infrastructures and environmental elements significantly influence speed and visual attention, with implications for safer, user-friendly urban cycle infrastructure design. Through innovative sensor technologies and observational studies, this research demonstrates that the continuous assessment of pedestrian pathways can yield actionable insights for enhancing safety and infrastructure quality. The findings, for the Bologna case study, reveal that specific lighting setups, notably those with orange beacons (Condition 1) and fixed in-curb LED lighting (Condition 5), significantly reduce vehicle approach speeds compared to standard lighting alone. Lower

approach speeds, particularly under these configurations, resulted in a higher proportion of vehicles traveling at speeds below 25 km/h, the threshold enabling drivers to safely stop for pedestrians. Notably, Condition 5 achieved the best results, with 85% of vehicles allowing pedestrians to cross safely, compared to 56% under Condition 1. The results emphasize that lighting configurations play a critical role in pedestrian safety, as confirmed by a one-way ANOVA showing significant differences in driver speed responses. Condition 5, in particular, demonstrated notable improvements in driver behavior, validating its effectiveness as a measure to enhance crossing safety. These findings suggest that integrating adaptive lighting systems in pedestrian crossings can provide a reliable means of improving safety in urban areas, guiding future urban planning and infrastructure policy to prioritize similar configurations in high-traffic pedestrian zones.

In conclusion, this thesis not only bridges the gap between theoretical concepts and practical implementation but also provides a robust framework for future urban planners and policymakers. Notably, these monitoring methodologies are essential tools for policymakers and urban planners to effectively respond to the evolving needs of urban mobility and maintain high standards of safety and accessibility. The findings contribute to a deeper understanding of the practical challenges and opportunities inherent in sustainable transportation and lay the groundwork for future research that will continue to shape the cities of tomorrow.

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List of Annexes

- I. M. Pazzini, L. Cameli, C. Lantieri, V. Vignali, G. Dondi, and T. Jonsson, “New Micromobility Means of Transport: An Analysis of E-Scooter Users’ Behaviour in Trondheim,” *Int J Environ Res Public Health*, vol. 19, no. 12, Jun. 2022, doi: 10.3390/ijerph19127374.
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- III. L. Cameli, M. Pazzini, C. Lantieri, C. Mazzoli, K. Douka and A. Ferrante “Application of an impact model to assess the development of urban regeneration project: the case study of DumBO district”, CSUM Conference Proceedings, Sept 2024.
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Article

New Micromobility Means of Transport: An Analysis of E-Scooter Users' Behaviour in Trondheim

Margherita Pazzini ^{1,*}, Leonardo Cameli ¹ , Claudio Lantieri ¹ , Valeria Vignali ¹ , Giulio Dondi ¹
and Thomas Jonsson ^{2,*}

¹ Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, Viale Risorgimento, 2, 40136 Bologna, Italy; leonardo.cameli2@unibo.it (L.C.); claudio.lantieri2@unibo.it (C.L.); valeria.vignali@unibo.it (V.V.); giulio.dondi@unibo.it (G.D.)

² Department of Civil and Environmental Engineering, Norwegian University of Science and Technology (NTNU), Høgskoleringen 7A, Gløshaugen, NO-7491 Trondheim, Norway

* Correspondence: margherita.pazzini2@unibo.it (M.P.); thomas.jonsson@ntnu.no (T.J.)

Abstract: Negative effects of a massive use of cars, such as congestion, air pollution, noise, and traffic injuries, are affecting the cities everywhere. Recently introduced shared vehicles, such as e-scooters and electric bicycles, could potentially accelerate the transition towards sustainable mobility. Although these vehicles are becoming increasingly common and accepted within regulatory frameworks, some local governments are not yet ready to integrate e-scooters into their transport systems. Indeed, the legislation is unclear as it is not easy to determine whether the e-scooter is more like a bicycle or a vehicle. Moreover, it is difficult to predict the impact of e-scooters on road traffic, as well as the type of road infrastructure chosen by e-scooter drivers or the possible interaction of such vehicles with weak road users, such as pedestrians or cyclists. This study showed an analysis of speed and behaviour of e-scooter drivers in the city of Trondheim (Norway) to investigate how to manage this mode of transport. A total of 204 e-scooters were observed on six different roads in the city centre. The speed of e-scooter drivers was measured by a speed tracker (average value 15.4 km/h) and their behaviour recorded by a hidden observer in the field. Gender, age, distance from pedestrians, speed adaptation to the environment, and type of vehicle used were registered for each e-scooter. Through a Binomial Logit analysis, the data obtained were used to analyse the type of road infrastructure preferred by e-scooter drivers. Results showed that the cycle path is more widely used with percentage value from 60% to 90% of users. In addition, the probability of choice depended mainly on the road environment. The aim of this analysis was to assist local authorities in regulating the safe use of e-scooters and developing appropriate policies for their integration into cities.

Keywords: e-scooter; vulnerable road users behaviour; speed analysis; path choice



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1. Introduction

In urban communities the popularity and the use of micromobility is rapidly increasing, especially for the “last-mile” transportation solutions. Last mile transportation covers the gap between conventional transportation hubs (train station, bus stops, modal interchange parking spots, etc.) and the final destinations, especially in cases where infrastructures are very crowded [1]. In the report written by the International Transport Forum (ITF), micromobility is defined as: “[...] the use of micro-vehicles: vehicles with a mass of no more than 350 kg (771 lb) and a design speed no higher than 45 km/h”. This definition includes both human-powered and electrically assisted vehicles such as bicycles, e-bikes, kick scooters, and e-scooters but also skateboards, one-wheeled balancing boards, and four-wheeled electric micro-vehicles [2]. Micromobility can offer flexibility and efficient door-to-door accessibility, while public transport is characterised by higher speeds and greater spatial reach. The resulting synergy of high speed (and thus spatial reach) of public transport with the door-to-door accessibility provided by micromobility creates

a degree of access, speed, and comfort that can compete with that of private motorised vehicles [3]. Therefore, this combination makes modal shifts more attractive as well as potentially contributing to making cities more liveable, less congested and with reduced levels of air and noise pollution. In order to fully exploit the potential of micromobility towards a transition to more sustainable urban mobility systems, it is essential to analyse and study micromobility in the context of access to the first and last mile to and from public transport [4]. The concept of micromobility is constantly evolving. For this reason, the definition of micromobility is rather broad, as it is designed to be tested in the future and cannot be limited to a certain type of vehicle or source of energy. It can be used to facilitate the regulation of new vehicles placed on the market and to create a category that includes all micro-vehicles regardless of the vehicle characteristics, such as number of wheels or driving position [2]. The “E-scooter” is classified as a type of vehicle called powered standing scooter. This one must satisfy some conditions to enter in the micromobility category: weight below 500 kg, provision of a motor, and availability as a shared service. The speed range of the e-scooter, which makes its driving force, is strictly dependent on the battery of the model, but usually it is between 12–40 km/h [5]. This vehicle is smaller (occupying less space on the streets), lighter (making its transport easier) than a bicycle, and requires less maintenance. However, e-scooters have small batteries (i.e., less travel autonomy) and if they run out, there are no alternative ways to use them. The lack of pedals reduces flexibility and makes them a less healthy transport mode for users [6]. The two main types of shared systems are station-based and dockless sharing systems. While in a station-based system users can start or end their trips only at predefined locations, the dockless system allows users to start or end their trips (almost) anywhere in the city. Actually, e-scooter regulations differ widely among jurisdictions, with effects on the extent and nature of safety issues. It is important to establish the relationship between dockless e-scooters and existing bike sharing in order to be able to decide on fair transport policies and the infrastructures to be created including both bikes and e-scooters. For example, in Washington D.C., the spatial and temporal patterns of dockless e-scooters were explored to define trip origins and destinations. In addition, these data were compared to those of traditional docked bike-sharing services. Bikes are primarily used by individuals commuting to and from work, while e-scooters are used for leisure and tourist trips [7]. As for the type of use of an e-scooter based on its purpose, research in Austin (TX) showed that users tend to ride both bicycles and e-scooters with a lower average speed for leisure purposes (i.e., over weekends and off-hours) than during commuting or for other transport purposes (e.g., on weekdays and during working hours). The e-scooter speed, especially for transport purposes, is as high as the speed of a bike, but the results show that the average travel speed for bicycles (12 km/h) is slightly higher than the average travel speed for e-scooters (10 km/h) [8]. To prove the link of these two modes of transport, a study carried out in Chicago analysed the data of two sharing companies. The results proved that users of bike sharing decreased by 10.2% in the area reserved for shared vehicles with the introduction of shared e-scooters [9]. However, the real difference between these two transport modes lies in safety. In fact, focusing on the accidents, a study in Salt Lake City showed a significant increase since the arrival of e-scooter in the urban context. The largest number of types of injuries comprised orthopaedic and cranial injuries. With an increasing number of e-scooters and the spread of their use, these injuries are expected to increase as well. [10,11]. Another study confirmed that this increase in injuries results from the illegal and risky behaviour of both shared and private e-scooters [12]. Considering the danger associated with the use of e-scooters, Europe is trying to find rules for e-scooters, but unfortunately there is no ‘conformity’ or union within the countries of the European Union. A report of the European situation [13] was realised by the Forum of European Road Safety Research Institutes (FERSI), a non-profit organisation forming a flexible network of European road safety research organisations. A short questionnaire was created to make an inventory of the information available in different countries, in terms of legal status, use, and safety. Norway, Italy, and Denmark classify e-scooters as bicycles. In Switzerland, Portugal, and

Sweden the legal e-scooter category depends on the maximum speed of the e-scooter. In Austria, Belgium, Germany, France, and Spain e-scooters are considered as a separate category regulated by special laws, but, in general, the rules for bicycles have been applied for them. A particular situation is in Belgium where e-scooters belong to the category of ‘personal transportation devices’ with two sub-categories, motorised and non-motorised. These devices cannot be wider than 1 m and motorised devices, which e-scooters belong to, cannot go faster than 25 km/h. In all the countries considered, except for Hungary, there is a general maximum speed limit for electric scooters of 20 or 25 km/h. In Italy, the maximum speed limit is 20 km/h on mixed paths, both pedestrian and cycling, and 6 km/h in pedestrian areas. In Finland and the Czech Republic, the maximum speed limit is 25 km/h. If the e-scooter can travel at higher speeds, it is classified as a moped. In addition, in France, the speed of the e-scooter is limited to 25 km/h, but its speed limit is 45 km/h on the roads. In Sweden, there are three categories for e-scooters based on their maximum speed. If the e-scooter can reach 20 km/h, it is classified as a bicycle, 25 km/h it is classified as a class I moped, and 45 km/h classified as a class II moped. This survey highlights how countries are working to find a legal status for this means of transport and are still working to develop more targeted or specific legislation.

Authorities have to face important problems related to the use of e-scooters in the city, namely safety problems and urban space use issues. Moving on the empiric point of view, this research aimed to contribute to the literature through data obtained from field analyses of speed and behaviour, in terms of choice and interaction with the other weak users of the road. Moreover, the identification of the factors choice of the path may help local politicians to develop policies and rules based on concrete evidence and mobility planners to develop actions for better integration of e-scooters in cities.

2. Materials and Methods

Norway has been a e-scooter development hub, especially in Oslo where 17,984 e-scooters cover a service area equal to 246.09 km² (the second highest in Europe) [14]. Taking this into account, Trondheim is the third largest city in Norway by number of inhabitants with a high percentage of students, the right place to experiment on the use of shared e-scooters by a private company, the Ryde Technology AS. In summer 2019, this company distributed about 200 e-scooters around the city [15]. The measurements analysed in this study were taken within one month, from mid-September to mid-October 2019, between 8:00 a.m. and 6:00 p.m. with the peak time between 1:00 and 2:00 p.m. Six different road sections were defined in the city center of Trondheim. The geometric and functional characteristics of each road were analysed through an instrument consisting of a wheel with a counter measuring the distance travelled according to the number of revolutions completed by the wheel. The different roads are the following ones (Figure 1):

- Elgeseter, with a cycle path and a sidewalk on each side. This is an important bridge connecting the city center and the other part of the city;
- Olav Tryggvasons Gate, also with a cycle path and sidewalk on each side. This carriageway has a lane for each direction on which buses, trucks, and cars pass;
- Nordre Gate, a pedestrian street with a lot of interactions between pedestrians and cyclists; it is crowded in the afternoon when people leave work and schools;
- Innherredsveien, an important connection between the suburbs and the center, consisting of a sidewalk and a cycle path;
- Øvre Alle, a one-lane road with a sidewalk on one side; it connects NTNU University with some schools in the neighbourhood;
- Munkegata street, with two-lanes, parking spots, and two wide sidewalks for each side.

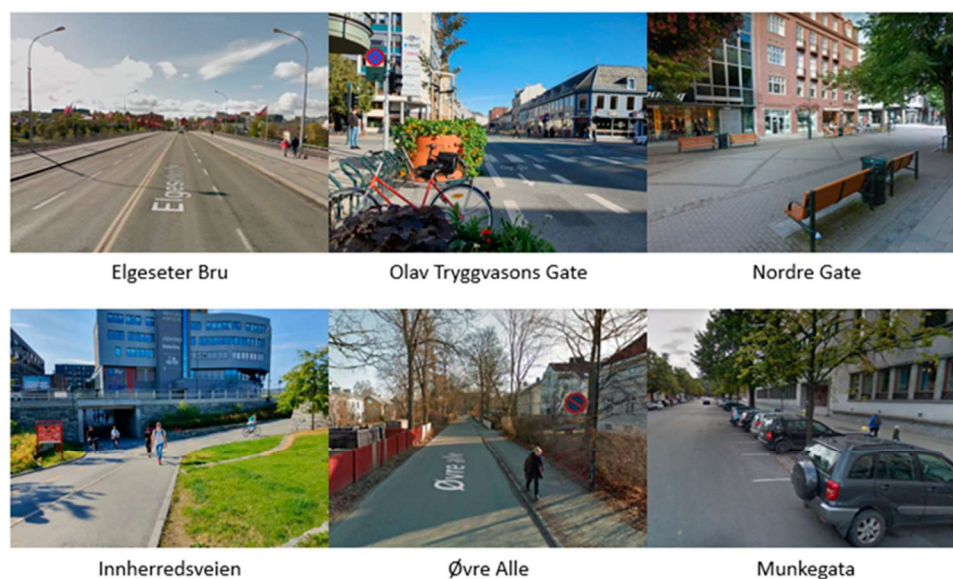


Figure 1. Pictures of the measurement points.

A traffic radar (Genesis VP Directional) was used to measure the speed of e-scooters. The radar instrument was installed in a hidden point, adjacent to the road section so as not to affect the user's behaviour. For precise measurements, the angle of inclination of the radar, regarding the direction of the users' motion, was as small as possible. If necessary, the measured speed based on the angle was corrected according to the manual instrument (Figure 2).

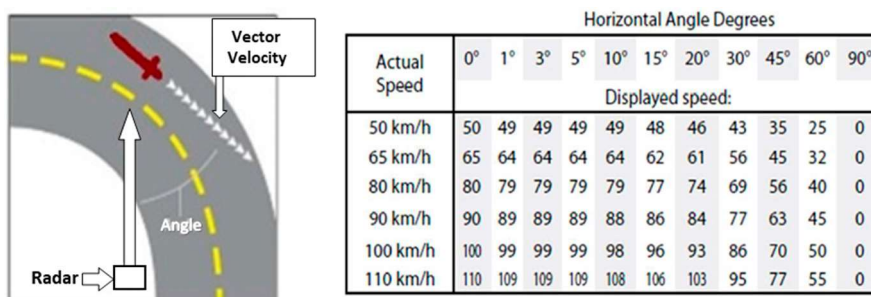


Figure 2. Relationship between antenna target angles and speed.

During the e-scooter ride, the observer collected other information to define the type of user and their behavior such as:

- Gender and age of driver divided into two groups, 18–35 and >35 years.
- Type of e-scooter used (shared or private).
- The path used by e-scooter riders (cycle path, cycle lane, sidewalk, pedestrian zone, or roadway).
- Number of people on the e-scooter at the same moment.
- The distance observed between the e-scooter and the other road users when overtaking. Overtaking is defined as the process of overcoming a slower means of transport or a person travelling in the same direction. Distances were measured at the beginning of the overtaking. The observer fixed some reference points on the analysed section, empirically defining the distances and measuring them. The differences were divided into four categories: no interaction with others, distance 1 m, distance 50 cm, and distance 30 cm (Figure 3).
- Driver behaviour in the presence of other users. It was divided into three categories: straight, when the e-scooter's users go straight without any influence from obstacles although these are very close; "zig-zag", when the drivers do not decrease the speed to

avoid or to overcome obstacles. The last category includes drivers who reduce speed in the presence of other users (Figure 4).

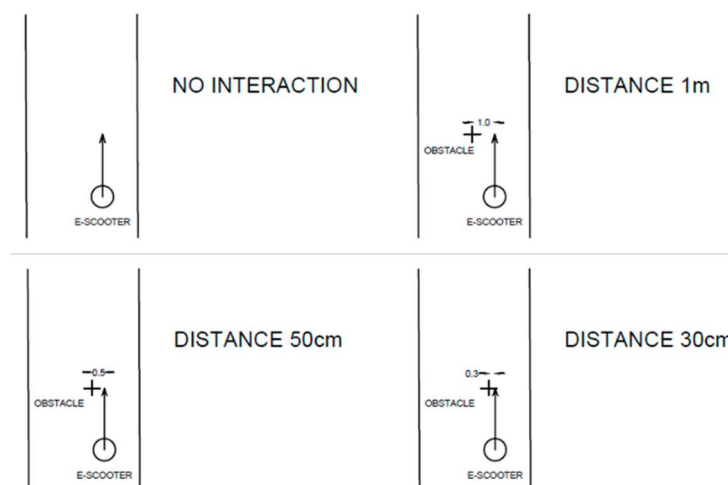


Figure 3. Different types of distances considered.



Figure 4. Different types of driver behaviour considered.

2.1. Statistical Analysis of the Data

2.1.1. Generalised Linear Model and Student *t*-Test

The Generalised Linear Model (GLM) was used to establish the relationship between the factors defined above (user characteristics, crowding, etc.) and speed (dependent variable) with the SPSS program. Thanks to GLM, the dependent variable was linearly related to the factors via a specified link function that described the relationship between the linear predictor and the mean of the distribution function. This ordinary linear regression predicted the expected value of a given unknown quantity (the dependent variable) as a linear combination of a set of observed values (predictors). When the dependent variable had a normal distribution, this model was appropriate to describe a random variable with real values that tended to concentrate around a single mean value. To estimate the parameters, the GLM used the Maximum likelihood estimation: this method estimated the parameters to maximise the probability of obtaining values of the depending variable on the values of the independent ones. Initially, after uploading the observed data and defining the variable types, the linear scale response could be chosen in SPSS, specifying Normal distribution and Identity as a connection function ($X\beta = \mu$; where X is the independent variable, β is the linear combination of unknown parameters, and μ is the average distribution). After that, the program wanted to know which variable was the dependent one (speed). The aim was to understand how and how much the speed changed in accordance with the other variables present in the model. Type I and Type III analysis were chosen because the former was generally appropriate when there was a fixed reason for ordering predictors in the model, while type III was more generally applicable. After these steps, the program was ready to calculate the results. For Type I, the 95% confidence interval was calculated for one factor at a time. The width of this range was directly related to the number of available data. According to previous research found in literature [16], through the Student's *t*-Test it

was possible to perform a test of statistical hypotheses in order to analyse any correlations between different categories within the same variable. The test was used to determinate whether the average values and the standard deviation of two datasets were significantly different from each other. The statistic t was calculated as follows:

$$t = \frac{B_1 - B_2}{\sqrt{se_1^2 - se_2^2}} = \begin{cases} < 1.96 \text{ no significant} - \text{present some correlations} \\ > 1.96 \text{ significant} - \text{the means are different} \end{cases} \quad (1)$$

- B_1 and B_2 are values returned by the model for each variable.
- se_1 e se_2 : standard error returned by the model for each category.

It is important to assess that the probability of rejecting the null hypothesis when it was true (the level of significance) for each category was equal to 0.001. The significance level (sig.) of 0.001 indicated a 0.001% risk to detect a difference when there was no actual difference. This was because speed had to be higher than 0 km/h. In fact, lower levels of significance indicated that stronger evidence was required before rejecting the null hypothesis. In addition, this test allowed to find statistical differences or similarities within the same factor between the different categories considered. By analysing the correlation of the variables, it was possible to determine three contexts:

- A complete overlap when the two categories were statistically similar;
- A complete separation when the two categories were statistically different;
- A partial overlap when the two analysed categories could be statistically similar or different. In this case, it was necessary to study carefully if there was a correlation.

2.1.2. Statistical Analysis of the Collected Data

The statistical analysis of the collected data showed the relation between categories inside the same variable. The aim was to understand how these categories were related and if the separation from the reference level could be relevant. The reference level was set on a young female rider who travelled on a private scooter without interactions with other road users in a pedestrian zone with also a cycle path present in Elgeseter Blu at a speed of 13.96 km/h. In this analysis, the SPSS program had information on the dependent variable (speed), categorical variable information, and the characteristics of the model as input. In output the model defined

- Test of model effect, (Table 1) where the level of significance (sig.) of each factor considered in the model was defined for analysis type I and III.
- Parameter estimates, a table (Table 2) providing for each parameter the intercept (reference level speed), the speed value in relation to the reference category, the 95% confidence interval, and the hypothesis test with the significance value. The last element showed how much a category within the variable was statistically significant in relation to the reference category.

Table 1. Tests of model effects.

Source	Tests of Model Effects					
	Type I			Type III		
	Wald Chi-Square	df	Sig.	Wald Chi-Square	df	Sig.
(Intercept)	4011.752	1	0.000	253.281	1	0.000
Street	34.623	5	0.000	4.502	4	0.342
Number of people	1.678	1	0.195	1.745	1	0.186
Gender	0.769	1	0.381	1.408	1	0.235
Age	0.808	1	0.369	0.787	1	0.375
Crowding	7.896	3	0.048	5.838	3	0.120
Behaviour	1.198	2	0.549	1.390	2	0.499
Path	2.598	2	0.273	2.598	2	0.273
AddInfo	0.002	1	0.965	0.002	1	0.965

Dependent Variable: Speed; Model: (Intercept); Street; Number of people; Gender; Age; Crowding; Behaviour; Path; AddInfo.

Table 2. Parameter estimates.

Parameter	Parameter Estimates						
	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Intercept)	13.96	21.7	9.69	18.22	41.18	1.00	0.00
(Street = OvreAlle)	0.48	22.3	−3.90	4.85	0.05	1.00	0.83
(Street = OlavTrygg)	−0.96	0.82	−2.56	0.63	1.40	1.00	0.24
(Street = Nordre)	−2.92	0.85	−4.59	−1.25	11.69	1.00	0.00
(Street = Munke)	−0.85	12.4	−3.27	1.57	0.47	1.00	0.49
(Street = Inherred)	0.75	0.82	−0.85	2.34	0.84	1.00	0.36
(Street = Elgeseter)	0 ^a						
(Number of People = 2)	−1.83	13.8	−4.54	0.88	1.75	1.00	0.186
(Number of People = 1)	0 ^a						
(Gender = M)	0.66	0.56	−0.43	1.75	1.41	1.00	0.24
(Gender = F)	0 ^a						
(Age = o)	0.58	0.65	−0.70	1.86	0.79	1.00	0.38
(Age = g)	0 ^a						
(Crowding = distance 50 cm)	0.17	16.1	−2.98	3.33	0.01	1.00	0.91
(Crowding = distance 30 cm)	−1.29	18.9	−5.00	2.42	0.47	1.00	0.49
(Crowding = distance 1 m)	1.90	16.7	−1.38	5.18	1.29	1.00	0.26
(Crowding = a no interaction)	0 ^a						
(Behaviour = zig-zag)	1.41	13.9	−1.31	4.13	1.03	1.00	0.31
(Behaviour = straight)	2.00	19.2	−1.77	5.76	1.08	1.00	0.30
(Behaviour = reduction speed)	0 ^a						
(Path = sidewalk)	−1.12	0.79	−2.67	0.43	1.99	1.00	0.16
(Path = roadway)	0.79	18.8	−2.89	4.46	0.18	1.00	0.68
(Path = pedestrian zone)	0 ^a						
(Path = cycle path)	0 ^a						
(AddInfo = sharing e-scooter)	−0.03	0.62	−1.25	1.19	0.00	1.00	0.96
(AddInfo = private e-scooter)	0 ^a						
(Scale)	12.055 ^b	11.936	9.929	14.637			

Dependent Variable: Speed; Model: (Intercept); Street; Number of People; Gender; Age; Crowding; Behaviour; Path; AddInfo. ^a. Set to zero because this parameter is redundant. ^b. Maximum likelihood estimate.

2.1.3. Backward Analysis

With SPSS it was also possible to carry out a backward analysis. This is a technique to analyse randomised algorithms from output-to-input. This process started with the statistical analysis of collected data (parameter estimates, Table 2) with all the internal variables. At each step, the GLM ran without the variable with the highest sig. value, which was statistically insignificant for the analysis. Table 3 shows an example of the test of model effect obtained after each step. The intercept showed the speed of the reference variable, and the B value was returned by the model for each variable.

It was possible to know what the most significant variables for the model were. After removing these variables, a change might occur in B value of the intercept or of other variables. Variables with the sig. value less than 0.06 were statistically significant while in other cases variables were not statistically significant. Although the check value was usually 0.05, 0.06 was chosen because the amount of data was not so wide, and the significance level had to be determined based on the context of the experiment performed. The value of 0.06 indicated that type I error was likely to be committed with 6% probability. This type of error occurred when a wrong hypothesis was made, and it was accepted [17].

Table 3. Test of model effects without street, Addinfo, and age.

		B	Std. Error	Sig.	
Intercept		13.545	1.983	Value	Diff. Absolute Value
NOP	2	−1.741	1.372	0.205	0.031
	1	0	-		
Gender	M	0.677	0.541	0.211	−0.017
	F	0	-		
Crowding	distance 50 cm	0.478	1.572	0.131	−0.001
	distance 30 cm	−0.869	1.865		
	distance 1 m	2.201	1.652		
	a no interaction	0	-		
Behaviour	zig-zag	1.954	1.303	0.237	0.032
	straight	2.635	1.835		
	reduction of speed	0	-		
Path	sidewalk	−1.909	0.659	0.000	0.000
	roadway	0.723	1.016		
	pedestrian zone	−3.184	0.751		
	cycle path	0	-		

2.1.4. Binomial Logit Model for the Pavement Choice

The binomial logit model was used to calculate the choice probability of using the sidewalk, a cycle path, or lane or the roadway by the e-scooter users. The purpose of this analysis was to understand how the choices of e-scooters were distributed. The binomial logit analysis was focused on the roads with sidewalks and cycle paths. Only these two kinds of infrastructures were chosen in order to analyse the interactions with the other road's users such as pedestrians and cyclists (only the data related to Elgeseter Bru, Olav Tryggvasons Gata, and Inherredsveien were considered). The logit analysis was possible with the SPSS software choosing the path as a dependent variable. The binomial logit method calculated the probability for an observation to fall into one or two categories of a dependent variable (in our case the probability to choose the cycle path or the sidewalk) based on one or more independent variables that could be continuous or relevant to the category (Street, Gender, Age and AddInfo). Therefore, the dependent variable was the path, the probability distribution chosen was the bi-nomial one, and the link function was the logit one. With the data and information on the categories obtained, it was possible to carry out tests of different possible effects on the model. These tests showed the significance level of each factor considered for the model, the probability of choosing the type of infrastructure, the standard error, and the significance value for each category. The software took the sidewalk as a reference level and the probability calculated was referred to the choice to ride on the sidewalk. The estimation of the parameters was followed by the estimation of the probability. The following formula of the Logit model should be used:

$$P = \frac{e^{\beta x}}{1 + e^{\beta x}} \quad (2)$$

where P is probability to choose the infrastructure and βx is given by the sum of all the parameters returned by the program and included in the choice of that infrastructure with

those specific conditions $\left(\beta x = \sum_i^n \beta_i\right)$. A backward analysis highlighted which variables influenced the choice of the e-scooter users.

In conclusion, the Figure 5 shows the flow chart about the used methodology implemented in this research.

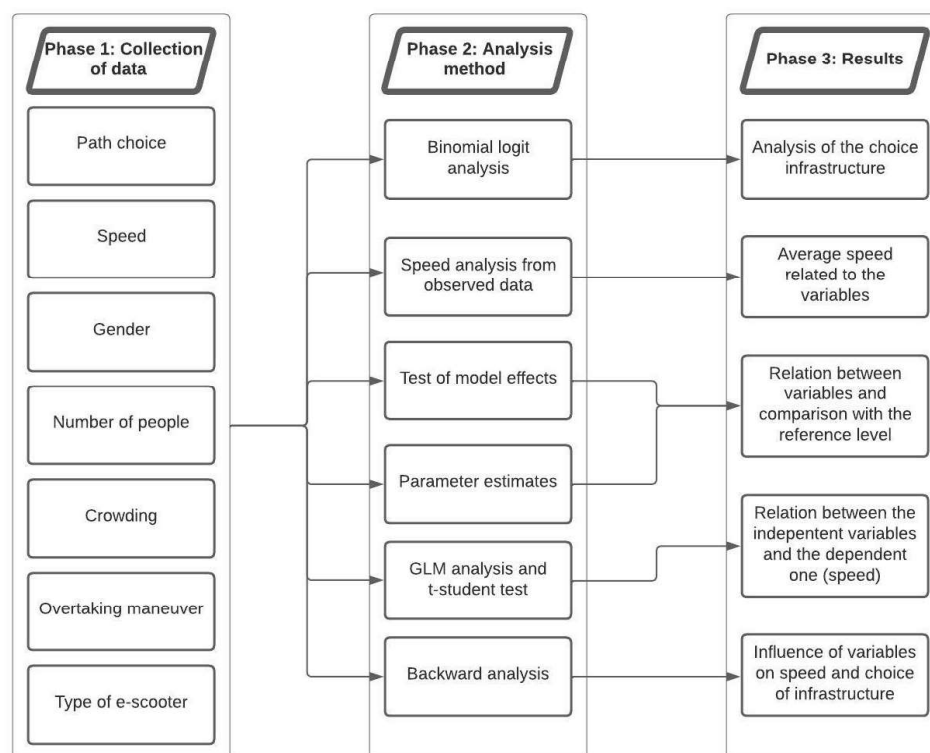


Figure 5. Flow chart of the research phases.

3. Results

3.1. E-Scooter Users

A total of 204 e-scooters were observed (Table 4) and the percentage of the different categories of e-scooter users was collected.

The table shows that in Trondheim most e-scooter users are men, although women were present (31.9%) too. As for the age, e-scooters are mostly used by young people. Comparing the results of this research with a Parisian survey, the percentage of men and women was the same (69% of men and 31% of women) as well as for the age (86% were under 35 years old and 14% other ones) [18]. This survey confirmed the trend of Trondheim, but the number of women was higher than in the Parisian context. Therefore, the most common e-scooter user is a man aged between 18 and 35 years old with a shared e-scooter, travelling without interaction with other road users and proceeding straight while moving on the cycle path.

3.2. Speed Analysis from Observed Data

By focussing on speed, it was possible to determine the average speed and the Standard Deviation showed no large variations of the speed value (Table 5). In addition, the speed distribution and normal distribution associated from the speed dataset recorded on the field were analyzed.

Table 4. Data collected by observer.

Categorical Variable Information				
		N	Percentage	
Factor	Street	Overalle	10	4.90
		Olavtrygg	45	22.1
		Nordre	45	22.1
		Munke	15	7.4
		Inherred	45	22.1
		Elgeseter	44	21.6
		Total	204	100.0
	Number of person	2	7	3.4
		1	197	96.6
		Total	204	100.0
	Gender	M	139	68.1
		F	65	31.9
		Total	204	100.0
	Age	18–35	37	18.1
		>35	167	81.9
		Total	204	100.0
	Crowding	distance 50 cm	24	11.8
		distance 30 cm	9	4.4
		distance 1 m	24	11.8
		a no interaction	147	72.1
		Total	204	100.0
	Behaviour	zig-zag	40	19.6
		straight	153	75.0
		reduction speed	11	5.4
Total		204	100.0	
Path	sidewalk	57	27.9	
	roadway	14	6.9	
	pedestrian zone	45	22.1	
	cycle path	88	43.1	
	Total	204	100.0	
Addinfo	sharing e-scooter	159	77.9	
	private e-scooter	45	22.1	
	Total	204	100.0	

Table 5. Average speed and standard deviation.

		N	Min Speed (km/h)	Max Speed (km/h)	Average Speed	Std. Deviation
Dependent Variable	Speed	204	9	27	15.4	3.88

By comparing speed with the age and gender of users, it was possible to see that male users aged 18–35 years represented the fastest category. This result is in accordance with a study in China, focused on the red-light running behaviour. It showed that age and gender were significant variables to predict the behaviour of drivers at traffic lights with red lights. In fact, young men aged 18–35 and middle-aged men drivers were more likely to accelerate than older people in front of the red light [19]. In addition, users who proceeded straight maintained a higher speed than the other categories (15.80 km/h), followed by the zigzag (14.58 km/h) and speed-reducing users (12.82 km/h) when meeting other road users. With reference to the chosen path, the highest speed was recorded on the road (17.21 km/h) followed by the cycle path (16.59 km/h). Users on the pedestrian zone or sidewalk were the slowest (13.49 km/h and 14.61 km/h respectively). This is evidenced by the gap between e-scooter and pedestrian speed. In fact, a study on the speed pedestrian at the crossing [20]

showed that the users speed fluctuated from 2 to 8.5 km for hours. So, the gap between the two categories was equal to 10 km/h. The behaviour of e-scooters drivers in vicinity of a pedestrian route was analysed in relation to the measured speed, comparing the data on the crowding and different paths (Table 6). As for the path, the pedestrian zone, the cycle path and sidewalk were the only ones to vary because they were the only ones with interactions. Table 6 shows the relations between the above categories and the speed:

- on the cycle path, the users with a distance lower than 50 cm from the other road users during the overtaking were the fastest (16 km/h);
- in the pedestrian zone the rider driving 1 m from another road user, during overtaking, was the fastest. The other two categories held the same average speed. One explanation might be that the driver overtaking another road user at a distance of less than 50 cm did so during rush hours, when the road was busier, and people were driving faster as they were in a hurry;
- on the sidewalk the difference between the average speeds of the two different categories, without interaction and with 50 cm, was equal to 2 km/h. One explanation might be that the driver in a crowded situation usually reduced the speed to avoid interactions and to overtake others with a shorter distance than in other cases. Those who drove keeping 1 m from other road users were as fast as those who drove without finding interactions. In fact, the first category was made up of drivers who were in a hurry and did not reduce the speed but overtook the others maintaining a good distance.

Table 6. Relations between the variables crowding, path, and speed.

Crowding	Average Speed Measured (km/h)			
	Cycle Path	Pedestrian Zone	Sidewalk	Total
No interaction	16.59	12.81	15.00	15.63
Dist. ≤ 50 cm	17.00	12.93	13.00	13.45
Dist. 1 m	16.00	16.00	15.46	15.71
Average	16.59	13.49	14.61	15.26

3.3. Speed Statistical Analysis from Observed Data

Trough GLM analysis it was possible to calculate the 95% confidence interval and the statistical hypothesis with the Student's *t*-Test for each variable of categories (Table 7). This statistical analysis underlined the possible relation between the independent variables and the dependent one (speed). Table 8 shows the average speed, the standard error, the 95% confidence interval, and the value of significance for each path.

Table 7. Parameter Estimates for the Path Factor.

Parameter	B	Std. Error	Parameter Estimates				
			95% Wald Confidence Interval		Hypothesis Test		
			Lower	Upper	Wald Chi-Square	df	Sig.
(Path = sidewalk)	14.61	0.48	13.67	15.56	924.44	1.00	0.00
(Path = roadway)	17.21	0.97	15.31	19.12	315.04	1.00	0.00
(Path = pedestrian zone)	13.49	0.54	12.43	14.55	621.77	1.00	0.00
(Path = cycle path)	16.59	0.39	15.83	17.35	1839.44	1.00	0.00
(Scale)	13.169 ^a	1.30	10.85	15.99			

Dependent Variable: Speed; Model: Path; ^a. Maximum likelihood estimate.

Table 8. *t*-test for the variable Path.

	Average Speed	Sidewalk	Roadway	Ped Zone	Cycle Path
	[km/h]	<i>t</i> -Test Value			
Sidewalk	14.61404				
Roadway	17.21429	2.40			
Ped zone	13.48889	1.55	3.35		
Cycle path	16.59091	3.20	0.60	4.66	

Focusing on the relation between the different paths detected by Student's *t*-test (Table 8), some categories revealed statistically more significant differences compared with others:

- Sidewalk–Roadway: these two categories were statistically different with a *t*-Test value higher than 1.96. This was because those who drove on the road had to pay attention to many things compared with those who proceeded on the sidewalk. The same can be said for the relationship between sidewalk and cycle path;
- Roadway–Pedestrian zone: these two intervals were separated because the speed and the behaviour of riders were statistically different;
- Pedestrian zone–Cycle path: these two intervals were separated. Differences could be found in the different environments and related behaviours this type of path entails as the bike path is included in the road.

The next step was the Statistical Analysis of the collected data used to understand how the speed and the other variables analysed were related and whether the difference with the reference level could be relevant (Figure 6). Analysing the most important variables, the following considerations can be made:

- Street: Inherredsveien was the fastest street because the section chosen for the analysis was on a small hill and people could run faster than in the plain. The slowest road was Nordre Gata because this was a pedestrian zone and speed had to be reduced to avoid interaction with other road users;
- Crowding: the relationships between the categories did not change too much. The fastest category was those of riders overtaking other road users with a certain distance (1 m) followed by users without interactions. The slowest consisted of those who overtook with less than 50 cm from the others.
- Behaviour: the difference between the fastest and the slowest speed was very relevant in this case, 2 km/h. The same trend was shown by the simple analysis of the data considering one factor at a time;
- Path: the user on the road was faster than on the other paths but the slowest was the user who rode on a sidewalk due to interactions with pedestrians.

A backward analysis was carried out to check the influence of the variables considered (such as path, gender etc.) on the speed.

The variable with the highest significant value (sig.) was excluded at each step. When the significant value of the variable was 0.00 it meant that the variable was statistically significant for the analysis. The removal of the variable "Street" implied a reduction of the significant value for Behaviour, Path, and AddInfo. On the other hand, the removal of Gender, Age, and Crowding led to an increase of the significance value. There were changes of speeds for the Path categories: those who rode on the roadway were the fastest followed by the cycle path users and sidewalk users. People in the pedestrian zone were the slowest. After that, the categories "Additional Information", "Age", Number of people, and Gender were removed. This did not involve a large variation of the significance value of the different variables and the changes of the other variables were very limited since these factors were not so relevant in the model. The next variable to be erased from the analysis was "Behaviour". In this case, the crowding was the only variable that improved its significance value. The only thing changing was the order of different speeds within

the crowding factor: those who overcame with distance 1 m were the fastest followed by the users with no interactions and the users with 50 cm distance when overtaking. The statistically significant variables for the model were Crowding and Path (Table 9) with a low significance value.

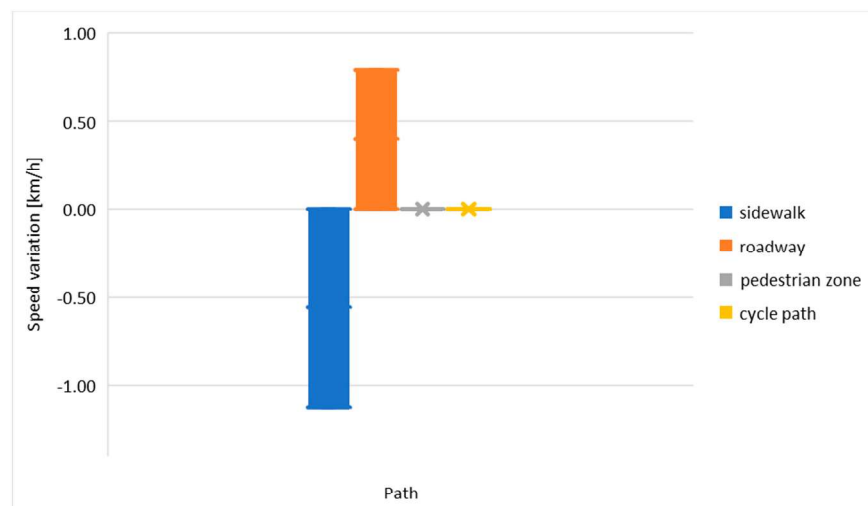


Figure 6. Differences of the absolute value of the speed with reference to path.

Table 9. The test of model effects with statistical significative variables.

		B	Std. Error	Sig.	
Intercept		16.576	0.383	Value	Diff. Absolute Value
Crowding	Distance 50 cm	−0.361	0.838	0.064	0.011
	Distance 30 cm	−2.190	1.281		
	Distance 1 m	1.387	0.851		
	No interaction	0	-		
Path	Sidewalk	−2.029	0.663	0.000	0.000
	Roadway	0.638	1.027		
	Pedestrian zone	−3.081	0.719		
	Cycle path	0	-		

3.4. Analysis of the Choice Infrastructure Percentage by Users

It was then possible to calculate the probability to choose the sidewalk or the cycle path considering the variables Street, Gender, Age, and AddInfo referred to the analysed section. The result of the binomial logit model for the three streets with these different infrastructures (131 measurements) were as follows:

1. For the two streets with a good separation between the roadway and the cycle path (Inherredsveien and Elgeseter) all e-scooter users preferred to choose the cycle path (Table 10). This was also supported by the backward analysis because the program returned the same trend regardless of the variables considered within the model (Table 10, last column).
2. For the street with a cycle lane adjacent to the roadway without any physical separation, it was possible to see a different behaviour with reference to the age of the users: a higher percentage of young people (18–35 years) chose to ride on the sidewalk (Table 11); the opposite was for the category > 35 years old. A backward analysis showed that for this street the only variable involving some changes was the Age. When street was the only variable, the results showed a higher probability to choose the sidewalk instead of the cycle lane (Table 11, last column).

Table 10. Probability to choose the cycle path (Pcp) and sidewalk (Psw).

	Inherredsveien								B.A
	Male Old Shared	Male Old Private	Male Young Shared	Male Young Private	Female Old Shared	Female Old Private	Female Young Shared	Female Young Private	
Psw [%]	3.75	4.13	7.71	8.45	2.73	3.00	5.67	6.23	6.67
Pcp [%]	96.25	95.87	92.29	91.55	97.27	97.00	94.33	93.77	93.33
	Elgeseter								B.A
	Male Old Shared	Male Old Private	Male Young Shared	Male Young Private	Female Old Shared	Female Old Private	Female Young Shared	Female Young Private	
Psw [%]	26.89	28.89	44.09	46.55	20.93	22.62	36.20	38.52	38.64
Pcp [%]	73.11	71.11	55.91	53.45	79.07	77.38	63.80	61.48	61.36

Table 11. Probability to choose the cycle path (Pcp) and sidewalk (Psw) for case 2.

	OlavTrygg								B.A
	Male Old Shared	Male Old Private	Male Young Shared	Male Young Private	Female Old Shared	Female Old Private	Female Young Shared	Female Young Private	
Psw [%]	41.54	43.97	60.37	62.72	33.83	36.09	52.29	54.76	54.76
Pcp [%]	58.46	56.03	39.63	37.28	66.17	63.91	47.71	45.24	45.24

A backward analysis was also carried out to find out which variables most influenced the choice of the type of infrastructure. Considering all the factors, the variable with the highest significant value was excluded at each step as statistically not significant for the analysis. In Inherredsveien and Elgeseter, not all categories created to differentiate the type of users were necessary. Depending on the model used, the users chose the type of infrastructure in relation to the geometry and the environment of the road considered. There were no differences between the different categories except for the value of the choice probability. The information about the different means of transport, shared or private, did not affect the choice of the favourite infrastructure for that model. The different types of e-scooter used had very little influence on the infrastructure chosen. After the backward analysis, it was possible to notice that the removal of the variables from the analysis did not involve major changes, especially for the significance value.

4. Discussion

E-scooter users analysed in Trondheim showed similarities within the European contest. In FERSI survey [13], the main users of different European countries were analysed. Half of the countries (such as Norway and Germany) indicated that young adults were the main users of e-scooters. The other half (including Italy and Spain) did not have information about what age group the users mainly belong to. Outside Europe, a survey in Minneapolis [21] showed the ratio between the percentage of the young population and the male and female and results were like those in Trondheim, namely that most e-scooter users were young men. This trend was confirmed by a questionnaire in Greece where the results showed that e-scooters increase the gender mobility gap instead of bridging it [22]. On the contrary, gender research in Seoul about the use of e-scooters showed greater uniformity with the percentage between men (52.6%) and women (47.4%) [23]. As for speed, the results obtained in this study on e-riders were compared with the average speeds of cyclists. Research in Sweden found that the average speed held by cyclists was between 12.5 during daytime and 26.5 km/h [24]. A similar result was measured in Italy [25] where it was shown that the average speeds of cyclists varied between 14.6 and 22 km/h. This

result was also confirmed by research in San Jose, California [26], where e-scooter speed ranged between 14 and 18 km/h. So, the average speed of e-scooters (15.4 km/h) was about the same as that of cyclists in all the research. On the other side, a research study on the vibration given by the path showed that e-Scooter riders experienced more severe vibration impact than cyclists if they were running on the same facilities. So, the e-scooter riders were subject to increased safety challenges due to the increased vibrations, speed variations, and constrained riding environments [27]. It was also interesting to identify the characteristics of the road chosen and how it influenced the behaviour of drivers. The analysis showed that that Øvre Alle was the fastest street, probably because it was a small street connecting NTNU University with some schools in the neighbourhood, so it was particularly crowded only in the morning during peak hours (around 8:00 am). Nordre Gata was the slowest one maybe because it was a pedestrian zone shared by cyclists and pedestrians. In fact, e-scooter-users reduced speed in the presence of vulnerable users on the same way or in crowded conditions since they had to pay more attention to avoid interactions. Drivers on roadways were the fastest, followed by those who rode on the cycle path. Moreover, speed of e-scooters decreased during overtaking when the distance between them and other users decreased and when they found other road users on their way. This trend was confirmed by the behaviour of cyclists whose speeds were influenced by the presence of other road users. In fact, when the path was shared with pedestrians, the cyclists' speed decreased accordingly [25,28]. The cyclist adjusted the speed when meeting pedestrians just like e-scooter drivers did [13]. Gender and Age, on the contrary, did not affect the speed of e-scooters. Statistical analysis carried out by SPSS software showed different results from the analysis of the measured data, possibly because the program considered all factors together, instead of each separate variable as the present study did with the data collected. On the contrary, as for the road infrastructure chosen, the characteristics of users, and the crowding of the road with respect to the speed, the same conclusions were reached as the analysis of the collected data. At the end of the backward analysis carried out thanks to GLM results, it was possible to conclude that the factors that mainly influenced the GLM model (and the speed accordingly) were Street and Behaviour. In fact, their removal led to big changes in the results of the analysis. Significant factors for the model were also Path and Crowding, fundamental to give relevance to the model when analysing the variation of speed. Finally, there were no relevant differences between the average speeds for the variables Gender, Age, and AddInfo. Analysing the type of road chosen, according to FERSI survey [13] about e-scooter riders in Europe, most countries replied that e-scooter drivers are likely to use bicycle facilities, if available. When not available, they are expected to use the road in Austria, France, Germany, Portugal, Sweden, and Switzerland if the speed limit on that road is not higher than 50 km/h. In Norway, e-scooters are allowed to use all parts of the road, and they are supposed to use the sidewalk only when pedestrian traffic is low and they are not dangerous for pedestrians. This research in Trondheim confirmed the European trend in the use of the cycle path. As in Inherredsveien and Elgeseter, the choice of the infrastructure was closely linked to the road environment and did not depend on other variables. The same behaviour was recorded in a study carried out in Virginia using the data collected by the Global Positioning System. The model results suggested e-scooter riders were willing to travel longer distances riding on cycle paths (59%), multi-use paths (28%), and the remaining percentage on other way [29]. Different results were recorded during the pandemic: e-scooter users were attracted to sidewalk infrastructure, even though curb use policies often prohibit it. This could be explained by the feeling of protection from the sidewalk given by the roadway [30]. The users' speeds showed that in the section with pedestrian zone and cycle path or in the local roads the average speed was higher than that of a two-lane road (two lanes in two directions) with pavements, one on each side, as in Munkegata. The Age variable was fundamental for Olav Tryggvason Gata. In fact, according to the model, the over-35-year-old category preferred to use the cycle path while younger riders preferred the sidewalk, possibly because in this street, the cycle path was at the same level as the road without any protection and the sidewalk was very

wide. Younger users chose to ride on the sidewalk at a lower speed than on the cycle path. As for the distance that e-scooters kept from the other road users during overtaking, and those who overtook with 1 m distance and those who had no interactions were the fastest.

5. Conclusions

Few data are available on e-scooter riders based on speed, their behaviour on the road, and safety. The concern of policy makers is increasing accordingly because of the lack of appropriate regulations for e-scooters. Although not such a large sample was analysed in Trondheim, from the analysis of data this study provided some answers that could help to adapt e-scooters into a regulatory framework with appropriate laws:

- Most e-scooter users are young men, but women are present too and the percentage is increasing.
- Gender and Age do not affect the speed of e-scooters.
- In terms of speed, there is not a great difference between bicycles (15–18 km/h) and e-scooters (15.4 km/h).
- Both cyclists and e-scooter drivers choose the infrastructure that makes them feel safer when travelling with limited interaction with weaker users.
- E-scooter riders prefer infrastructures separated from cars, such as cycle paths (90% and 60% in Inherredsveien and Elgeseter, respectively), bike lanes, or sidewalks (55% in Olav Tryggvasons Gate) which allow higher speed and less interactions.
- E-scooter users reduce speed in the presence of vulnerable users on the same way or in crowded conditions.
- The different types of e-scooters, shared or private, do not influence the choice of the infrastructure.

As said before, probably the number of analysed e-scooters, divided between shared and non-shared, could be increased in order to reach a greater precision in the analysis. Additional data on the relationship between the behaviour of e-scooters and interactions with other users and cyclists could be collected with a survey through the app used to rent e-scooters and installing cameras. Information about the busiest hours of the day, the average speed and the length of each trip may also be collected. In addition, it could be very interesting to simulate e-scooters in city-centre traffic through a microsimulation, especially in situations of extreme crowding. These data could be useful to deepen the problem of the distance maintained by e-scooter riders especially during overtaking. But they could also be useful to decide what solutions to take to improve the coexistence of e-scooters with pedestrians and cyclists, as well as the best places to install parking lots. Finally, e-scooters could replace non-active means of transport or very crowded public transport without major investments in public mobility.

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Participatory process for upgrading public spaces through sustainable mobility and social inclusiveness

Leonardo Cameli^{1, *}, Claudio Lantieri¹, Cecilia Mazzoli², Anna Chiara Benedetti², Annarita Ferrante², Roberto Corbia³

Abstract: The EU project “CrAFt - Creating Actionable Futures” aims to promote participatory processes to support cities’ transition to climate neutrality, according to the “City as a Commons” approach. The City as a Commons framework, developed by the city of Bologna, provides a reference for designing and deploying Climate City Contracts (CCCs) that support innovative forms of inclusive, participatory governance and integrated urban planning strategies with increasing implementation of digital technologies and innovative management. Bologna is an example of a “collaborative city” that improves the principles of “urban collaborative democracy”. Tactical Urbanism is a process of urban transformation providing a cohesive activities package to support cities in realizing collaborative local governance models for reshaping urban spaces with temporary and not expensive elements. Citizens are involved by activating a feedback loop to collect their opinions about the regeneration intervention. For selected road sections, the Municipality of Bologna redesigned experimental pedestrianization projects through Tactical Urbanism to create new large spaces to be used for recreational functions. This experience, conducted by Fondazione Innovazione Urbana (FIU) in the city of Bologna, shows that this participatory and co-creative process allows for transforming poorly organized street areas into new spaces for sociality, mitigating the city's environmental impact.

Keywords: tactical urbanism, sustainable mobility, social inclusiveness, participatory processes, public spaces, New European Bauhaus

¹ Department of Civil, Chemical, Environmental, and Materials Engineering—DICAM, School of Engineering, University of Bologna, 40126 Bologna, Italy

² Department of Architecture, University of Bologna, 40126 Bologna, Italy

³ Fondazione Innovazione Urbana 40124 Bologna, Italy

* Correspondence: leonardo.cameli2@unibo.it; Tel.: +39 0512093522

1 Introduction

The concept of an ideal city is a fallacy, as is the notion of a singular path to achieving climate neutrality or an ideal social innovation process. Each city is unique and has to find itself at a different stage in the trajectory toward climate neutrality. Despite the varying contexts, challenges often relate to well-known transition bottlenecks such as users' behavior change, goal setting, funding, and overcoming regulatory barriers. The challenges differ in specific characteristics from one city to another, necessitating a standardized yet adaptable approach. The European Commission works in this way launching the New European Bauhaus (NEB) which wants to translate the European Green Deal into the ground, in buildings, in public spaces and also in fashion or furniture [1]. The CrAFt project aims to address these transition bottlenecks directly by providing a comprehensive set of activities to support cities in the development and implementation of collaborative local governance models, regardless of their starting point. The project seeks to co-create and test NEB-inspired collaborative local governance models in three Sandbox Cities to identify stakeholder needs and match them with concrete opportunities. The Sandbox Cities will aim to document and optimize the real-life performance of the collaborative governance models at different stages of development, learning from and inspiring others while disseminating project knowledge. Within CrAFt, three Sandbox Cities and 60 Reference Cities will contribute to refining and implementing a NEB-inspired Impact Model. The Impact Model will help identify essential leverage points for systemic change towards climate neutrality by incorporating all aspectual layers of sustainability, including ecological, infrastructural, social, cultural, economic, aesthetical, and legal considerations. The Impact Model does not replace the indicator sets cities already use; instead, it complements them by providing a guidance instrument to improve shared understanding and support cross-cutting decision-making between stakeholders from different sectors and disciplines. Recently, the Impact Model will support the Cities Mission in deploying Climate City Contracts (CCCs) by helping cities create and implement local collaborative governance models that leverage inclusiveness, aesthetics, and sustainability in the context of their specific city's transformation towards climate neutrality. Bologna is a Sandbox city and will be used as a test field. This city in the last years developed the city as a commons approach". The City as a Commons approach is deeply interconnected with the concept of collaboration, collaborative governance, and democracy. Additionally, it is based on participatory processes in which co-creation and "living labs" are valuable tools.

The City as a Commons approach is founded on the capacity of the city to adapt, transform, make, and remake according to the citizens' needs and requirements. Participatory processes, such as co-creating, co-designing, and co-governing, are promoted by the cooperation between local administrations, municipalities, citizens, and other facilitators, such as local associations, economic actors, and other stakeholders, to convey the concept that the city consists of urban commons everyone takes care of and enables regeneration practices. The "City as a Commons" concept is linked to cities' openness and capacity to make, remake, adapt, and transform themselves according to their inhabitants' needs and "to compete for the people and

goods that help to grow and sustain them” [2]. The governance model of “urban collaborative governance” focuses on social and economic equity or inclusion. The term participation is related to empowerment in order to support inclusiveness, diversity, and democracy. It’s necessary to deal with persistent problems such as social exclusion, spatial dichotomies, and segregation. In the innovative social theory, the bottom-up processes are a significant tool for the activation of the communities. Furthermore, participatory processes are conceptualized as “self-organization”, civic-initiated action to influence the urban environment [3], [4]. Co-creation is part of participatory practices. In urban development, co-creating relies in part on the knowledge and experience of private sector processes, which are applied to public service delivery [5]. In addition, this term refers to the general knowledge about citizens and their experience with public services. Citizens can actively contribute through their knowledge and ideas in order to create new collaborations. In particular, the concept of co-creation is a “mosaic” of ideas and norms from varied research traditions and activities, as well as sectors such as urban planning, design, innovation, marketing, and management. The City as a Commons model proposed by Foster and Iaione [6] comes from the research of Elinor Ostrom [7], whose design principles need to be adapted to rethink the governance of cities according to the City as a Commons. The innovative perspective offered by the City as a Commons proposes a different insight into the city administration based on co-creating, co-designing, and co-governing practices. This governance model is called “urban collaborative governance” and focuses on social and economic equity or inclusion. In this system, the state is a facilitator and a relational state, which redistributes its decision-making power and influence to the public. In this vision, municipalities have to engage their citizens and foster collaboration between them and public authorities to convey the idea that the city is a common resource everyone should take care of. In this regard, Bologna can be considered an important example of implementing the City as a Commons approach and a “collaborative city” that used and still uses the language of the commons according to the principles mentioned above of “urban collaborative democracy”.

In this way, the municipality of Bologna, has activated tactical urban planning policies in different areas within the city. These are particular interventions for the transformation of poorly organized road areas, designed to obtain new spaces for socializing and mitigating the environmental impact of the city increasing the functional and architectural quality of urban space. Past and current experiences in Bologna offer an innovative lesson in terms of governance, collaboration and caring for common goods, but they are part of a process that is still ongoing.

2 The support of the district lab for the sustainable mobility

The "COVID-19" emergency has imposed and continues to impose, to live in the city and its spaces in a different way, in particular the space focused on social relations and mobility. In this situation, the dimension of "proximity" and the presence of public spaces spread throughout the city, represent an enormous value in the qualitative dimension of people's lives. Bologna in the future, from this point of view, can only confirm and strengthen the path taken through the planning tools it has equipped itself

with in recent years, accelerating implementation times and implementing some actions also of an experimental nature. In responding to the needs and requirements that have emerged and been mapped in the various parts of the city in recent years, these will immediately affect the reconfiguration of spaces, thus giving answers to citizens. Since the publication in 2014 of the Regulation on Collaboration Between Citizens and the City for the Care and Regeneration of Urban Commons[8], more than 800 collaboration pacts have been signed between the Municipality, local associations and citizens to promote the realization of regeneration actions in defined urban areas. The Municipality of Bologna, together with the Urban Innovation Foundation (FIU) and the University of Bologna (UNIBO) have participated in and fostered many collaborative initiatives through laboratories in the districts where the citizens, local associations, and stakeholders can join and start a shared path based on listening, dialogue, and prototyping. Bologna was the first city to implement the city as a Commons approach and the “co-city” protocol, articulated in the following phases: “cheap talking” (meant as dialogue interaction), mapping, practicing, prototyping, practicing, and modeling.

All these concepts and practices are the basis for a new form of civic engagement called “living labs”. These labs got popular, especially under the heading of smart cities and inclusive activities. In Living Labs, citizen and user involvement is central, and innovation takes place as a result of bringing together complementary knowledge, skills and resources in real-life experimentation. About 7,000 people participated in the District Labs in 2017-2018 through neighborhood public assemblies and online topic meetings, which resulted in 60 projects for participatory budgeting. In this way, the Regulation on Collaboration Between Citizens and the City for the Care and Regeneration of Urban Commons was the first regulation for care and regenerating the urban commons identified as mostly public spaces, abandoned buildings, infrastructures, and urban green areas. The Regulation identifies the collaboration pacts as the legal instrument for establishing public-community partnerships between citizens/local inhabitants, local officials/PA, local NGOs and local businesses. In 2014-2016, 261 proposals were developed, and 245 collaboration pacts were signed within the municipal territory regarding different fields: maintenance of green spaces, public spaces, and schools; interventions to improve bicycle paths, roads and squares and elimination of architectural barriers. The first two years of implementation of Bologna Regulations positively affected the city in terms of the number of collaborative initiatives but, at the same time, highlighted the importance of creating a network of stakeholders and collective economic institutions that could provide significant financial support, acting at the neighborhood level and throughout the entire city. Additional valuable tools as implemented in the City as a Commons in Bologna are:

- Towards the Urban Innovation Plan with District Laboratories [9]: the Plan started in December 2016 with the aim of tracing a transversal innovation perspective for the Municipal Administration of Bologna. The process of territorial engagement was grounded on the “District Laboratories”, spaces for discussion and decision-making, whose main objective is to connect policies and decisions with the networks.
- Tactical Urbanism: it is a process of urban transformation that allows the use of space to be quickly changed with temporary and not expensive elements, analyzing

their effectiveness and defining the final adaptive design following the users' reactions to the space. The aim is to understand how experimentations work and identify, directly from citizens' reactions, which aspects need to be changed according to the final intervention. The areas, chosen for this process, typically have traffic and environmental problems and the implementation of tactical urbanism usually regards the temporary pedestrianization of this type of area. The key to tactical urbanism is that the final design should better respond to the needs of the inhabitants and the environment because people have already had the opportunity to experience the space through temporary experimentation and opportunities to suggest improvements.

For these type of actions, the municipality of Bologna has provided the experiments of tactical urban planning of via Milano, via Procaccini, explained in the following paragraph. In addition, new areas of experimentation have already been identified in March 2023. In particular, these are experimental interventions for the construction of school squares, aimed at solving the problems of viability affecting the conflict between cars and pedestrians in the hours of entry and exit of students. These projects involve the reorganization of the flows of vehicles and people, stimulating diversified ways of accessing the school complex. In particular, "kiss & ride" areas will be created at different distances from the building to prevent the concentration of cars in front of the school.

3 The pedestrian temporary area: the case study of Bologna

The new pedestrian areas are conceived as experimental interventions of pedestrianization of road sections now used for car traffic or parking, through creative interventions of tactical urban planning, aimed at creating new large spaces to be used for recreational / sports / cultural proximity functions [10]. Pedestrianization has been imagined with different gradients and intervention characteristics. Some may be continuous, others are limited to certain times. In addition to those directly related to the requests of traders for the de hors, will be of three categories:

- a) Spaces for pedestrians near school entrances with widening of spaces near schools, the transformation of road or parking areas into pedestrian areas moving the missed parking, speed limitation, etc.
- b) Design of playground with the insertion of urban furniture even green and any physical game elements (sitting, planter, baskets etc.)
- c) Urban regeneration through tactical urbanism.

The interventions in most cases will be born with a first phase of experimentation, a subsequent evaluation, and, if this is successful, an implementation for a definitive transformation of the public space. In order to enhance the urban contexts of intervention, from the environmental point of view will apply design solutions that encourage sustainable mobility, implement the presence of vegetation also cultivable, include the use of mineral materials as well as clear paints to reflect the sun's rays or where and when possible, provide for de-paving and water use. At the same time,

interventions will have an impact on local actors, urban communities and people enhancing the identity of these places through the creation of comfortable and balanced spaces that use innovative and creative urban furniture, the creation of unconventional play spaces, the pedestrianization of today's driveway or unused spaces. To ensure that the interventions dialogue deeply with the social context in which they are inserted, it will be necessary, especially in the comparison that will lead to the realization of the final works, provide for listening and involvement of schools, parents of schools, local traders and urban communities. The guiding criteria for the choice of areas of intervention were poor availability of public space, presence of other projects in progress or attractive poles that can be of support to the success of the intervention, criticality analysis and feasibility assessment without works (for experimentation) or with reduced works (floor painting/light furniture) and sustainability of the intervention in terms of use and management. Based on the results of the technical evaluations, a first selection of potentially feasible interventions was made, which were subsequently submitted to the competent assessors and the opinion of the districts. Two research cases, that express the application of tactical urbanism in Bologna has reported.

3.1 The pedestrianization of Via Milano

The area consists of an 80-meter-long pedestrian route in a driveway (intersection of Via Milano and Via Corrado Mazzoni) [11]. This zone is marked by the presence of public housing sectors, where traffic primarily consists of pedestrians, bicycles, scooters, and wheelchairs. The main objective is a decisive transition towards sustainable mobility. This action wanted to explore alternative ways of using public space through an innovative temporary set-up that would allow public space's cultural, recreational and sporting functions to maximize its potential. The intervention was designed to accommodate people of different ages and potential interests in the use of space, but pre-established functions are not identified. The various elements (Figure 1) can be interpreted by those who live and enjoy them.



Fig. 1 Aerial photo of the transformed urban area located in via Milano © Margherita Caprilli, FIU

The colors, materials and compositions used aim to encourage curiosity, supporting people to participate in the area transformation process. Observation and monitoring of the public space were conducted using methods that are based on empirical evidence obtained using rigorous analytical tools. The goal is to understand the impacts of an intervention on people and the urban context. Each tool has its own characteristics and a protocol through which it was employed. Specifically, the tools used for the monitoring activities were the count of the number of people and vehicles in the space, questionnaire through various channels, and interviews. The results show that the urban renaissance activities were effective in creating an inclusive public space, demonstrating a significant increase in the number of visitors and users of the area. Furthermore, the monitoring showed a 60% reduction in vehicular traffic in the area with an increase in the perception of safety by the people in the area. The report also highlights the positive impact on commercial activities and property values in the area, thanks to the transformation of public spaces. Overall, the monitoring has shown that the urban renewal project has had a positive impact on the quality of life of citizens, on the quality of public spaces, and on the reduction of environmental and vehicular traffic impacts.

3.2 The first schoolyard of Via Procaccini

Another urban tactical action consists of the realization of the first schoolyard near the middle school in via Fioravanti [12]. This experiment aimed to offer a new pedestrian space, guaranteeing students greater autonomy and safety in the paths

between home and school and new areas dedicated to play and meeting. The experimental and temporary intervention involved the creation of a schoolyard with elements dedicated to the students and, generally, to all the people who attend the area (Figure 2).

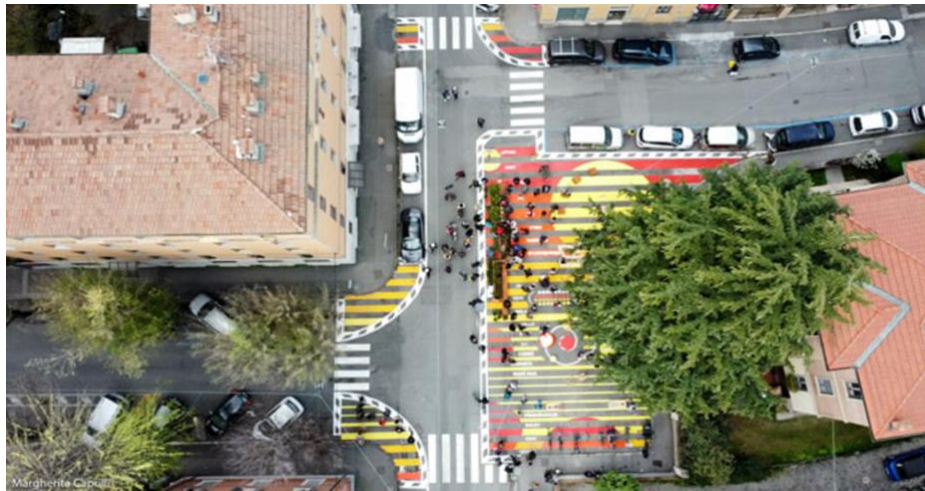


Fig. 2 Aerial photo of the transformed urban area located in via Procaccini © Margherita Caprilli, FIU

This project planned to pedestrianize an area of about 300 square meters through the use of white paint on the ground, vertical signs and other elements for the pedestrians (benches, a game drawing and writings on the ground, tubular benches, wooden tanks and ornamental plants). The colors, materials and compositions used are chosen to foster curiosity and support people in imagining and practicing uses, thus taking part in the space's transformation process. In the morning, pedestrianization is active between 7:40 and 8:10, while in the afternoon it is active between 13:50 and 14:30. At these times, the nearby shops are closed with barriers to close motor vehicles traffic.

The intervention lasted about 12 months. The area was also the subject of the study conducted by Systematica and Transform Transport, aimed at monitoring pedestrian and vehicular flows during the pre and post-intervention phases [13]. Monitoring was carried out through observations supported by a video camera and automated image analysis techniques. The research produced a series of analyses related to the flows observed in the pre-and post-intervention area, in order to support the iterative design process based on the tactical urbanism approach. The monitoring was carried out through camera-supported observations and automated image analysis techniques. The study produced a series of temporal and spatial analyses related to the observed flows in the area (e.g., density maps, space use, average speeds, road crossing behaviors, etc.). Following these principles, the camera was installed on a pole at the corner of Via Procaccini and Via di Vincenzo (north side), at the height of about 3m and with a mean axis of framing parallel to Via Procaccini facing the area of intervention.

The results of the analyses were elaborated in order to:

1. Identify the activation times of the study area before and after the redevelopment of the scholar square, through metrics describing the cumulative pedestrian density and the cumulative residence time;
2. Define the global characteristics of space use, discretized on a 1m x 1m grid, through metrics related to cumulative dwell time and average speeds;
3. Characterize the uses related to the study areas following the redevelopment of the square (e.g. roadway, square, furnishings, etc.);
4. Calculate the overall difference in use before and after surgery.

The results of the analysis showed a 43% increase in the cumulative residence time recorded in the area following the redevelopment intervention. In particular, the cumulative residence time in the square, transformed from a crossing area to a rest and play area, increased by +216%. Strong changes in the spatial distribution of pedestrians in the study area are also highlighted. New characteristics of use related to the furnishings in the square emerge, which present the most significant cumulative residence times in the area. The analysis of the results of vehicular flows shows a decisive reduction in average speeds near the turns with subsequent crossings, contributing to the safety of pedestrians who use pedestrian crossings.

The presented analysis has made it possible to quantify the effectiveness of the urban regeneration intervention of Via Procaccini, confirming the transition from a crossing area to a comfortable and safe rest and play area for children. The study also confirms the proposed methodology, based on the use of sensors and innovative analysis technologies for the collection and analysis of data to support the design of urban regeneration interventions.

Discussion and Conclusion

The research highlights the valuable experience gained from Bologna's collaborative city approach and the potential to integrate criticalities and potentialities within the City as a Commons framework. The involvement of citizens and local actors through participatory processes and laboratories is the core for promoting changes and urban transitions, and the collaboration pacts are the instrument that legitimate citizens' commitment to generating a transition. Overall, the City as a Commons approach highlights the importance of participatory processes and collaboration among stakeholders in urban transformations. The research analyzes the use of video analysis technologies for the evaluation of urban mobility experiments in Bologna. The importance of measuring the impact of urban mobility policies based on quantitative metrics is discussed, and it is argued that monitoring activities can be more effectively carried out using video analysis techniques. A concrete case study is presented to demonstrate the usefulness of this technology, highlighting how video analysis is able to provide detailed information on the effects of urban mobility experiments on mobility and the environment. The author concludes by emphasizing the importance of using video analysis techniques in the planning of urban mobility policies and in the evaluation of their results. The study found that video analytics can effectively measure urban mobility metrics such as vehicle speed, traffic volume, and pedestrian flow. It

also found that the technology can help identify areas for improvement in the city's transportation infrastructure. Considering the implementation nature of these interventions, the path taken can be a guide for future evaluations of other areas on which it is being decided whether to intervene or not.

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Application of an impact model to assess the development of urban regeneration project: the case study of DumBO district

Leonardo Cameli^{1*}, Margherita Pazzini¹, Claudio Lantieri¹, Cecilia Mazzoli², Konstantina Douka², Annarita Ferrante²

¹ Department of Civil, Chemical, Environmental, and Materials Engineering—DICAM, School of Engineering, University of Bologna, 40126 Bologna, Italy

² Department of Architecture, University of Bologna, 40126 Bologna, Italy

Abstract. The European Commission states the mission of the New European Bauhaus (NEB) as the initiative that wants to connect the European Green Deal to the living spaces. It calls to create together a sustainable, beautiful, and inclusive future. Given this new target, the Creating Actionable Futures (CrAft) European project wants to support the implementation of the NEB principles in the cities. The consortium starts to develop the CrAft's NEB Impact Model as a guidance tool oriented to a systemic approach to be adopted in complex urban interventions. In that sense, the cities can use their existing indicator sets for integrated planning and sustainable goals. This paper aims to analyze the applicability of a new methodology for the assessment of urban mobility based on the Impact Model tool. The pilot case in Bologna is analyzed to define the impact of urban transformation that has been realized in the Multi-functional Urban District of Bologna (DumBO). DumBO is a space of continuous transformation in which an urban regeneration space, where an old freight yard have been addressed to culture, art, social activities in close relation with the territory culture, sociability and sustainability. Thus, it is a place where associations, business companies and citizens collaborate and contaminate each other. The research examines indicators, starting by the sustainable mobility, the active and the public transport KPIs. In this way, this set of indicators will contribute to the assessment of aspects related to mobility. This research will help the decision-makers to assess and promote sustainable solutions through this set of indicators that clarifies complex aspects during the urban regeneration process.

Keywords: sustainable mobility indicators, KPI, urban regeneration, New European Bauhaus

1 Introduction

The New European Bauhaus (NEB) is an initiative that connects the European Green Deal to daily lives and living spaces of all the citizens [1]. It recalls different European cities to imagine and share a more sustainable, beautiful and inclusive way to live. By creating bridges between different backgrounds. Moreover, by cutting across disciplines and building on participation at all levels, the NEB inspires an urban movement to facilitate and steer the transformation of our societies along three inseparable values: sustainability, from climate goals to circularity, zero pollution, aesthetics and inclusion, from valuing diversity to securing accessibility and affordability. In this context, the EU project [HORIZON-MISS-2021-CIT-01-02] Creating Actionable Futures – CrAft [2] is part of the (NEB) initiative of the European Union and will place the transition to climate neutrality at the heart of urban. CrAft is a 3-year project launched in May 2022 with eight lead partners all across Europe headed by Norwegian University of Science and Technology. CrAft supports the Mission Board on Climate-Neutral and Smart Cities and the NetZeroCities platform[3] in designing and deploying Climate City Contracts, based on knowledge from CrAft’s 3 Sandbox Cities (Bologna, Prague, and Amsterdam) and more than 60 CrAft reference cities. The project engages key stakeholders such as municipalities, citizens as active contributors, communities, property owners and tenants, cultural, artistic and creative sectors, universities and arts and design schools. The NEB Impact Model(IM) is one of the tools created by the CrAft Consortium in the research and publications [4]. CrAft’s NEB Impact Model is an assessment and guidance tool geared at a whole systems approach to use in diverse and complex urban contexts. The IM can be optimally work at the district and urban scale levels of intervention. It is created in a way that cities can use it for the integrated planning, steering, monitoring, and evaluation goals. Thus, it will help to identify essential leverage points for systemic change towards climate neutrality and resilience, by including different layers of sustainability (ecological, infrastructural, social, cultural, economic, aesthetic, legal, etc.) into innovative models for local collaborative governance model and value creation. Specifically, the municipality of Bologna in collaboration with University of Bologna (UNIBO), examine the challenges and methodologies in the context of “The City as a Commons” approach. Furthermore, it is essential the application of the NEB Impact Model as a tool to discuss with key stakeholders and understand the peculiarities of the urban space. The framework is based on the key role of citizens as active contributors through participatory processes in which co-creation and living labs are valuable tools for the urban regeneration projects that encourage the development of the sustainable mobility. In this direction, the municipality tests several projects and actions inspired from the tactical urbanism such as temporary pedestrian areas, school square using the concept of the tactical urbanism [5], [6]. Thank to these activities, citizens can actively contribute through their knowledge and ideas to reinforce new forms of public participation. Bologna, is one of the “sandbox cities” of the project, that serves as innovation playgrounds to document and optimize the real-life performance of the collaborative governance models and to learn, inspire and disseminate project knowledge. For this reason, UNIBO identified several urban areas aban-

done and degraded where the municipality took action through innovative planning solutions.

2 Literature review

The first step of the research has been to retrieve and collect several indicators which might be used in the evaluation of environmental and mobility performance. These specific indicators would be useful to measure the impact of future interventions in a certain area from different perspectives. To enrich the importance of findings, firstly it was important to collect and report the most valuable and inspiring tools and sources. The first one was the Sustainable Urban Mobility Indicators (SUMI) [7] and it's a useful tool for cities and urban areas to identify the strength and the weaknesses of the mobility system and to find potential solutions for the improvement of the area. The European Commission selected a consortium led by Rupprecht Consult – Forschung & Beratung GmbH (Germany) to support the testing of Sustainable Urban Mobility Indicators. The starting point for the SUMI project was the "SMP2.0 Sustainable Mobility Indicators" developed by the World Business Council for Sustainable Development (WBCSD) [8]. Over the last years, cities, and generally urban areas, develop SUMP (Sustainable Urban Mobility Plans) and work towards EU policy goals. The EU commission indeed, has developed a comprehensive set of practical and reliable indicators, that support cities to perform a standardized evaluation of their mobility system and to measure improvements as a result of the new mobility practices or policies. SUMI is an indicator set, used to evaluate and monitor, and which target audience are small cities, medium-sized cities, large cities and metropolitan region. Another significant analyzed framework is the "Healthy Streets" project [9] developed by Lucy Saunders, a specialist in public health and transport. It refers on the approach of policies and strategies to deliver healthier and more inclusive cities where people can freely choose to walk, cycle and use public transport. It's mainly devoted to vulnerable road users. This new vision and approach aims to improve the whole experience through a more pleasant, safe, attractive streets, where the most common traffic externalities like noise, air pollution, accessibility and lack of seating and shelter are not barriers that prevent VRUs from getting out. The Healthy Streets Approach is composed by 10 Indicators. To measure the "healthiness" of streets Transport for London (TfL) has developed an "Healthy Street Toolkit" [10], [11] which is useful to embed the Healthy Street Approach into the three main phases of a project: initial assessment, project implementation and project evaluation. A qualitative assessment tool summarizing the essential aspects of the 10 Healthy Streets Indicators by using questions as prompts [12]. There are two main indicators:

- Pedestrian from all walks of life
- People choose to walk, cycle and use public transport

The other eight indicators require to support these two main indicators, but actually to understand how the built environment affects the human sense. This observation it is essential to understand that a more interdisciplinary approach it is mandatory to create more healthy streets in the cities and promote the sustainable and safe mobility. The

developed tool is a spreadsheet to be used by designer as support. Taking inspiration of these projects, subsequently in this research, the IM application, based on the methodology and the indicators found in literature, will contribute the sustainable mobility part. Thus, it is selected a particular area, presented in the next paragraph.

The research aims to explore the application of the IM, focusing on the sustainable mobility KPIs. In particular, thanks to the knowledge that comes from the Mobility Urban Plans in different scale of the analyzed region [13], [14] and the indicators found in literature, It was possible to investigate the potentiality of the tool for the area.

3 The case study of DUMBO: Urban Multifunctional District of Bologna

Bologna is home to a unique project, a temporary urban regeneration place known as DumBO. The term stands for “Multifunctional Urban District of Bologna”, and it's a location where innovation, culture, and community intersect. [15]. The ancient railway yard where DumBO is located covers over 40,000 square meters and is made up of six structures and several outdoor areas (Fig. 1.1). It remains the property of FS Sistemi Urbani, a corporation owned entirely by the Italian State Railways, which is in charge of redeveloping and improving railway infrastructure that is no longer operational [16]. But DumBO is considerably more than a temporary multifunctional space. It's an initiative that brings together social integration, entertainment, culture, experimentation, sustainability, and teamwork. DumBO provides a platform where associations, corporations, and residents may interact and infect each other's ideas, generating fresh and innovative methods to urban development. The DumBO space promotes a local identity that embraces the urban landscape while also bringing together professionals, artists, and society in a collaborative effort to regenerate abandoned sites. DumBO is a collaborative example of urban regeneration since it repurposes these places and incorporates collective artistic expressions. Diverse cultures cohabit in DumBO. Each has distinct manifestations and initiatives that promote a sustainable, inclusive, and attractive way of living and serving the city. From public discussions to live art, residents actively contribute to the project and engage throughout the process.

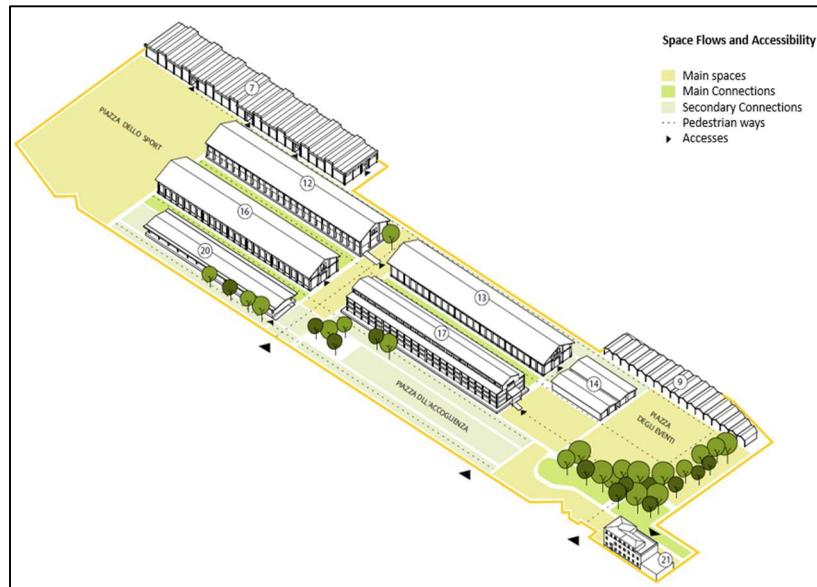
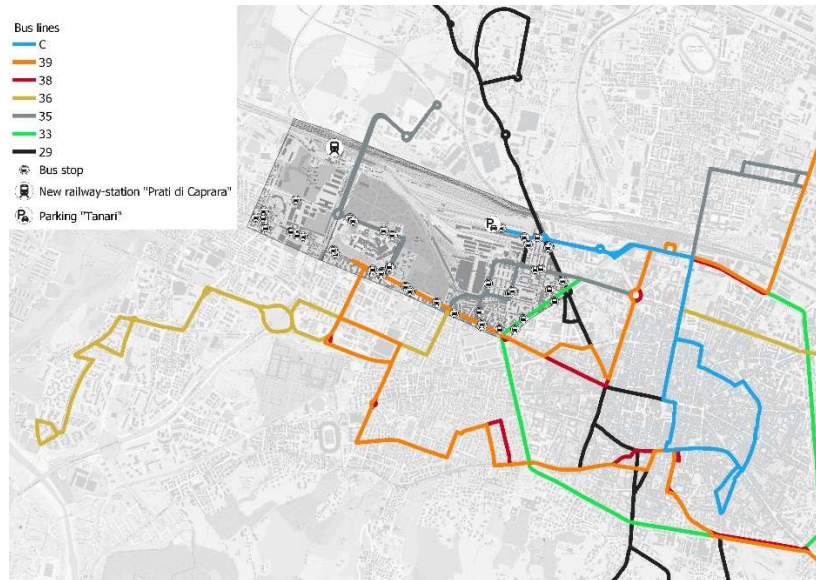


Fig. 1.1: Dumbo spaces and Buildings;

DumBO space is part of the area Prati-Ravone, that is located in the north-west suburbs of Bologna, between via Zanardi (orange in fig.1.2b) and via Emilia (purple in fig.1.2b). In the following figure the main road axis has been detected. Currently, the district is object of urban transformation, through the construction of a new railway station and a road axis foreseen that connects the district also from the west side, directly with the main suburban road and highways. The IM can be applied to measure the current status of the area in different stages of the till the urban regeneration will be concluded.

Fig. 1.2: a) Main road axes in the Prati-Ravone district; b) Public Transport Lines connected the area





In the western part of the city, road works are planned that substantially modify the current infrastructural grid. In particular, Via Emilia (the purple one in fig. 1.2a) will be affected by the construction of the first tram line, within 2027, that modify its functionality, towards the implementation of Local Public Transport together with the reinserion of pedestrians and cyclists at the center of mobility policies. The current situation presents a service of bus lines with the following lines underlined by the figure 1.2b. The area is covered by the line 29 that connects the north and south part of the city, as well as for the line 19 that links the western to the eastern part. Furthermore there is a car park, which is configured as a junction point for the modal interchange car/PLT (where shuttle C bring to the city center) and also as a bike interchange, offering convenient prices and services for the users.

Another way to reach the Bologna railway station is by using both the bus lines (35 or 36) and the existing cycle/pedestrian paths. In addition, also from the railway side, the station Prati di Caprara, that is part of the P.I.M.BO. project [17] and will possibly explore potentialities for further development.

Related to the bicycle and pedestrian accessibility, the project area is equipped with cycle path on Via Casarini and Via Tanari and one-way bicycle lanes on both sides of the road (fig. 1.3). The present bicycle paths connect the #1 Samoggia-Imola and #5 Bologna-Trebbio routes. The intervention area it is connected through the bicycle path on via to the bidirectional bicycle path built along the ring roads and allowing to reach important urban polarities. The realization of the tramway line as per the map of the western part of the city and the implementation of the plan for bicycles (BICIPLAN) [18] will significantly implement the accessibility of the area in terms of public transport and cycling. The administration is also committed to transform the city with 30 zones that will increase space sharing in favour of active mobility.

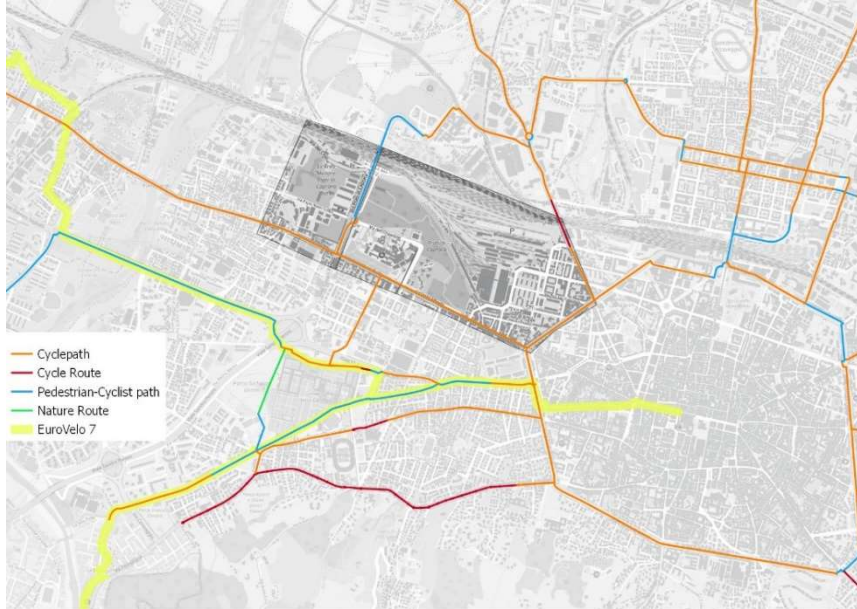


Fig. 1.3: Cycle network in the Prati-Ravone area

4 CRAFT NEB Impact Model (IM)

The Impact Model considers 5 main intervention domains, called ‘pillars’, and 17 impact categories [19]. The 5 pillars consist of the well-known triple bottom line for sustainable development (planet, people, prosperity). The 17 impact categories refer to essential aspects of integrated sustainable development (ecological, infrastructural, social, cultural, economic, aesthetical, legal, etc.). In order to achieve a balanced approach towards integrated sustainability, inclusivity and beauty, they recommend that all 17 categories are taken into consideration. Within the 17 impact categories, it has been identified a variety of relevant indicators. The IM suggests a list of 46 indicators, intended as an indicative set of primary Key Performance Indicators (KPIs). The list will guide the selection of indicators from existing sets and reporting tools already in use by the city or found in literature, the project or the process at stake. At the same time, the pillars, the impact categories and the suggested indicators help to detect possible gaps as well as to find more opportunities. The indicators may be evaluated by using proxies, until a more appropriate indicator will be founded or developed. For example, a proxy for the accessibility of a service may be the average distance to that service. The indicators may be assessed by a mix of quantitative and qualitative methods. For instance, social network quality in a district may be assessed both by counting the number of neighborhood associations and community events, and by asking residents and users for a qualitative judgement of the social networks in that specific neighborhood. The IM preferably should work from the early stages of a

project, process or intervention. In this way, project actors and stakeholders can eventually identify conflicting of interests during the process.

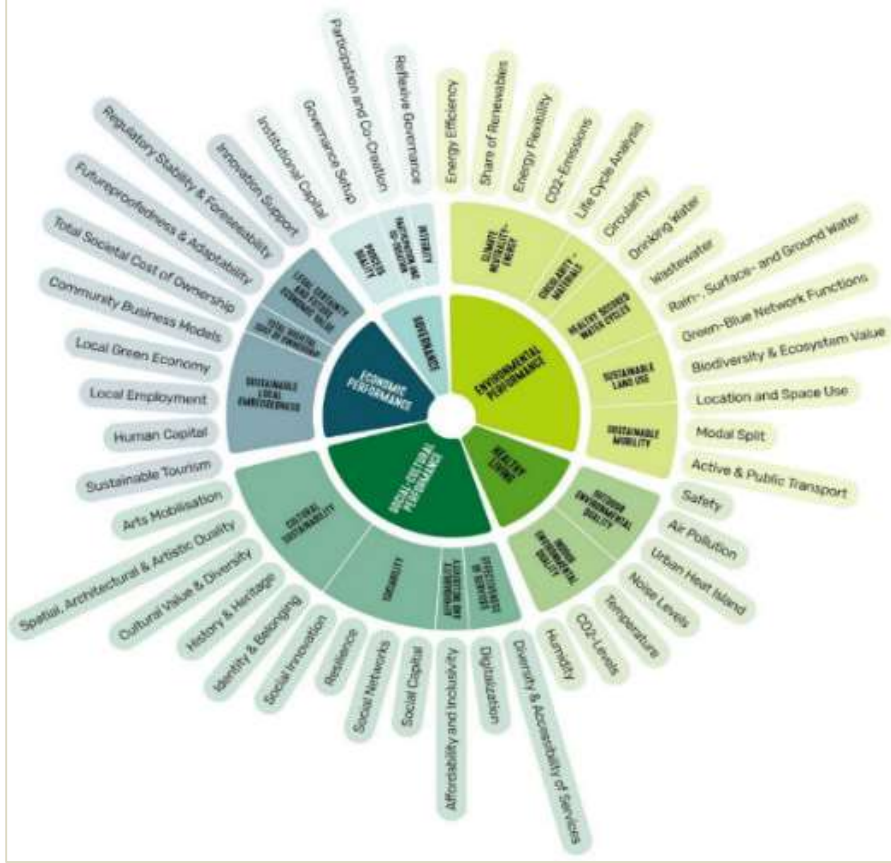


Fig.1.4 Impact Model Framework

The analysis is focused on the environmental performance, especially in the impact category of sustainable mobility, that it consists by: studying the proximity and accessibility of an urban center (in order to first reduce the mobility demand following a ‘trias’ approach), the servicing level by active and public transport and the adopted mobility land use in urban environments. In this research, the impact categories related to the sustainable mobility has been developed based on the indicators mentioned in the literature. Starting from the SUMI indicators, selected for their adaptability and flexibility in different cities and levels[20], the following indicators were selected:

- *Opportunity for active mobility:* this indicator considers the length of the bike lanes (L_{bl}), length of sidewalks (L_{pv}), 30 km/h (L_{z30}) and pedestrian zones (L_{pz}) over the total length of the road network of analysis (L_{rn}).

The value from the following ratio is an average of the length of road network adapted to walking and cycling.

$$R_{am} = \frac{L_{pv} + L_{bl} + L_{z30} + L_{pz}}{L_{rn}}$$

- *Access to mobility services*: Percentage of population served by LPT. The indicator (AccI) value is on a scale from 0 to 10.. The level of accessibility takes into account both the distance from the stop and the departures of the service of public transport. The formulation is the ratio between the number of people living in the “I” zone weighted with the dimension of the analyzed area and the number of inhabitants in the urban area.

$$AccI = \frac{\sum_i PR_i * W_i}{cap}$$

- *Multimodal Integration*: Index between 0-100 showing the average level of multimodal connection of the analyzed area within an urban transport network. The data for this indicator were collected by studying the network characteristics and facilities of the public transport. The list of all the transport modes in the urban area is predefined and for each zone a percentage is calculated of the number of modes available compared to the total ones.
- *Mobility Space Usage*: Proportion of land use by all city transport modes, including direct (LD, for main and secondary roads) and indirect uses (LI, for sidewalk, parkings etc.). It is calculated from the square meters of direct and indirect mobility space usage per inhabitants (cap).

$$LUM = \frac{\sum_i (LD_i * LI_i)}{cap}$$

The other inspiring example for the mobility evaluation comes from the sustainable urban mobility plan of Bologna (PUMS) [14] and Security Urban Plan (PSSU) [21], focused on the accident prevention, that indicates the following parameters:

- *Modal split*: Percentage of the usage by inhabitants for the different modes of transport (active mobility, private cars, and public transport).
- *Cycle Index*: the meters of the cycle path or lanes available for the inhabitants of the analyzed area. The analysis was realized by GIS software.
- *Fatality Index*: Number Death/1000* inhabitants.
- *Injuries Rate*: Number Injuries/100* inhabitants.

5 NEB Impact Model application for measuring sustainable mobility

In this section, the Environmental pillar and its indicators will be enriched with a proposed set of indicators to have some quantitative data. The pillar which has been analyzed is the one related to “Sustainable Mobility”, which is embedded into the

“Environmental Performance” pillar. Specifically the research till now includes several quantitative and qualitative tools such as:

1. **Collection of data from the open-dataset:** starting from the regional and municipality open data set, the needed data for the calculation of the selected indicators have achieved.
2. **Definition of the indicator scale:** the calculation of each indicator, is related to a scale of application. It depends from the collected data. This differentiation is useful to understand the challenges
3. **Creation of spatial maps for the calculation:** in this phase, some indicators need different ways to be measured. This one was realized by using GIS software, that are able us to create some spatial maps to assess the impact.
4. **Definition of the baseline:** after the selection and calculation of each indicator, a literature review of the baseline and targets to achieve was realized. Mostly the baseline is defined by European target (as for the case of Opportunity of active mobility) or regional plan (I.e. the Cycle Index). The score from 1 to 5 is given for each indicators follow the founded targets. It was possible because these indicators show quantitative targets (i.e. m/inhab of cycle path) to achieve or percentage (i.e the access to mobility services).

In the table below, the characteristics of each indicator are defined with, the used methodology. Furthermore, the impact score has been assigned on the base of the available and converting the results on the reference scale 0-5. The highest score has fixed based on the literature or on the European/local target to achieve, for a specific indicators. This procedure allows the creation of a scenario in which all indicators are defined with the best possible result and this can be considered as an optimal scenario, which allows one to observe how the real situation differs from the ideal one

Table 1.2. Calculation of the selected indicator

Indicator	Scale	Results	Target of 5 points	Impact Score (0-5)
Modal Split	City	58 private car 19 LPT 23Active Mo- bility	>50private car >20 LPT >30Active Mobility	4
Cycle Index	Urban	1,67 m/inhab	>1,5 m/inhab	5
Active Mobility	Urban	84,2 %	100%	4
Services Accessibility	Urban	86,59 %	100%	4
Intermodality	Urban	55,56	70-100%	4
Space For Mobility	Urban	15,55%	100%	2
Fatality Index	City	0,064	0,3-0	2
Injuries Rate	City	0,66	0,02-0	4

The spreadsheet used for the determination of the scores provides, a graphical result showing what has been achieved so far, also showing the final score assigned to

the category considered. The radar graph (Figure 1.6) is useful to observe how the existing scenario diverges from the ideal situation.

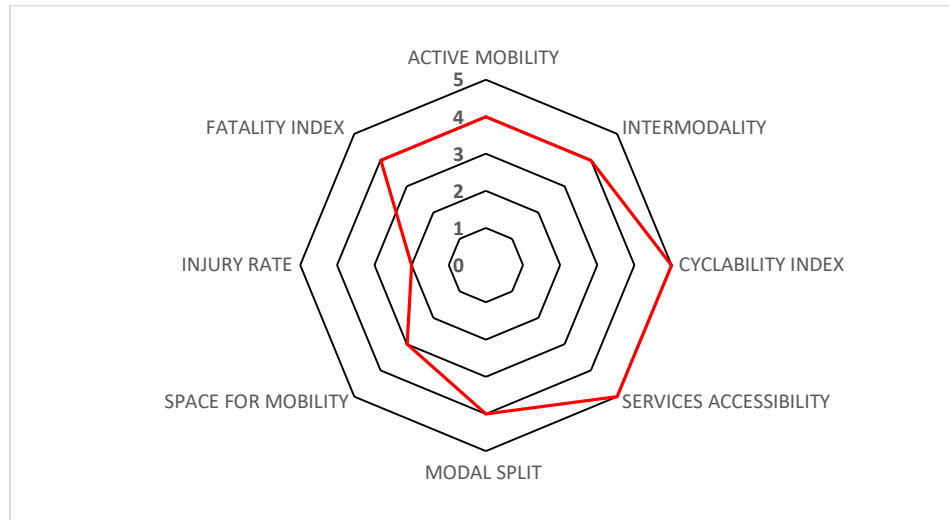


Fig. 1.6. Spider Graph about the indicators score

Conclusions

The research till now, demonstrates that the impacts related to the mobility of an area is a very complex and multifaceted process that requires a deep understanding of the variables and brings to the table new issues to discuss and analyze [22]. The EU project Creating Actionable Futures – CrAft itself, wants to evaluate how an urban regeneration project could improve the impact on the surrounding environment. For this reason, the consortium begins, from the development of a set of indicators used by city, to assess the IM framework. This tool could be used as evaluation tool of a regeneration area in an analysis in different stages of the project or for monitoring the changes after the implementation. In addition the possibility to use indicators with different level of scale, can show and give the opportunity to see the changes from the lowest details to the macro-scale.

Analysis of the DumBo case study

For testing this methodology, the research involves the project DumBO in Bologna, that aims to create a dynamic and inclusive environment for the third sector and people. The project wants to revitalize the area and create a lasting impact by repurposing the former freight yard Ravone into a hub for creativity, innovation, and collaboration. Since its inception, DumBO had a significant impact for Bologna through the many participatory processes and the active role of citizens. The temporary use of the space allowed for the testing of new ideas and approaches towards urban regener-

ation. DumBO has the potential to become a valuable paradigm for a more affordable urban environment by including the NEB principles.. To assess the impact of DumBO and make necessary adjustments, regular evaluation and feedback mechanisms will be required. In this research the evaluation of the macro-scale changes was provided by the IM indicators related to the “City” scale . This tool could validate a methodological and holistic framework focused initially, in this research, on the evaluation of indicators related to sustainable mobility. The proposed indicators that comes from different sources, both European and regional, should be calculated with the available and open data available website of the the region and the municipality. In this way it could be flexible and user-friendly. The indicators are divided by the scale for giving a complete state of art of the analyzed topics. Indeed firstly, the modal split and the incident rates shows that Bologna is on the good way for the European target of the 0 accidents and the modal shift to the sustainable mobility modes. Going more in deep-en to the project scale of DUMBO, from the calculated impact scores, shows an excellent starting point for encouraging more sustainable mobility. Indeed, the indicators point out excellence from the point of view of the bicycle network with a 5 points rating for the cycle index. The intermodality indicator collects 4 points rating due to the accessibility of the area (confirmed to the Accessibility Indicator too). The area is well served by bus services and well-connected to stations both in terms of public transport infrastructure and active mobility.

Future Developments

In this context, the IM can be a very useful tool. In fact, by showing the situation in terms of replicable KPIs, it can help identify the project's weakness. Some solutions that can be envisaged to further increase this score could be the introduction of more pedestrian zones, bicycle lanes, 30 zones (a solution already strongly implemented by the Municipality of Bologna in recent weeks) and introducing new modes of Local Public Transport such as, for example, the tram, which is already under construction but not considered in this analysis. In addition for completing those indicators that are not quantitative, it will be possible to elaborate preliminary surveys together to mark some key points and proceed with a more extensive one to the local communities and stakeholders [23]. It will be provided for some cases to do also interviews with key stakeholders like the municipal authorities to have more detailed data. This collection of information will help to quantify where is possible some indicators of the IM, to proceed then with the correlation of the different Impact categories.

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Article

BIM Modelling of the AQP Touristic Cycle Path

Margherita Pazzini ^{1,*}, Leonardo Cameli ¹, Claudio Lantieri ¹, Valeria Vignali ¹, Daniele Mingozi ² and Giuseppe Crescenzo ²

¹ Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM), University of Bologna, 40126 Bologna, Italy

² ENSER, Via Zacconi, 16, 40127 Bologna, Italy

* Correspondence: margherita.pazzini2@unibo.it

Abstract: BIM (building information modelling) has led to substantial improvements in all design steps. Applied mainly as an information management system in the digital design of structures and buildings, only in recent years has the use of BIM also extended to the construction of road infrastructure. The so-called I-BIM (infrastructure building information modelling) methodology supports the designer in the phases of construction and execution of the design considering all aspects related to the project, including sustainability. Through the software “Roads” of “SierraSoft S.r.l.”, in this article, the I-BIM approach has been used to design a 35 km cycle path as sustainable as possible. From an operational point of view, the design of a cycle path section begins with the modelling of the infrastructure in all its aspects: a study of the route, analysis of interference, modelling of the infrastructure (floor plan, profile and sections) and an intersection study. Creating an infrastructure that increases soft mobility vehicles through a comprehensive design, attracting as many users as possible, is the real innovative challenge.

Keywords: building information modelling (BIM); cycle path; sustainable mobility; infrastructures building information modelling (I-BIM); road



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1. Introduction

Transport infrastructure networks are currently developing both in terms of technology used and implementation. The growth in transport demand requires any nation to create resilient infrastructure to support this increase in travel. Methodologies are needed to monitor the design phase to minimise waste of resources and emissions, but also to encourage a modal shift towards soft mobility. Considering the sustainable development goals (SDGs) set by the European Union for safety and the environment, many conventional transport systems are changing, but significant challenges still remain towards a full transition to sustainable transport [1]. Policies and actions are being developed across the cities to encourage cycling for both physical and environmental well-being in the urban context [2,3].

Investments should also be targeted at projects that aim to guarantee the rights of cyclists on the road in addition to those of motorists, encouraging harmony between two different types of users on the move. In this perspective, the construction of cycle paths could help optimise road use for both categories [4,5]. The use of building information modelling (BIM) from the design phase of a cycle path can be very useful by streamlining the various steps and preventing possible waste [6–8], as is already the case in the United States for the public sector [9].

However, although BIM research for transport facilities is on the rise, the focus has been mainly on highways and bridges, limiting its application to minor roads and cycle paths [10,11]. BIM is a digital system for 3D modelling from the physical, performance and functional data of a building [12]. The interoperability of people involved is placed at the centre of the process, creating collaboration and communication among them. In

doing so, each figure provides all the information on the model to complete it with all the features necessary to outline any problems that may occur in the useful life. Interoperability is the fundamental activity and is mainly articulated in two forms of exchange [13,14]: the proprietary one is limited to reading the content only to some software and the technical specifications are not in the public domain. The second format is a data system based on the technical specifications in the public domain, without time limits called the IFC: neutral, open and standard. It is not controlled by suppliers and is managed by BuildingSMART [15–17]. However, BIM is not to be thought of as just a simple 3D geometric modelling. It is important to consider the possibility of developing a digital model that can anticipate, already in the design phase, many of the verification analyses that usually take place during the project execution phase. Operationally, there are, therefore, two distinct phases: code checking that verifies the adherence between the model and the design requests and the clash detection phase that implements a preventive analysis of geometric conflicts present (and not) in the model. In particular with the introduction of 4D BIM, an organization of the activities related to the schedule of the times of the model is obtained, which allows to extract and visualize the progress of the activities during the life cycle of the project. In this way, BIM helps professionals to reduce trial and error in the construction phase which enhances productivity while diminishing risks associated with time and cost. The risks could also be visualized, simulated and quantified through BIM capabilities [18]. The BIM 5D model concerns the calculation of the work through the “quantity take-off” methodology. Project measurements are extracted to obtain the quantities of materials needed for construction and to estimate the relative cost. Indeed, the 4D/5D software is able to involve several project data in a unique and shared environment [19]. The 6D BIM dimension concerns the operational management and maintenance of the work and its components throughout the life cycle. Finally, dimension 7D assesses the energy efficiency and sustainable development of a new or existing project [20,21]. In this way, the relationship between BIM and LCA can also be particularly beneficial for a comprehensive sustainability analysis and for avoiding rework [22]. As mentioned above, currently, BIM modelling leads to improvements in all phases of design and is mainly applied to structures and bridges, while only in recent years it is embracing the field of infrastructure. The latter represents a much more complex world because of the limited availability of libraries of infrastructure components, the difficulties in assigning parameters to the geometries of objects, the specific characteristics of the infrastructure that are not always easy to understand and the inadequate workflows and tools in the architectural field. Land and territory management, for example, are infrastructure-related issues. The digital modelling of road infrastructures starts from the analysis of the territory, in which the model will be realized, and from the evaluation of probable interferences with the infrastructures or the already existing works. For this reason, in the field of infrastructure, data is processed in different formats. Often the use of GIS systems is required, typically with point or linear representations [23]. In the field of infrastructure, there is a “horizontal” BIM, which has aspects other than “vertical” (referred to as structures). In horizontal BIM, because there is a management of information and surfaces that are not always linked to objects, the ground becomes the fundamental element for design (marginal for vertical BIM) to obtain buildings, while in the vertical these products are made in an industrial way, and thus the work has a high impact on the territory and the exchange formats still in maturation. One major differencing factor between a building (vertical) and a transportation (horizontal) structure is the coordinate system that is used in the design, planning and construction. Vertical construction uses the Cartesian coordinate system as a single reference, while horizontal construction uses multiple stations and alignment curves for references. This difference has been a major barrier to the direct adoption and application of traditional BIM software for transportation [24]. To create an interaction between these two worlds, always having as a background the achievement of sustainable goals, this research investigates the application of the BIM methodology for the construction of a cycle path surrounded by nature. Smart highways and sustainable infrastructure are integral

parts of Smart Cities. With the development of IoT research efforts, more cities are now being planned for smart and intelligent infrastructure. There is an increasing demand for the adoption of Smart City guidelines and governments even considered incentives for further research in this area to foster this evolution, aiming to increase the quality of life for their citizens, as well as the sustainability and resiliency of their cities [25]. In addition, many interesting applications of BIM could be used. It can be integrated with GIS [26] in order to eliminate technical/environmental conflicts [27] and WEB integration in the fields of urban planning and management [28–30] and with a laser scanning framework [31] for an expeditious and accurate acquisition of the as-is building geometric data [32,33].

2. Case Study

In recent years, a national system of tourist cycle routes (SNCT) has been implemented in Italy, a network of cycling routes of tourist interest that extends throughout the nation with variable lengths. The objective of the following research is the study of the final project related to the intervention in the “Realization of the Apulian Aqueduct Tourist Cycle Route”, adopting BIM methodologies. The overall project of the A.Q.P cycle path starts from the sources of the river Sele in Campania that, after crossing the Basilicata near Venosa, enters Apulia in Spinazzola and continues along the Alta Murgia National Park and the Itria Valley, crosses the Salento and ends in Santa Maria di Leuca after a journey of over 500 Km. In this way, the cycle path is transformed from a path to reach places of tourist and cultural interest to the objective of cycling tourism itself. Moreover, crossing three regions of southern Italy (Campania, Basilicata and Puglia), it connects some of the most fascinating and still undervalued places of the Italian peninsula. The realization of the cycle path represents an opportunity for environmental enhancement, a “culturally evolved” way to enjoy the territory. It also becomes an opportunity to network environmental and cultural emergencies together with commercial and hospitality activities in those locations, contributing to the overall growth of the territory crossed. Basically, the project aims to integrate the infrastructure with the environment passed through, develop a network of organic and safe cycles, make constructive choices to reach maximum use and accessibility and achieve complete sustainability in terms of durability, maintenance and life cycle of the works. The route identified for lot P1700 of the Apulian Aqueduct Cycle Route runs along the hinterland of the province BAT (Barletta-Andria-Trani), for an extension of about 35 km. It focuses on the service road of the main channel of the Apulian aqueduct, on existing inter-polar roads or on other existing roads as summarised in the Table 1.

Table 1. Different types of cycle paths.

Type of Cycle Path	Extension [m]	% of Total
Sections in reserved areas of new construction (new cycle path on areas to be expropriated)	1920	6%
Sections in reserved areas of new construction (cycle path as conversion of private roads to be expropriated)	2145	6%
Sections on existing AQP service trail	25,210	72%
Mixed sections on public roads	5683	16%
Total	34,958	

Most of the route runs along private areas (84% of the total). In this regard, it must be pointed out that the sections on the AQP service trail can only be crossed by motorized vehicles serving the Apulian aqueduct or by local residents—who are otherwise unable to reach their properties—and therefore comparable to a bike path on its own headquarters. Mixed sections are limited to municipal roads with reduced traffic (less than 500 vehicles/day) which will be regulated with a speed limit of 30 km/h or with the obligation to cross the village of Spinazzola where specific measures have been taken to moderate vehicle traffic.

3. Methodology

From an operational point of view, the design of a cycle path section involves the modelling of the infrastructure in all its aspects: a study of the route, analysis of interference, modelling of the infrastructure plan and of the longitudinal profile (altimetry), signage design, intersection study and relevant modelling. In line with the project guidelines, the project cycle path will primarily involve the Apulian aqueduct service track and, secondly, low-traffic roads, converted carriage roads and newly built sections. As already specified, the service track sections that are separated from the main road, where there is the transit of AQP service vehicles (or, for short sections, the transit of local residents who are otherwise unable to reach their properties) are to be considered as occasional. The cycle path will have a useful transit width of 3.00 m (1.50 m for each direction of travel) with exceptional and local reductions to 2.50 m at particular point interference, such as manholes or inspection wells or in urban areas where the standard width is not technically feasible or cost-effective. The surface of the track floor will be smooth and drained to ensure the safety of motion and braking. Consistent with the entire project, the floor will be made of a mixture of loose stabilized limestone adopting a molten grain size to ensure the closure of the mantle and its durability over time. In this way, the hygiene of drinking water transported in the Main Canal, on the service track, will be not compromised. For sections with a slope of more than 3%, mixed soil stabilized with cement will be used to ensure better resistance to surface erosion. In urban or mixed sections on roads with low traffic, the surface will be made of bituminous concrete. The transverse slope will be about 2% to ensure proper water drainage and an adequate coefficient of adhesion. Horizontal bending radii are generally designed with an internal radius of more than 5 m. visibility distance (regulated by the D.M. n. 2367 of 21 June 2004) is adequately sized to ensure safe stopping spaces. The longitudinal gradients are strongly influenced by the morphology of the land and by the need to maintain the path mainly on the AQP track. Normally, slopes are less than 5%; values of 10% are locally reached for short ramps. The route of a cycle path is mainly developed in three areas: on the AQP service track, on new paths and on existing low-traffic roads. For each of these situations, a typical section has been defined, and further detailed to consider the multiple situations at the boundary.

In detail, the type sections are as follows:

- Typical section in embankment/trench/along the hillside on service path—routes with already adequate width (**Figure 1a**);
- Typical section in embankment/trench/along the hillside on service path—routes with insufficient width (**Figure 1b**);
- Typical section on newly implemented paths alongside existing roads (**Figure 1c**);
- Typical section for routes mixed with vehicular traffic (**Figure 1d**).

Most of the track is located on the current area of the AQP service track, whose sections have heterogeneous bearing capacities. For this reason, two main situations have been distinguished in the design phase:

- Soil with low bearing capacity (PT layers type in **Figure 2**);
- Soil with good bearing capacity (PS layers type in **Figure 3**).

The first case is typical of sections characterized by silty clay and organic soils, where the service track has the characteristics of a dirt track and turf often invades the track, recognizable by the groove of the wheels of vehicles. The original assorted gravel flooring has practically disappeared. In those sections where the longitudinal slope exceeds 3%, the surface layer is replaced by soil stabilized with cement. The second case is typical of the sections where the service track has kept the original assorted gravel path or is set on rocky (calcareous) soil.

AQP (intervention P1700) develops from the border with the Basilicata region (municipality of Spinazzola) for an extension of 34,925 km to Castel del Monte (municipality of Andria) entirely in the province of Barletta-Andria-Trani (BAT). The cycle path studied crosses three villages: Spinazzola for an extension of 17.20 km, Minervino delle Murge for

an extension of 9.65 km and Andria for an extension of 8.08 km. The change in altitude of the section matches with the service road of the Main Canal and only locally overlaps the existing carriageways or reduced traffic roads. The average gradients of the sections are usually less than 5%; however, there are steeper ramps locally even more than 10%. To summarize:

- Slopes with more than 5% inclination are extended for 3956 m equal to 11% of the total extension of the lot;
- Slopes with more than 7% inclination are extended for 1419 m equal to 4% of the total extension of the lot;
- Slopes with more than 10% inclination are extended for 176 m equal to 0.5% of the total extension of the lot; the most demanding ramp reaches a slope of 11% for a length of 60 m.

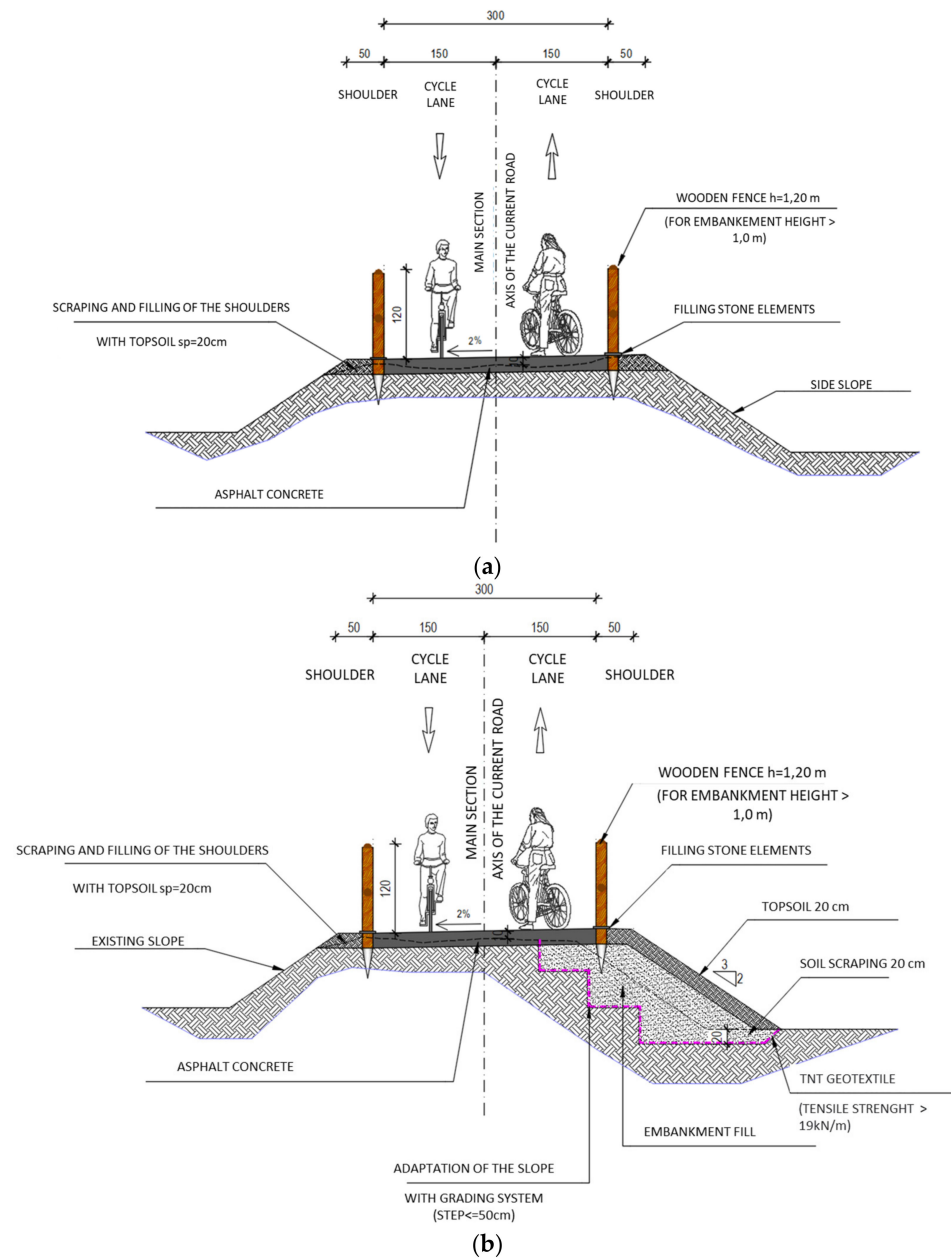


Figure 1. Cont.

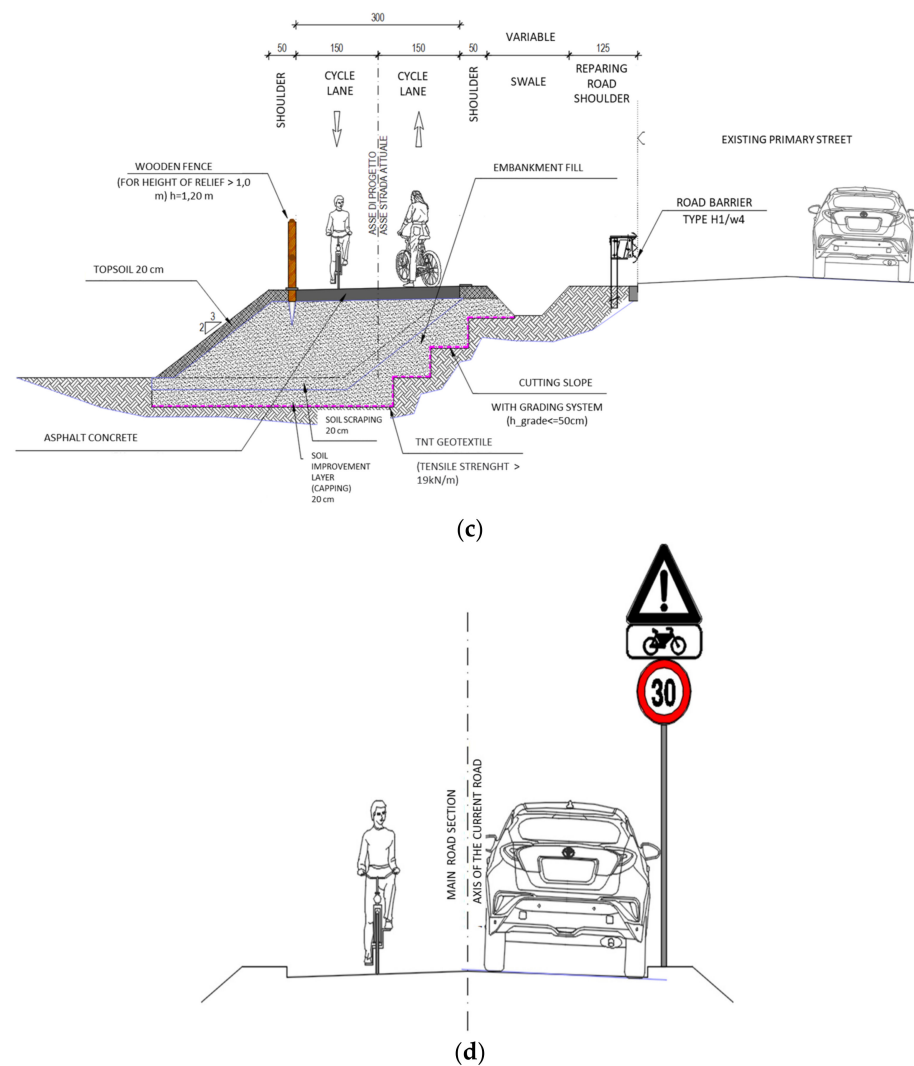
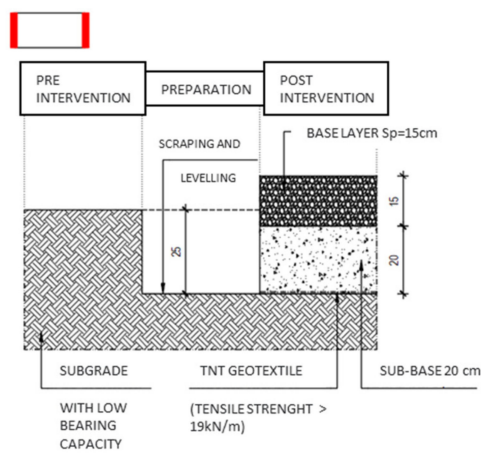


Figure 1. (a) Typical section in embankment on service path—routes with already adequate width; (b) typical section in embankment on service path—routes with insufficient width; (c) typical section on newly implemented paths alongside existing roads; (d) typical section for routes mixed with vehicular traffic.

PAVEMENT TYPE PT1

LAYERS FOR SLOPE < 3% on soil with low bearing capacity



PAVEMENT TYPE PT2

LAYERS FOR SLOPE > 3% on soil with low bearing capacity

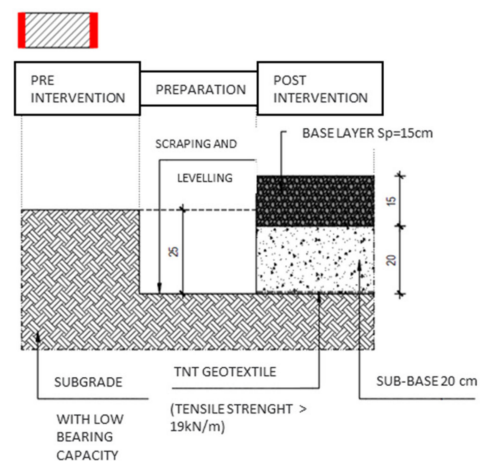


Figure 2. Road section type PT1 and PT2.

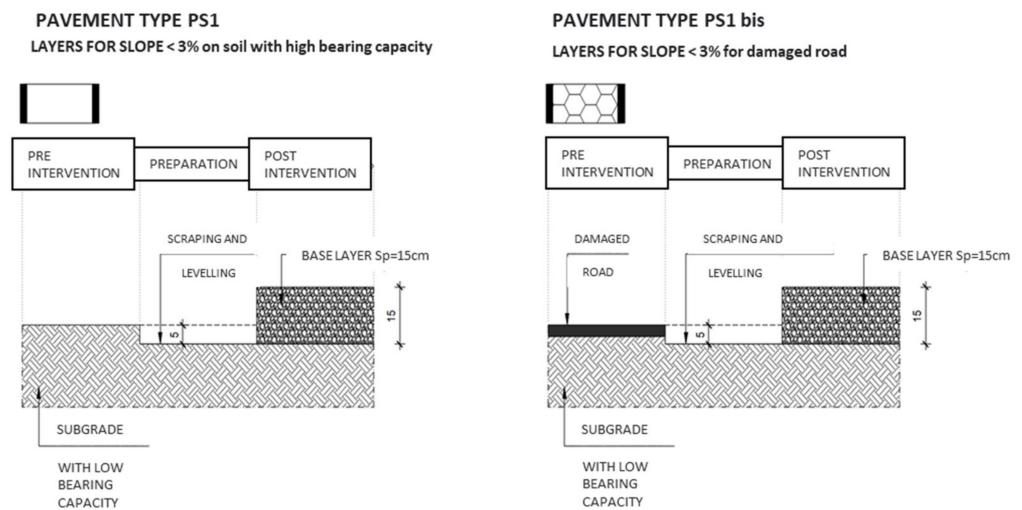


Figure 3. Road section type PS1 and PS1 bis.

The steepest sections are located around the village of Spinazzola. The first kilometer of descent/ascent from Spinazzola towards the Murge and the last 700 m of descent/ascent towards the SP 222 are particularly challenging. In this sense, 7.5% of the planned route does not comply with the requirements of DM n 557/1999 and the Ministerial Directive Protocol 375 of 20 July 2017. However, since it is an adaptation of existing infrastructure and not new construction, it is considered appropriate to use the analogy with road designs that involve an adaptation of existing locations, whose legislation falls into D.M. n. 2367 of 21 June 2004. Therefore, the D.M. n.6792 of 5 November 2001 turns out to be an element to which to tend and not to have been complied with too fully. The present project has solved all the intersections of the cycle path with the territorial road network. The solutions were differentiated according to the administrative competence of the road, level of traffic, divided into low and medium/high (TGM over 500 vehicles/day), geometric characteristics (speed limit, width), and road surface of the interfering street. On the basis of these criteria, the following typological interventions have been identified and agreed upon with the operators of the interfering roads. Each of these interventions was developed for the specific situations identified in the project and listed below:

- N01—traffic lights intersections for provincial roads of width greater than 6.5 m (Figure 4);
- N01bis—traffic lights intersections for provincial roads of width less than or equal to 6.5 m;
- N01ter—traffic lights intersections for a cycle path on the road with the maximum degree of protection for the cyclist;
- N02—intersections with enhanced signals
- N03—municipal or local asphalted roads;
- N03 bis—dirt local roads.

Analysing in detail the most innovative solutions to obtain the maximum protection in the traffic light intersections on the bike path is a sensor system. It can detect the presence of a bicycle or a car, stop traffic and allow access to the main road or its crossing in total safety. The cyclist's priority is guaranteed by the insertion of a short, dedicated lane that allows the cyclist to stop in front of the cars and have a position ahead of the cars when the green is activated, keeping it throughout the crossing.

Another innovative design solution N02 (Figure 5) has been used in the cases of crossing municipal roads, where bike crossing should be strongly signalled, but a traffic light is not necessary. This is because vehicle flows allow users to find the right time to easily cross the road.

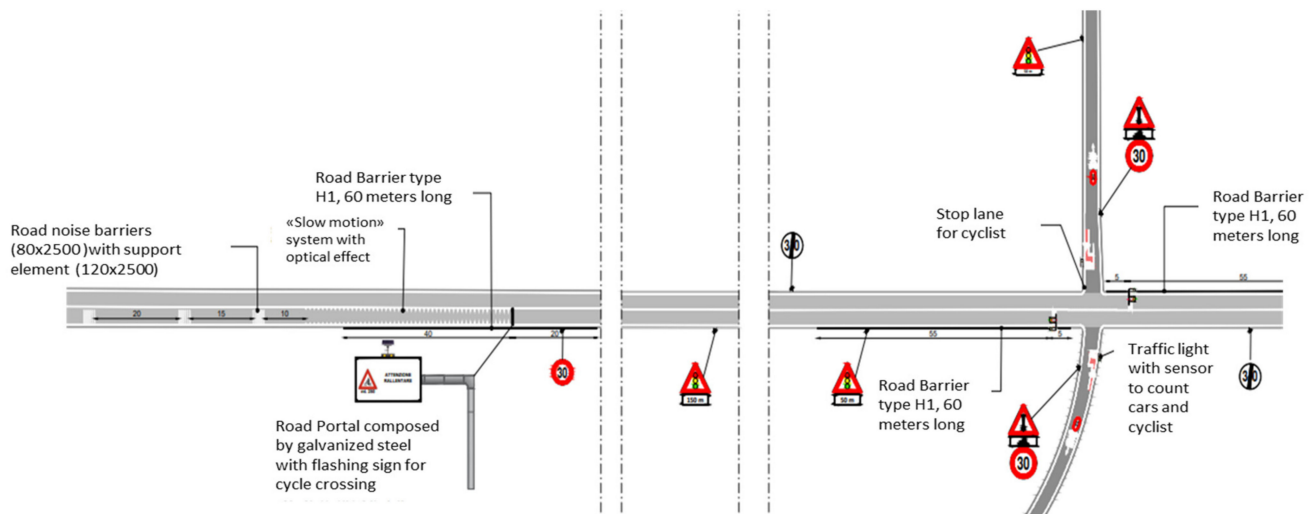


Figure 4. Solution N01—traffic light intersections for provincial roads of width greater than 6.5 m.

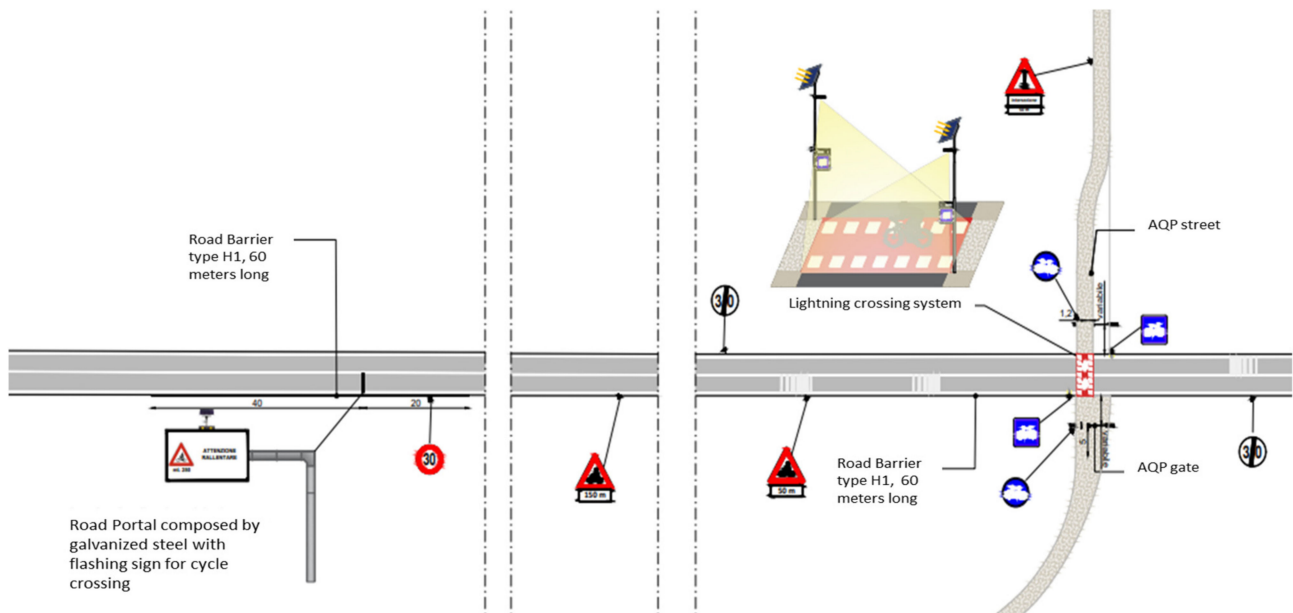


Figure 5. Solution N02—intersections with enhanced signals.

Modelling of Section 3

Once the basic elements are found, the engineering design of the tourist cycle route can start. The design is carried out using the “Roads” software. First, the bicycle axis has been realized as a basic design element. Consisting of straight and curved lines, the axis has been obtained using a polyline, representing the route the cycle path will follow. The initial polyline design, equal to 35 km, has been broken into 7 sections to facilitate the modelling of the axis and to differentiate it later according to the specific characteristics of the territory in a certain stretch. This paper focuses on the modelling of the third section.

Reference elements such as orthophotos or drone surveys are used to obtain the cycling axis with the Roads software. Orthophotos represent a zenithal and georeferenced aerial photograph of a certain zone used for the aero photogrammetric (aerial) restitution of the topographic survey. Compared to traditional topographical surveys, drones allow a survey of a very large area in much less time than the more common procedure. In this case, drone detection is represented by a very large number of triangles, or DTM2 faces, which allow the analysis of the geographical context in which the axis must be modelled, exploiting

the information in order to have a faithful 3D reproduction. The digital terrain model extrapolates the level curves, which are essential for calculating volumes. Having defined the axis of the cycle path from the planimetric point of view, it must also be managed from the elevation point of view. Defining the altimetry of an axis means assigning a reference quota to the graph at the lowest point of the profile and drawing some levels, such as straight segments of different slopes and lengths, reproducing the path of the ground as close as possible. Planimetry and altimetry of the axis are defined, and the generation process is performed. Next, the axis made at first is checked to really resemble the axis that will be modelled. Section by section it must be really in the centre line and not encounter any obstacles. The view of the section offers a precise picture of the geographical context, detecting possible earthworks, excavations or surveying, and so on. Once an axis consistent with all the data collected is established, platforms are defined based on the type sections within the specific modelling environment. Platforms faithfully reproduce the stratigraphy of the ground and represent the roadway, ditches, roadsides, slopes and all those elements necessary for the design. All these features can be parameterized and depend in turn on other elements that, in a sense, represent the geometric key data that, by varying, change all the others related to them.

In this project, platforms are multiple according to the division into sections operated at the beginning. Platforms can be differentiated immediately according to the slope of the levels. This difference basically consists of the creation of two types of carriageways:

- Mixed quarry for a slope less than 3%;
- Mixed cement for a slope of more than 3%.

The study of the project sections shows the differences between soil with low and high bearing capacity measured with a specific site test. When the platform is on the ground, in addition to the roadway, there is a sub-base 0.2 m thick.

As for the regulations, there is a big difference, both in theoretical and practical terms, in the construction of a bike path on its own headquarter to those made promiscuous. Separated cycle paths on their own headquarters run parallel to the carriages intended for vehicular traffic and are recognized thanks to physical separations such as curbs or pavements. Cycle paths with optical separation belong to this type: portions of the path indicated only by vertical and horizontal signs, without physical separations and reserved for the transit of bicycles. Cycle paths in promiscuous can be of different types:

- Promiscuous urban cycle–pedestrian path: routes without physical barriers that separate the road intended for vehicular traffic from the cycle path;
- Cycle paths adjacent to the pavement: a rather wide pavement allows two paths, the internal one for pedestrians and the external one for cyclists;
- Cycle–pedestrian routes: usually found in green areas where access to motor vehicles is not allowed, or often also in cycle tourism itineraries.

In the present case of the separate bike path, the analysis of the territory was fundamental to define the platform that more closely reproduced the best type section. In detail, the section will consist of a track width of 1.5 m, with a road pavement thickness of 0.1 m and a foundation thickness of 0.2 m. A realistic view (Figure 6) and reliable axonometric (Figure 7) of the design under consideration is allowed by the software.

Once the insertion of all standard platforms is finished, quantities are calculated for the definition of volumes and amounts of earthwork and ground survey. The calculation of quantities is made by cross-section polylines, each with its own code, and on the basis of the set calculation sequence. Calculating each partial area relative to a given layer, the final area of the layers is calculated as the sum of each single partial area. The line code (which defines the polyline of the reference section for the calculation of the partial area), the processing/characteristic (type of processing that will be performed from the set reference line, depending on whether it is earthwork or survey) the reference code (section code to be compared with the reference line set as “Polyline Code”) and the quantity code (reference code in a certain area calculated by the processing) are inserted within the calculation

section. Before proceeding with the BIM of the final project, the last step is to model the signs, both horizontal and vertical, of the tourist cycle route. Operationally, vertical signage was designed from blocks related to the different signals of the Highway Code (previously created and inserted in the software library). For the horizontal signs, in addition to the insertion of blocks, the function “Smart Polyline” was used to realize, for example, the bicycle crossings. Figure 8 shows the realization of the project for Section 3 of the tourist cycle route.

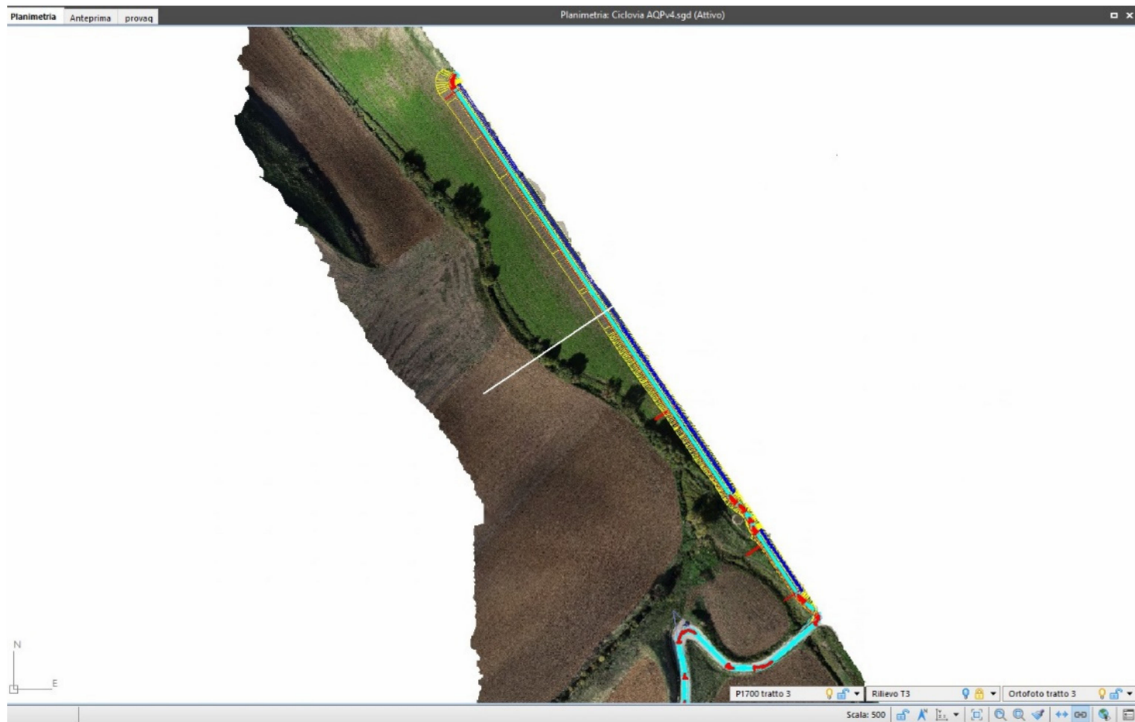


Figure 6. Realistic view of separated cycle path.

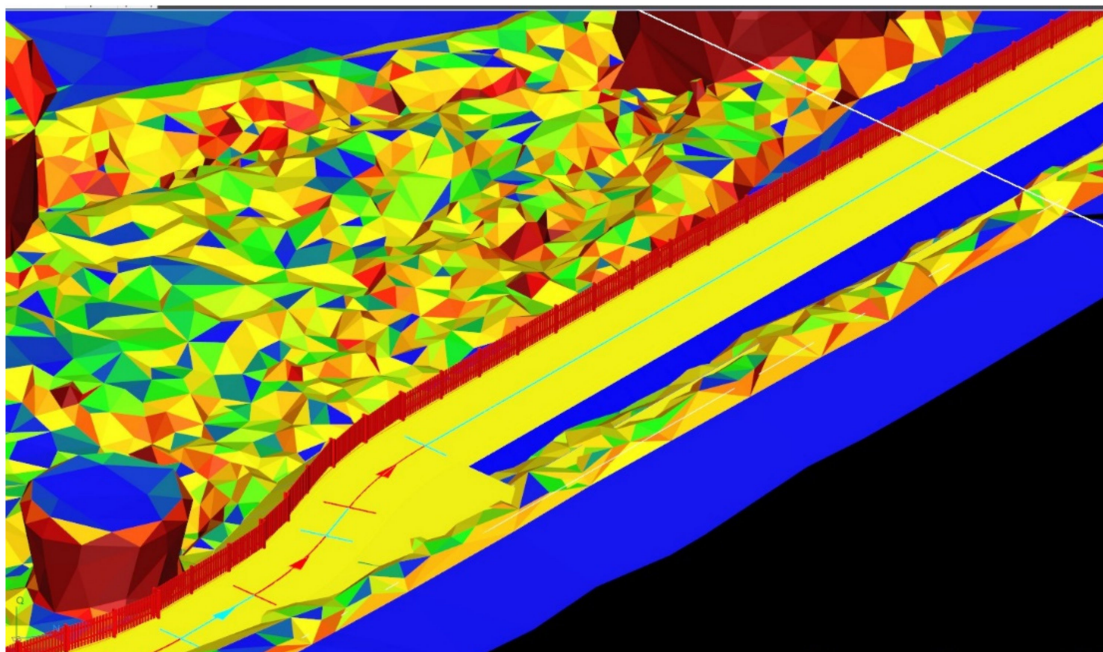


Figure 7. Example of a reliable axonometry of the section for the separated cycle path.

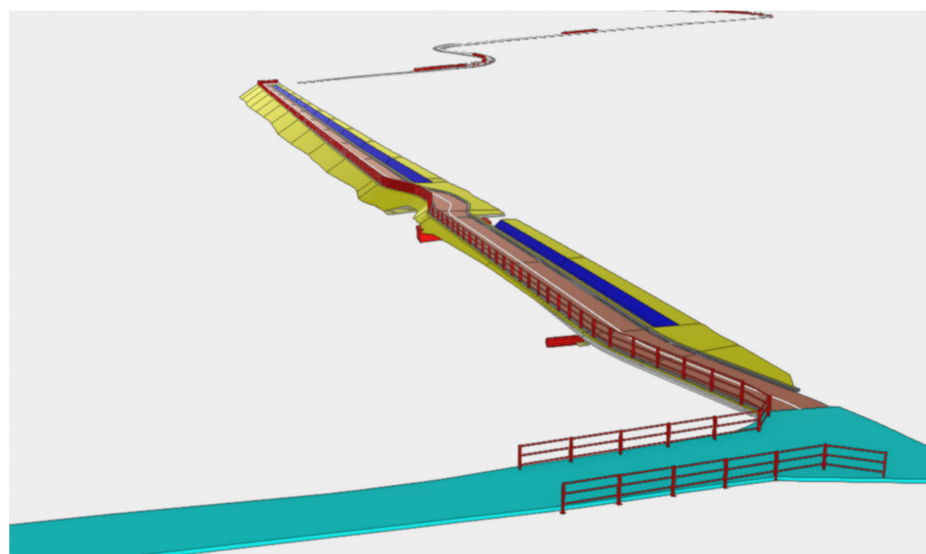


Figure 8. Section 3 of the tourist cycle route.

4. Discussion and Conclusions

Studying the literature on BIM, this tool has proved to be poorly applied to the transportation world but is mainly used in other different contexts. Several literature reviews have found that applications of visual programming tools have focused on architecture projects rather than infrastructure. However, the application of such tools in civil engineering projects is growing [34] and, especially in the design of soft mobility infrastructures, BIM is useful to define the best project. The creation of a cycle path certainly represents an opportunity for environmental enhancement, a form of culturally evolved use of the territory and an opportunity to connect environmental and cultural emergencies with commercial activities and hospitality, thus contributing to the overall growth of the territory crossed.

All phases of design and BIM have been considered, leading to a model that will be realized during the project execution phase. The design of a cycle path is a complex operation containing aspects of the multidisciplinary character (engineering, spatial planning, economics, etc.) and is based on multiple needs: functional, structural and geotechnical, harmonious integration in the landscape, environmental, etc. The project pursues fundamental objectives such as integration of the infrastructure in the environment it crosses, convenience in order to develop an organic and safe cycling network, constructive choices aimed at maximum use and accessibility, sustainability in terms of durability and maintainability and life cycle of the works.

The objective of this study is to provide a complete analysis of the project for the realization of the tourist cycle path in Puglia. The design of the cycle path begins with the precise definition of the geometry of the territory with its altimetric profile. Then, sections and intersections are to be determined and, finally, the structural works to be encountered along the path (hydraulic works, architectural elements, lighting, signage, etc.). In the BIM phase, each object is defined by its properties: name, location, dimensions, materials and technical specifications. For the design and modelling of the track, “Roads”, an integrated software was used, available in the study of “Enser S.r.l.” and provided by Sierrasoft.

By producing realistic virtual simulations, I-BIM allows designers to compare different scenarios and select the best project in terms of feasibility, cost and environmental impact. Additionally, in the case study relating to the construction of a cycle path in the city of Catania, it is shown how the I-BIM approach is useful for the implementation of the choices promoted by the SUMP (Sustainable Urban Mobility Plan) [35].

However, BIM also has some limitations. These are related to high implementation costs, the availability and quality of the information provided by the customer and suppliers

of materials and equipment that must be carefully analysed and selected in order to use only those that are really necessary for design and construction. For these reasons, the design of this cycle infrastructure has shown little applicability and flexibility compared to BIM. However, given the regulations and the desire to move towards sustainable planning, increasingly focused on the construction of cycle paths, the necessity has risen to shape also the more marginal elements of the infrastructural planning with the new instrumentation to the disposition of the planners.

In the future, the use of the BIM methodology will lead to important developments in the infrastructure sector [36]. Virtual reality will bring benefits to any type of construction site by simulating the construction process and identifying any problems before work begins. This will facilitate understanding of the projects, improve collaboration between the members of the different teams involved and increase security for all operators.

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Article

Exploring Virtual Environments to Assess the Quality of Public Spaces

Rachid Belaroussi ^{1,*}, Elie Issa ², Leonardo Cameli ², Claudio Lantieri ² and Sonia Adélé ¹¹ COSYS-GRETTIA, University Gustave Eiffel, F-77447 Marne-la-Vallée, France; sonia.adele@univ-eiffel.fr² Department of Civil, Chemical, Environmental, and Materials Engineering (DICAM), University of Bologna, 40126 Bologna, Italy; elie.issa@studio.unibo.it (E.I.); leonardo.cameli2@unibo.it (L.C.); claudio.lantieri2@unibo.it (C.L.)

* Correspondence: rachid.belaroussi@univ-eiffel.fr

Abstract: Human impression plays a crucial role in effectively designing infrastructures that support active mobility such as walking and cycling. By involving users early in the design process, valuable insights can be gathered before physical environments are constructed. This proactive approach enhances the attractiveness and safety of designed spaces for users. This study conducts an experiment comparing real street observations with immersive virtual reality (VR) visits to evaluate user perceptions and assess the quality of public spaces. For this experiment, a high-resolution 3D city model of a large-scale neighborhood was created, utilizing Building Information Modeling (BIM) and Geographic Information System (GIS) data. The model incorporated dynamic elements representing various urban environments: a public area with a tramway station, a commercial street with a road, and a residential playground with green spaces. Participants were presented with identical views of existing urban scenes, both in reality and through reconstructed 3D scenes using a Head-Mounted Display (HMD). They were asked questions related to the quality of the streetscape, its walkability, and cyclability. From the questionnaire, algorithms for assessing public spaces were computed, namely Sustainable Mobility Indicators (SUMI) and Pedestrian Level of Service (PLOS). The study quantifies the relevance of these indicators in a VR setup and correlates them with critical factors influencing the experience of using and spending time on a street. This research contributes to understanding the suitability of these algorithms in a VR environment for predicting the quality of future spaces before occupancy.



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Keywords: pedestrian mobility; urban design; virtual reality; immersive visit; public space auditing; bicycle infrastructure

1. Introduction

This article focuses on the research of a practical application that combines the human perspective with virtual reality technology to assess and understand public spaces for the purpose of enhancing their design and functionality. By public spaces we mean two types of urban realm: sidewalks—which are often contiguous to a road network and mixed with cycling infrastructure—and public places—which include gathering places and parks.

User experience and perception assessment involves capturing and analyzing how users perceive and experience public spaces; it includes factors such as aesthetics, safety, accessibility, and overall satisfaction. A human-centric approach considers the experiences, perceptions, and needs of individuals who use or interact with public spaces. It is traditionally conducted through surveys with an on-street questionnaire, which asks people walking and spending time on a street about how they perceive the street. It is a more reliable method since the participants are inside the physical environment but it can be costly and time-consuming.

It can also be done through the exploitation of street view imagery, such as Google Street View, which can be panoramic, or through the use of more personalized videos or

still image acquisitions of the scene to be assessed. These types of methods of public space auditing cannot be done for prospective projects not yet constructed, but their methodology can be useful to assess future designs based on 2D drawings or VR setups. The utilization of VR technology suggests a forward-looking and technologically advanced approach to public space assessment. This can provide a more immersive and interactive experience for participants compared to traditional assessment methods.

The study may involve collecting data on user interactions and preferences within the virtual environment. Analysis of this data, through algorithms leading to high-level indicators, can contribute to insights into how people respond to different elements of public spaces. Findings from such assessments could have implications for the design and planning of public spaces, influencing decisions related to architecture, landscaping, and overall urban design. Indeed, the use of VR for public space assessment allows for potential applications in pre-occupancy evaluations, allowing planners and designers to anticipate the impact of proposed designs before physical implementation.

2. Literature Review

2.1. Related Works

Various approaches have been developed to evaluate the suitability of public areas for walking or cycling, primarily focusing on built environments like sidewalks and public places, which are the two main categories of “Public Spaces”. Insights gained from research on these subjects have been employed to create assessment methods intended to assist in developing strategies to promote non-motorized transportation and improve the overall quality of life. Previous studies have demonstrated that the design of built environments and people’s perceptions of them significantly influence individuals’ walking habits, a crucial aspect of neighborhood residents’ active lifestyles [1,2]. Table 1 provides a classification of our literature review based on five modalities: traditional field surveys, static virtual environments, static street view panoramic images, dynamic virtual environments (i.e., with traveler flows), and recorded panoramic videos of real environments.

The majority of research in this field employs subjective measurements to understand individuals’ perceptions of walkability at the neighborhood level. Broadly speaking, these methods consider various factors related to the streetscape that contribute to categorizing a specific road section or area as safe and comfortable for walking or cycling, often represented by a numerical score. In the context of walking, this evaluation is commonly referred to as “walkability”, while terms such as “bikeability” or “cyclability” are found in the existing literature when assessing cycling suitability.

One common method for assessing the comfort and safety of pedestrians is the Pedestrian Level of Service (PLOS) derived from the Highway Capacity Manual. Originating from the vehicular Level of Service (LOS), PLOS treats walking as a mode of transport and correlates pedestrian traffic characteristics with network capacity.

Jaskiewicz [3] computes walkability indicators, including the complexity of spaces and paths, buffering between pedestrians and traffic, presence of shade, and overhangs. We used his method, called the PLOS Trip Quality Method, as a reference in this article, but other PLOS algorithms exist in the literature.

Karatas and Tuydes-Yaman [4] investigated the variability in sidewalk Pedestrian Level of Service measures and ratings. Their paper highlights the lack of consensus and consistency in PLOS methods, comparing 29 different methods used in summarizing sidewalk PLOS studies. The assessments, based on pedestrian opinion and traveler perceptions, focus on traffic, safety/comfort, land use, infrastructure, and user/trip. The study evaluates 81 walkway locations on a campus in Ankara, Turkey, using two trained raters who assessed the campus as if it were a city street to minimize bias.

Another important aspect of urban streetscape is bikeability as walking and cycling are often mixed in urban areas. To optimize cycling facilities, an accurate representation of the bicycle system is essential. The Bicycle Level of Service (BLOS) serves as a quantitative measure, categorizing users’ perspectives on bicycle facilities and services. Assessing

BLOS is complex, primarily due to the significant role of comfort, which necessitates a delicate balance between individuals and their environment. This balance is shaped by physical, psychological, and sociological factors, resulting in a highly personalized evaluation dependent on individual characteristics. Key considerations in defining BLOS include bikeability, suitability, bicycle friendliness, bicycle flow, and bicycle comfort [5].

For example, Beura et al. [6] proposed a BLOS approach that incorporates factors such as effective road width, crossing pedestrian volume, volume of turning vehicular traffic across cyclists' paths, average stopped time delay for through cyclists, on-street parking turnover, surrounding developmental patterns, and peak-hour volume.

Resch et al. [7] proposed an interdisciplinary mixed-methods approach to analyze urban spaces, focusing on walkability and bikeability. The study emphasizes the importance of understanding people's perceptions and reactions to their environments, considering factors such as traffic volume, noise, safety, urban configuration, and greenness. The methodology involves using objective data from wearable physiological sensors, an e-diary app, first-person perspective videos from a chest-mounted camera, referenced interviews, and post-hoc surveys. The approach focuses on identifying and geolocating moments of stress and relaxation for pedestrians and cyclists in city centers.

Ewing et al. [8] addresses the challenging dimension of street design/landscape in walkability assessment. The book categorizes features into imaginability, visual enclosure, human scale, transparency, and complexity. Ewing et al.'s research evaluates the impact of street landscape on walkability compared to other dimensions, including diversity, density, destination accessibility, distance to transit, and demography.

Others study some aspects at a smaller scale within neighborhoods, employing various assessment tools to understand how neighborhood characteristics influence people's perceptions of walkability in empirical studies [9].

Existing tools for auditing public spaces often require time-consuming onsite fieldwork, surveys, focus groups, and document analysis, making them labor-intensive. The use of images has become a common and cost-effective approach to assess the aesthetic qualities of built environments. Compared to traditional methods, VR environments offer more dynamic and integral impressions, allowing respondents to perceive walkability dynamically with a sense of realism and experience [10].

Liao et al. [11] opted to gauge users' perceptions of walkability through recorded videos simulating neighborhood environments at the pedestrian's eye level. Belaroussi et al. [12] also used recorded videos of the virtual environment created under two scenarios, the current situation and the future situation after the redevelopment of a sidewalk, in order to assess possible improvements in walkability and bikeability. An advantage of this approach is that participants can gain an integrated view of the environment from the comfort of their homes, as videos do not require the complex setup necessary for a head-mounted display. The chosen scale for measurement is a street block, deemed an appropriate unit for mapping urban structures [13].

Oselinsky et al. [14] explored the acceptability of virtual reality assessment for walking in a virtual environment, particularly for pre-occupancy urban designs impacting walking. The study employed a wearable VR head-mounted display with a backpack computer, allowing young adults ($n = 40$) to freely walk through a large indoor gymnasium while virtually navigating a model of a modifiable urban streetscape. Participants strolled through a modifiable VR model of four city blocks in the historic downtown area of a mid-sized city in the western US at their chosen speed. Following the VR session, participants completed a survey covering VR adjustment, cybersickness, virtual realism, equipment comfort, controller usability, immersion, perceived safety, environment attractiveness, and perceived task difficulty.

Keil et al. [15] investigated the utilization of electrodermal activity wristband sensors with an HMD to measure skin conductance level and correlate it with specific urban planning scenarios, including trucks passing by, traffic noise levels, and traffic density. The study involved a small sample of six participants in a virtual environment.

The 360-degree video represents a relatively innovative technology for environmental observation, auditing, and modeling [16]. Previous studies, such as [17,18], have employed recorded real environments in the form of 360° panoramic videos. Participants were guided through virtual tours using a head-mounted display. The advantage of VR audits becomes more pronounced with the size of the study area. However, conducting research with HMDs can pose challenges when dealing with a large number of participants. For example, Kim et al. [17] involved a 10-person expert panel, and Mouratidis et al. [18] included 28 students who audited four streets and four public places. While Mouratidis' findings on perceptions of architectural styles are relatively straightforward, conclusions regarding perceptions of public space design, overall perceptions of public space, and affective appraisals of public space suggest dependencies on various factors rather than specific design features.

Table 1. Studies of public space quality classified by modality of audit.

Ref	Modalities	Methodology	Objectives
[3]	Onsite inspection of comfort and safety	Nine PLOS measures are proposed based upon aesthetics, safety, and ease of movement	Account for aesthetics and safety in addition to volume and capacity
[8]	Onsite field survey	Visual assessment of urban design qualities	Provide operational definitions and measurement protocols
[7]	Onsite physiological measurements and georeferenced interviews	Combine geospatial analytics and analysis of physiological signals	Localization of stress and relaxation hotspot in urban areas
[6]	Onsite bicyclist survey	Functional method to model BLOS based on infrastructure geometry and traffic flow	Analyze bicycle service quality at intersections
[11,12,19]	Recorded video of static Virtual Environments	Analysis of online questionnaires on perception of walkability	Study of infrastructure attributes and identification of best designs
[14]	HMD walkable visit of static Virtual Environments	Post-experience survey on acceptability of VR	Determine the suitability of VR setup: cybersickness, realism
[20]	Street view panoramic images and field audit	Intraclass correlation coefficient of field visits and street view questionnaire surveys	Compare assessments using Google Street View and field visits
[21]	HMD with panoramic images of real environment and Street view panoramic images	Statistical analysis of questionnaires on streetscape satisfaction	Compare landscape evaluation based on HMD or 2D-screen panoramic images
[10]	Dynamic Virtual Environments in HMD on a bicycle simulator or still images	Participants rating of cycling infrastructures based on aesthetic, safety and mode choice	Test cyclists' environmental preferences in HMD versus still images
[15]	HMD visit of dynamic Virtual Environments with physiological measurement	Analysis of skin conductance level	Fear and stress response to scenarios (traffic density and noise)
[18]	HMD with recorded 360° panoramic videos of real environment	Questionnaire survey on affective appraisal and environmental perception	Evaluations of contemporary versus traditional design styles in architecture and urban design
[17]	HMD with recorded 360° panoramic videos of real environment, street view images and field audit	Post hoc interview and questionnaire survey of experts analyzed by intraclass correlation coefficient	Examines whether immersive visits can replace field audits
[22]	HMD of recorded real environments in 360° panoramic videos and recorded videos of real environments	Questionnaire on infrastructures and walking willingness of diverse street environments in multiple nations	Characteristics of 360° cameras and HMD for streetscape evaluation
[23]	HMD with recorded 360° panoramic videos of real environment and field audit	Questionnaire related to aesthetic preference and landscape cognition	Agreement of on-site observation and VR stimulus in terms of public perception

2.2. Contributions of the Research

Although it is increasingly used to assess natural or urban landscapes, the validity of virtual reality in this particular case has been little explored. Few comparative studies exist. The oldest [20] compares the assessment of walkability using Google Street View, the point of view of local residents, and field visits based on 90 participants. The authors conclude that these three methods provide correlated results for traffic safety, aesthetics, sidewalk quality, and physical barriers, but that the Google Street View assessment is the most correlated with the assessment by locals. This result suggests that video is a good evaluation tool that deserves to be compared with immersive virtual reality.

Nakamura et al. [22] compared dynamic video with a fixed view to a 360° immersive dynamic video viewed through a headset. The same 50 individuals were confronted with both conditions but the order of presentation was counterbalanced. His results show a more favorable evaluation of walkability in the immersive condition.

Shi et al. [23] compared the immersive virtual reality condition ($n = 21$) with the site visit condition ($n = 16$) but the evaluation carried out focused more on the beauty and other appearance attributes of 11 landscapes. In this protocol, different people were placed in each of the conditions. The very similar results obtained in the two conditions prompted the authors to propose replacing the gold-standard on-site visit with virtual reality for reasons of efficiency. Finally, ref. [21] compared Google Street View images for a web-based administration of streetscape evaluation to an evaluation following an immersive virtual reality visit. In this study, 25 participants evaluated the two situations 7 days apart. They concluded that the VR-based streetscape evaluation method has better explanatory power than the web-based streetscape evaluation method. We aim to scrutinize this assertion using dynamic scenes and virtual environments.

Sustainable development issues encourage the design of spaces conducive to the use of active modes, which are defined in the literature as having good walkability and cyclability. Research has shown that these two characteristics are closely linked to how the spaces are perceived by their users [1,2]. It is therefore entirely appropriate to look at ways of taking users' points of view into account, both in the indicators to be used and in the methods of visualizing the spaces to be assessed. In this research, we use existing indicators (SUMI and PLOS), which we combine with other indicators such as the feeling of safety and relaxation, the perception of activities to be carried out in the space, and overall perceptions of the suitability of these spaces for walking and cycling in general and a behavioral intention to walk or cycle in these spaces.

One of the central challenges associated with the evaluation of spaces by their likely users is to get as close as possible to an evaluation following an on-site visit or by local people, which is the gold standard [23]. There is no longer any need to prove that these methods are costly and impossible in the case of the rehabilitation of a site that does not yet exist in reality. Virtual reality is, therefore, a promising alternative since the visual information in VR corresponds to that experienced in the real world, where the visual scene is updated with head movements.

Unfortunately, research into the validity of virtual reality in the assessment of landscapes or streetscapes has been reduced to very little. The literature has shown that video can advantageously replace on-site visits [21], particularly when they are offered with the possibility of a 360° view using virtual reality headsets [22]. As can be seen in Table 1, virtual visits to real environment have already been compared to on-site visits [23] or to static images via Google Street View [20] but public space auditing of real places was never compared to immersive visits in virtual environments. Our aim is therefore to test and compare two ways of visualizing a space that have never been compared. Specifically, we will compare on-screen videos in which the participant does not control image rotation by head movements, with dynamic virtual reality scenes in an HMD. We will seek to answer the following questions.

- How relevant of a tool is Virtual Reality-Immersive Visit (VR-IV) for prospective public space auditing?

- Is the order in which the proposed urban areas are classified according to the various indicators selected the same when the spaces are viewed with video or VR?
- Are there any significant differences between the qualification of a public space in a real video and VR-IV?

These answers will enable us to formulate recommendations for designers and evaluators concerning the use of virtual reality in the case of new projects to ensure that a space meets sustainability expectations.

3. Materials and Methods

3.1. Case Study

Figure 1 illustrates the map of the future district of interest with its building's footprint, its road network, and the location of various activities: Home, Work, Education, Shopping, Leisure, and a public transportation hub. The figure shows the urban and landscape framework planned for LaVallée; the site has all the assets for experimenting with a form of town planning attentive to the nature/city relationship, producing an exemplary living environment a few minutes from Paris, France. Three urban identities are present in the district: The outdoor Shopping mall with a more intense and active life, a Public place as an entry point to the district, and Living in a green environment with more leisure places. All these urban fabrics form as many identities as the neighborhood will reveal.

A portion of the neighborhood that has already been developed is the focus of this experiment. This includes the public space situated to the south of the district, serving as the primary entrance due to the presence of the tram station. Additionally, the shopping street, lined with stores primarily along the main road extending from the north to the south of the district, is examined. Perpendicular to the shopping street, there is a pedestrian walkway known as LaVallée's Garden—a public area mainly designated for recreational activities, marked by green circles, featuring abundant vegetation and children's playground activities.

These three points of interest will be investigated through two different modalities: real-time video footage portraying the current state of the built environment, and immersive visits displayed on a head-mounted display, such as the HTC VIVE, allowing for virtual reality exploration of these public spaces.

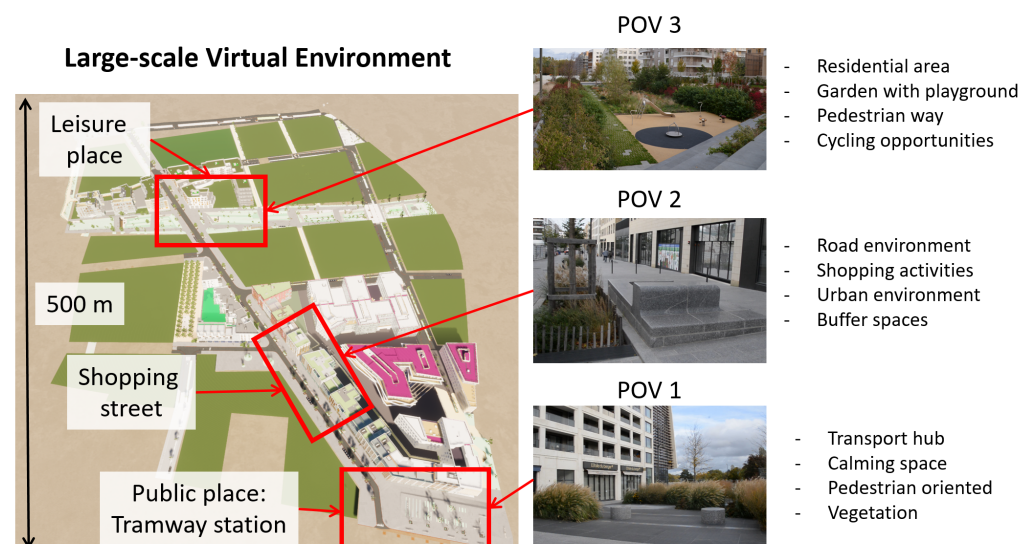


Figure 1. Overview of the points of view of interest and their interest: street views and 3D model.

Three Points Of View (POV) were selected in this digital twin of LaVallée, representing various aspects of urban areas. POV 1 is a public place and is the main entry point to the district. It includes a tramway station and a pedestrian walking space with vegetation.

POV 2 is a strip mall. It is the central artery of LaVallée and the main line to the majority of shopping activity. Along this stretch of boulevard are stores and restaurants in adjacent spaces in one long building with a narrow parking area directly in front of the stores and a central road for vehicles limited at 30 km/h.

POV 3 is a green space with a children's playground in the middle of the pedestrian way surrounded by some residential buildings. It is one of the leisure places of the district with a lot of vegetation and, to some extent, includes cycling opportunities.

The attention paid to the ground floors is essential in the constitution of an animated and lively district. Since we are collaborating with the real-estate programmer, we have access to the BIM data of the buildings: from them, a 3D city model was built. The 3D city models depict both natural and man-made spatial elements, such as buildings, roads, and vegetation, in the three-dimensional space. Key factors determining the quality of a 3D city model include its completeness, the precision of object locations in space, and the level of detail (LOD). The LOD measures the accuracy with which 3D objects represent intricate visual details of the corresponding spatial elements [24]. We used static BIM data with a high LOD for buildings, streets, vegetation, and urban furniture, complemented by GIS data to model the urban context and non-yet-existing buildings and for the tramway station. We populated the 3D scenes with dynamic elements such as non-playing characters: walkers, cyclists, and vehicles. Details about this 3D city model can be found in [25], which was built using Revit 2020 for BIM data integration, Infracore 2022 for the GIS data, and TwinMotion 2022.2.3 for the visualization and addition of dynamic elements.

3.2. Methodology

3.2.1. Procedure

For each POV, participants perform an immersive visit with an HTC VIVE head-mounted device followed by an online questionnaire, which they can access from a provided computer. Then, they watch the video of the real POV and answer the same set of questions. The experimental protocol is illustrated by Figure 2.

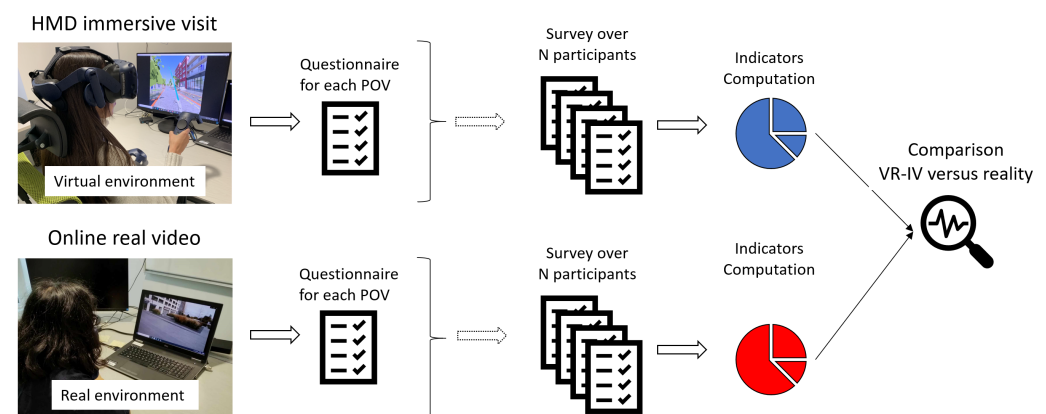


Figure 2. Experimental protocol: each participant is shown a POV in an HMD or in a video of the real built environment. After each virtual visit, they fill out a questionnaire. Based on the response of all participants, a set of indicators is computed for each modality: audit based on VR-IV visit is compared to audit based on real video.

The experiment begins with the following simple explanations and instructions: “In this study we are focused on the auditing of an urban district through selected scenes. The scenes are provided using videos of the district and the same scenes will be displayed through a head mounted device (Virtual reality glasses). The participation is anonymous and the whole survey will take you about 30 min. You will be shown three scenes of areas in the district and will then be asked questions related to the quality, walkability and liveability of the area.

This opinion survey may be published in a research paper: by completing it, you voluntarily consent to the processing and publication of your data.”

We have chosen to follow the experimental protocol proposed in [26] without providing specific definitions of urban space auditing to the participants. They have not been trained in the various subjective characterizations of urban spaces presented in the questionnaire, to avoid biasing their judgments.

The questionnaire consists of three identical parts, one for each POV, each featuring a VR-Immersive Visit (VR-IV) and a 1 min video of the same real scene acquired on-site. Participants are asked to imagine visiting the depicted space and respond to a set of questions. In our study, these questions are related to the real scene and the VR-IV of a 3D city model created from professional BIM data. Participants are encouraged to reflect on their feelings and evaluate the public nature of the urban space, the intended usage of the public space, and their impressions of walkability and cyclability during these virtual visits and during the display of real videos.

3.2.2. Sample

The voluntary participants consist of adults from the University Gustave Eiffel (France) not involved in the LaVallée real estate project. A total of $N = 22$ non-expert participants were included in this study with the only inclusion criteria being to be an adult. They all completed both the survey using the HMD and the reality videos. The participants are equally balanced in terms of gender: half male, half female. Most of them were aged between 22 and 30 years old; 73% were students, the remaining 27% being researchers. Personal questions were limited to age, gender, and occupation as the questionnaire was anonymous.

3.3. Measures: Indicators of Public Spaces Quality

To draw a comparison between the quality of the public spaces assessed by the users, a qualitative survey would only act to provide a surface understanding. To investigate a comparison between videos of the existing spaces and immersive visits of their digital models, a quantitative approach would allow for a more holistic statistical analysis. Many indicators can be used to assess the quality of public spaces, focusing on prime aspects such as the use of public transport, the driving experience in the areas, the bicycle level of service, etc. Due to our focus being primarily on the pedestrian experience in public spaces, and our points of view both virtually and in the videos placing participants at a pedestrian level, the indicators chosen had to coincide with this and assess the overall pedestrian experience within these areas. Thus, the indicators chosen for the assessment were the Pedestrian Level of Service (PLOS)—Trip Quality Method [3,4] and the Sustainable Urban Mobility Indicator (SUMI) for public space assessment [27].

3.3.1. Pedestrian Level of Service PLOS—Trip Quality Method

In general, the pedestrian level of service is a quantifiable measure that is typically prioritized in the assessment of public spaces and their pedestrian–environment interaction. PLOS can be measured both qualitatively and quantitatively using a multitude of methods and permits quantifying comfort and safety levels of existing and planned walkways allowing objective and sound evaluations of pedestrians’ perception and response to roadway environment. Although the methods to analyze the pedestrian level of service are vast, a limitation is that it had to match the prompt of the experiment and thus had to be applicable to both a virtual environment and a static video of the real environment. The Trip Quality Method (TQM) [3] was thus chosen.

The method allows raters to qualitatively rate a walkway from a pedestrian’s perspective in regards to pleasantness, safety, and comfort using nine measures: enclosure/definition, complexity of the path network, building articulation, complexity of spaces, transparency, buffer, shade trees, overhands/awnings/varied roof lines, and the physical component/condition. For each of these factors, a score between 1 (very poor)

and 5 (excellent) was assessed; afterward, the arithmetic average was taken to obtain a final score on the pedestrian level of service [4]. Additionally, [3] specified that the method is best served for city streets, shopping areas, and working spaces, all of which characterize the three points of view selected for the experiment.

Unfortunately, not all nine measures are relevant to the experiment, as the experiment's static nature does not allow for the sufficient testing of certain factors. Due to the method's simplistic arithmetic nature, we were able to effectively manipulate by extracting the four most relevant characteristics and having our participants rate those on the same scale previously mentioned, and then calculating their arithmetic average to obtain a final score out of five, considered the pedestrian level of service. This score is later weighed with a letter grade based on the following conversion table.

- LOS A = 4.0 to 5.0 = Very Pleasant;
- LOS B = 3.4 to 3.9 = Comfortable;
- LOS C = 2.8 to 3.3 = Acceptable;
- LOS D = 2.2 to 2.7 = Uncomfortable;
- LOS E = 1.6 to 2.1 = Unpleasant;
- LOS F = 1.1 to 1.5 = Very Unpleasant.

The four factors studied in the experiment are the complexity of the path network, complexity of spaces, buffer areas, and shade and trees. In terms of complexity in the path network, the factor focuses on the path network being complete and easy to understand. This means that from being in a static position, the user is not confused by the path network and does not feel as though it is poorly connected. Thus, to quantify this factor in a way that is easily comprehensible for the general participant (as the participants are not required to have a level of prior knowledge in the subject), the question used was "How simple is it to understand the pedestrian path network in the area?"

The second factor complexity of spaces is quite similar as it studies the completeness of the public space and its contribution to inducing simplicity in the comprehension of the functions of the space. The more complete the space is in terms of including all necessary features for its function, the more simple it is to understand said function. Spaces that can be studied with this factor include commercial districts, residential neighborhoods, courtyards, plazas, parks, and playgrounds. Objects that heavily influence the function of the public space include water features, trees, geometry, signs, street furniture, and any unique physical quantities of a public space. Places that miss these defining features are typically more difficult to understand, making them more complex. To best assess this factor, the question used in the questionnaire is "How simple is it to understand the function of the surrounding public spaces in the area?"

Thirdly, buffer areas were also used to obtain the pedestrian level of service indicator. Buffer areas are spaces in which people can stop to rest or converse with others while being at a sufficient distance from vehicular traffic without interrupting the pedestrian flow on sidewalks or public spaces. The presence of this buffer zone between a pedestrian and the flow of moving vehicles enhances pedestrian safety and comfort. If the distance is accompanied by solid objects between pedestrians and traffic, this physically improves safety as it reduces the likelihood of a pedestrian-involving accident occurrence. Additionally, perceived safety, which goes hand-in-hand with perceived comfort, is proportional to the size of buffer areas, as pedestrians feel safer when they feel further away from traffic. Objects that increase the feeling of safety in buffer zones include large trees, on-street parking spots, and other large street furniture elements. To assess this, the question used was "Rate the availability of buffer areas* for pedestrians to wait or converse in the space".

The last factors used to compute the PLOS-TQM indicator were shade and trees. The presence of shade within the walkway creates an atmosphere of comfort for pedestrians on summer days. In addition to protecting pedestrians from excess heat, it also adds a green aesthetic to the walkways and contributes to the concept of solid objects in the buffer space. This is found in the questionnaire through the question "Rate the sufficiency of shade and shelter provided along the area".

The questions were asked for each of the three POVs for both their real videos and their immersive virtual environment through our mandated questionnaire.

To summarize, the questions compiled in this indicator were the following.

- How simple is it to understand the pedestrian path network in the area?
- How simple is it to understand the function* of the surrounding public spaces in the area?
- Rate the availability of buffer areas* for pedestrians to wait or converse in the space.
- Rate the sufficiency of shade and shelter provided along the area.

A description of what is meant by “function” and “buffer area” was given as follows.

Examples of functions are: commercial, residential, educational, leisure, and touristic. Buffer areas: Spaces in which people can stop to rest or converse while being at a sufficient distance from vehicular traffic without interrupting pedestrian flow.

3.3.2. Sustainable Mobility Indicators SUMI

The Sustainable Urban Mobility Indicator Quality of the public space was the second indicator used for the quantification of our analysis. According to [27], indicators are used to offer technical assistance in assessing urban areas and their urban mobility. The indicators are endorsed and used by the European Commission and are developed based on the “SMP2.0 Sustainable Mobility Indicators” developed by the World Business Council for Sustainable Development. The European Commission through the indicators prioritizes supporting European cities in evaluating their mobility system and its sustainability. They also aid cities in tracking the impact of their policies through a widely accepted and harmonized approach.

The indicators present in the document include the following.

- Accessibility of public transport for mobility-impaired groups;
- Air pollutant emissions;
- Opportunity for active mobility;
- Multi-modal integration;
- Satisfaction with public transport;
- Traffic safety active modes;
- Quality of public spaces;
- Mobility space usage.

Between the predeceasing options, only a few were suitable for the premise of our experiment, which is based on the human sensation of public areas such as places, parks, and sidewalks. The most suitable and feasible link between the indicators was the quality of the public spaces indicator. The indicator was designed originally to analyze results from the European Commission’s urban audit, a perception survey on the quality of life in European cities which is being conducted by Eurostat based on telephone interviews on a regular basis. The parameter is an averaged score of survey responses conducted by the designer about the perception of satisfaction with public and green spaces.

The formulation used to compute the indicator from the aforementioned input is the following:

$$SUMI_{QPS} = \frac{1}{m} \sum_{k=1}^m \overline{Aspect_k},$$

m = number of aspects

aspects = {public spaces, green spaces}

$\overline{Aspect_k}$ being the weighted average of respondents ratings for aspect k , computed as follow:

$$\overline{Aspect}_k = \sum_h \frac{\text{number of agreement } h \text{ for aspect } m}{\text{number of respondents}} 10C_h$$

with h = strongly agree, $C_h = 1$, h = somewhat agree, $C_h = 2/3$,
 h = somewhat disagree, $C_h = 1/3$, h = strongly disagree, $C_h = 0$.

To calculate the indicator, two questions were asked: “Rate your overall satisfaction with the public spaces available in the area presented” and “Rate your overall satisfaction with the green spaces available in the area presented”. In general, public spaces are composed of markets, squares, and pedestrians. While green spaces include parks and gardens. For each of the two questions, the participant had to provide a ranking between 1 and 4, 1 insinuating satisfied and 4 insinuating not at all satisfied; this constitutes the agreement scale. Each possibility was given a fractional weight of ten. For each of the two questions, the number of surveyed participants was input and so was the number of responses for each option (satisfied, rather satisfied, rather unsatisfied, not at all satisfied). Then, based off of this input, two indicator values were computed, one for the public space satisfaction and the other for the green space satisfaction. Then, the average of the two was taken to obtain the final SUMI quality of the public space indicator.

4. Results

4.1. Virtual Environment Credibility

To the question “Overall, how realistic did you find the shown spaces?”, 91% chose the answers “Realistic” or “Very realistic”. They ranked characteristics according to the realism they give the space, with the scale being the most important, followed by the environment size of the model. The size of the buildings in comparison to the real ones was deemed convincing by 95% of the participants. Wall and roof material, as well as the possibility to look everywhere, were ranked as the third characteristic, giving realism to the VR-IV visits. Light and shadows were ranked last.

The virtual environment allowing immersive visits of the three urban identities was therefore deemed appropriate to lead a public space audit, but the question remained as to whether such an audit would be consistent with an audit based on inspecting the reality of the urban space or not.

4.2. Pedestrian Level of Service: Trip Quality Model

The PLOS-TQM integrates notions relative to the complexity of the path network, the complexity of the place, the presence of the buffer area, and the shades from trees.

The results of the PLOS-TQM can be seen in Figure 3. The two modalities of the experiment, VR and reality, agree in terms of ranking the POVs. Not surprisingly, POV 3 exhibits the highest PLOS; it is a place designed to enhance the walking experience of the public, a quality perceived both in VR and in reality. However, the difference with POV 2 is less pronounced in VR-IV than in reality.

POV 1 has a lower level of PLOS, but in this case, the difference is more noticeable in the VR-IV setup than in the reality videos. For example, the PLOS-TQM varies from 3.7 to 3.85 when computed from real scenes between POV 1 and POV 2. In the VR-IV setup, it varies from 3.9 to 4.34, indicating a larger difference.

Table 2 illustrates the relative difference in the computation of the PLOS-TQM between the VR-IV setup and the real scenes. The scores are systematically higher in the VR-IV from 5 to 13%. Indeed, both in VR and in reality, the ranking of public spaces from the pedestrian level of service is $POV3 > POV2 > POV1$.

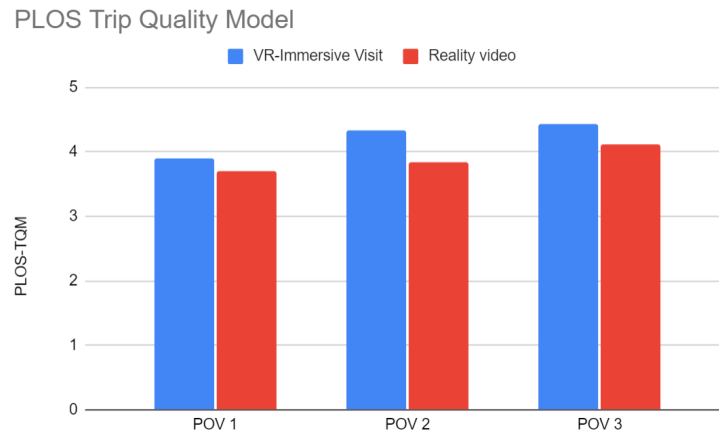


Figure 3. Pedestrian level of service. Trip quality model for the three points of view based on VR-immersive visit and video of the real scenery.

Table 2. Relative difference in Pedestrian Level of Service (PLOS)-Trip Quality Method (TQM) between Virtual Reality-Immersive Visit (VR-IV) and reality.

	POV 1	POV 2	POV 3
Difference in PLOS-TQM	5.4%	12.7%	7.8%

4.3. SUMI Quality of Public Space

From the perspective of the SUMI-QPS metric, the overall quality of public and green spaces was deemed more satisfactory for POV 3 compared to POV 1 or POV 2, as illustrated in Figure 4. This holds true for both the VR-IV and reality setups, where POV 1 and POV 2 elicited similar responses from participants. The superior quality of POV 3 is expected, given its incorporation of essential elements for a successful walking environment: pedestrian pathways, vegetation, parks, and recreational amenities.

However, the relative difference in SUMI-QPS between the VR-IV and reality setups is more pronounced than that observed with the PLOS-TQM indicator. Table 3 displays the relative difference in SUMI-QPS computation between the VR-IV setup and real scenes. A systematic overestimation of public space quality can be anticipated when using a VR-IV setup, ranging from 30% for urban scenes like the public space in POV 1 or the shopping street in POV 2, to 24% for the leisure area in POV 3.

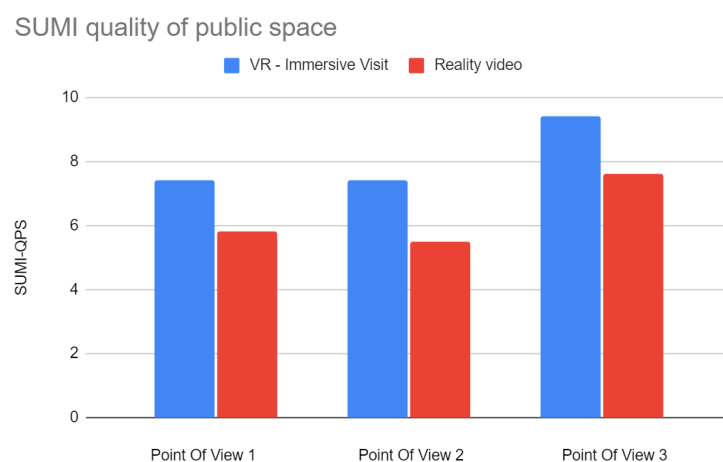


Figure 4. Overall satisfaction of public space and green space for the three points of view. Indicators are derived from the feelings of the same participants after VR immersive visits and based on real videos inspections.

Therefore, the predictive capability of virtual reality is somewhat challenged for this indicator, with a significant positive bias of up to 30%.

Table 3. Relative difference in Sustainable Mobility Indicators (SUMI)-Quality of Public Space (QPS) between Virtual Reality-Immersive Visit (VR-IV) and reality.

	POV 1	POV 2	POV 3
Difference in SUMI-QPS	30%	32%	24%

4.4. Other Independent Indicators

4.4.1. Safety and Sense of Relaxation

Safety and relaxation are two feelings closely related in a public space.

Figure 5 gives a visual indication of data from respondents in the form of boxplots; in blue are the answers after the VR-IV visit, and in red are the answers after watching the reality of a POV in a video. These graphics show how the values of each indicator are spread out on a 5-point Likert scale of (1) to (5). To the instruction “Rate the sense of relaxation promoted by the surrounding area”, the scale for relaxation goes from (1) for very stressful to (5) for very relaxing. To the instruction “Rate the sense of safety promoted by the surrounding area”, the scale for the safety indicator goes from (1) for very unsafe to (5) for very safe. The cross inside each boxplot represents the mean answer for each category of the experiment, the points shows the outlier data that lie either below the lower whisker line or above the upper whisker line.

Figure 5a shows that for POV 1, most of the participants chose a rating between 4 and 5 after the VR immersive visit. After watching the reality of POV 1, they rated it mostly between 3 and 5. POV 2 was deemed less relaxing than the other POVs, which is consistent with an area with a lot of shopping activity and so a lot of foot traffic. The VR-IV setup also promotes an overall greater sense of relaxation, and it is also the case with POV 3. As it is a green recreational area, POV 3 stimulates more relaxation in participants both in VR and reality.

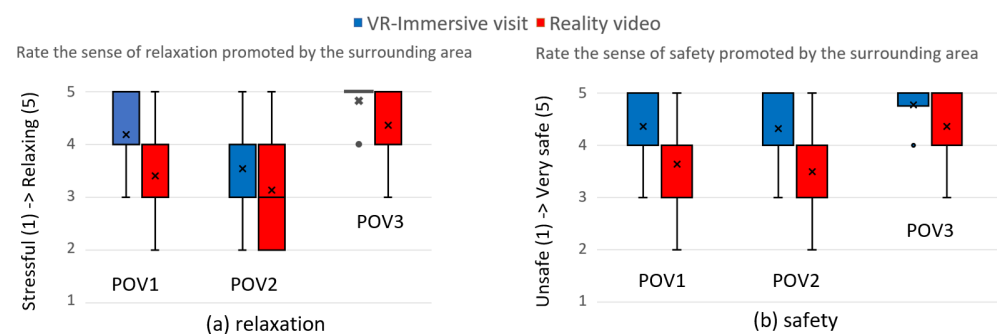


Figure 5. Sense of safety and relaxation from the three points of view. Compared to reality (in blue), raters tend to overestimate these feelings in a VR setup (in red).

The same type of corroboration can be made for the safety indicator, with a systematic bias of +1 for the responses after performing the VR immersive visit, as illustrated by Figure 5b.

4.4.2. Things to Do and Things to See

A diversity of street activities is often perceived positively for the walking experience while street isolation impels negative feelings; it is a fundamental perceived environmental quality. Activities are the reasons why people visit a place and why they continue to return. If there is nothing to do in a place, it will sit empty and unused in the long term leading to an unsafe area.

POV 1 is a central place with not much to do except as a meeting point and a commute place. POV 2 is a shopping street that has more amenities and is the center of urban activities

in the district. It is reflected in the responses plotted in Figure 6a. The specificity of POV 3 falls into four categories: green surrounding environment, perceived safety, children's sports and play opportunities, and aesthetic/comfort of the environment. Basically, it is a more social space, and there are more things to see in POV 3, as can be seen in Figure 6b.

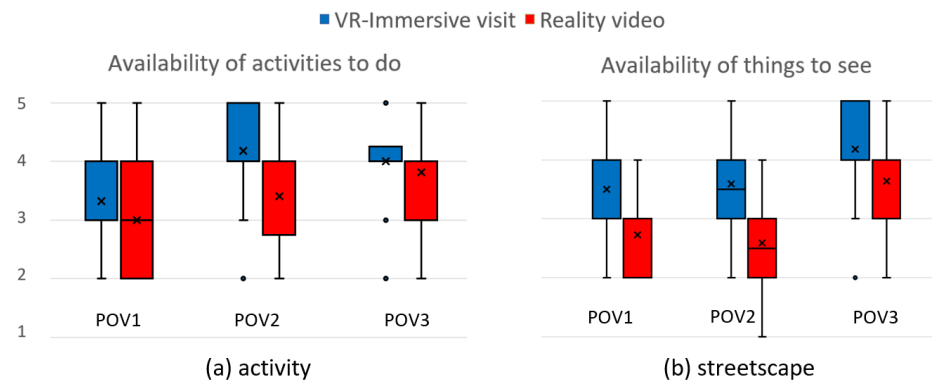


Figure 6. Things to do and things to see in the three scenarios. Comparison between reality (in blue) and the Virtual Reality-Immersive Visit (VR-IV) setup (in red).

Figure 6b shows a systematic bias of +1 in the scores given to the indicator related to the things to see in the area in the VR-IV setup, compared to the real video scenes.

4.4.3. Walkability and Bikeability

Walkability and bikeability are indicators usually computed from geometrical features and traffic flow of the road, but we asked participants to rate these qualities based on the following description of these attributes.

Walkability: Walkability is the extent to which the built environment supports and encourages walking as a means of transport by providing pedestrian comfort and safety.

Bikeability: The extent to which it is convenient and safe to use biking as a means of transport in an area.

The scale of answers proposed ranged from (1) for “Not walkable” or “Not bikeable” to (5) for “Highly walkable” or “Highly bikeable”. We also asked the participants their overall impression of the POVs, and if they would be willing to walk or cycle to move around the areas.

Figure 7 summarizes the result of this study. Figure 7a,b shows the perceived walkability and bikeability for the three POVs. As previously stated, the blue boxplots show the distribution of answers after performing the VR-IV experiments, and in red are the indicators perceived from the real videos. Table 4 reports the mean walkability and mean bikeability of the POVs given by participants, both in VR-IV and after watching the real videos. Walkability is rated sensitively the same in VR-IV and from the real videos, around 4.5/5 except for POV 3 which is slightly higher. The three areas are deemed less bikeable with a mean bikeability rate of around 3.5/5 in all POVs, except for the VR-IV setup of POV 2 where it reached 4.4/5.

Table 4. Mean walkability and bikeability in Virtual Reality-Immersive Visit (VR-IV) and reality, on a scale out of 5.

	POV 1	POV 2	POV 3
Walkability in VR-IV	4.6	4.6	4.9
Walkability in real	4.4	4.4	4.6
Bikeability in VR-IV	3.4	4.4	3.8
Bikeability in real	3.5	3.6	3.5

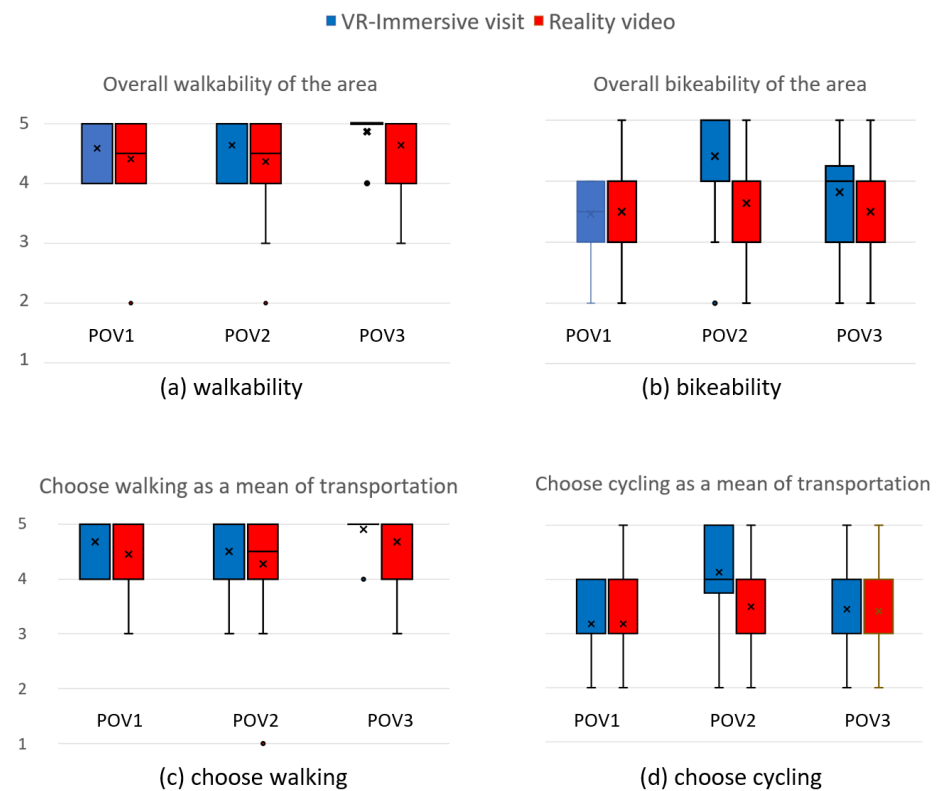


Figure 7. Perceived walkability (a) and bikeability (b) in the three points of view. (c) The willingness to walk. (d) The willingness to use a bicycle. VR scenes are in blue and real video scenes are in red.

Figure 7c,d illustrate the propensity to choose walking or cycling as a means of transportation in the area. A Likert scale was used from (1) for unlikely to (5) for very likely. People would likely choose walking in the three POVs whether the experiment is in VR or in reality. In POV 3 the choice was more marked in the VR-IV setup, but there is almost no bias between VR-IV and real videos. For the cycling choice, a positive bias can be noticed in POV 2, but the answers were the same for the two other POVs whether the experiment was performed in VR or in reality.

5. Discussion

In an experiment involving human participants, we evaluated three POVs on the basis of existing (PLOS [3,4], SUMI [27]) and independent indicators following a video viewing or a VR-IV. As in Chiang et al. [20], we were able to identify strong similarities in the evaluations carried out under the two conditions, which seems to endorse the validity of VR visits for assessing the walkability [28] or cyclability of a public place.

In particular, we were able to observe that on almost all indicators, the two modalities agree on the ranking of POVs. The SUMI indicator is more divided, with POV 1 and 2 equivalent in VR-IV, but POV 1 superior in video. Nevertheless, in both cases, POV 3 comes out on top. This result prompts us to support the use of VR to gather the opinions of likely future users of a site by proposing several design solutions for comparison. The trends are sufficiently accurate for evaluating a real estate project in a pre-occupancy phase. When comparing two distinct urban scenes, the resulting algorithm can be employed in VR-IV to assess the improvement in quality following modifications to an area, particularly in a pre-occupancy scenario. This result is in line with the opinion of the participants about the realism of the visited spaces. The proposed virtual environments were deemed realistic enough to conduct our study. Other studies obtained the same result [29,30].

Even if the realism of the VR-IV setup was found satisfactory by most of the participants, our results show a strong trend towards a more favorable evaluation of VR-IR

compared with video, with variations between POVs and indicators. This trend has already been shown in the literature [22]. In our case, this is likely due to the clarity of the 3D scenes in representing the functionalities of a place but lacking photorealism, especially in terms of urban ambiance, which is present in a real environment. Also, satisfaction stimulated by the virtual environment is heightened by the flawless and pristine appearance of the scenes, as depicted in some samples of scenery illustrated in Figure 8.



Figure 8. The three selected points of view of LaVallée. The first line is the virtual environment, second line is the reality scene.

Moreover, the fact that a POV scene seems more relaxing and safer in virtual reality than in videos of reality can be explained by a lack of performance of graphical engines when it comes to the influx of an urban ambiance, but also by the non-playing characters, which have a neutral or cheerful demeanor in their body language and their facial expression and also their dynamic, while in reality, people are often less open and walk fast to perform their daily routines. Finally, the VR graphical engine enhances the beauty of the scene and makes it more extra-ordinary than reality, which has a more habitual look of routine urban scenes. An interpretation of the difference can be the fact that, as can be seen in Figure 8, the VR views are less standard than reality, and as participants are accustomed to 3D gaming realism they are more curious, which makes it seems like there is more things to see in the VR-IV setup.

Practitioners or urban planners should be mindful, akin to the PLOS-TQM and SUMI, that VR tends to augment the positive perception of an area about mobility infrastructures, shades, streetscape, safety, sense of relaxation, activities, and things to see. However, it is interesting to note that the behavioral indicators relating to walkability in general, or to the participant's intention to walk in particular, are relatively independent of the viewing modality. The results are a little less robust with bikeability, which is not surprising since one has to keep in mind that the experiments were performed from the point of view of a pedestrian. The virtual reality immersive visit is therefore a good predictive tool to predict if an urban setup is fitted for walking or cycling. This result encourages the use of pre-construction VR assessments as a reliable way of ensuring high levels of active mode use in a neighborhood [21] and indicates improvements for the municipalities [31].

The evaluations formulated by the participants also allow us to propose recommendations on the design of VR visualizations. According to our participants, realism is essentially linked with scale, followed by the size of the environment and the model.

6. Conclusions

In this paper, the attempt to implement methods used to characterize public space elements for public auditing of urban places in a future district was investigated. A professional BIM software to build a 3D city model of a large district still under construction was used, focusing on three POVs. For each POV, a VR-immersive visit displayed on an HTC Vive HMD and a real video of one minute each was proposed to participants, followed

by a set of questions. The results support the valid use of VR-IV to assess the walkability and cyclability of a neighborhood based on several architectural proposals, especially because the ability of the place to be walked or cycled is fairly consistent between video and VR-IV. However, an overestimation of place quality is associated with VR-IV. This overestimation could be reduced by improving VR photorealism. Given the paucity of studies in this area, we can only hope that more research will be carried out in the near future. While the results of the study were quite promising, illustrating clear indications of feasibility on some fronts and potential for improvements on others, there are clearly some extensions that could be made for added value.

The first limitation of the work presented here is methodological. We have kept the same participants for the two conditions in order to limit the effect of inter-subjective differences but we were not able, for technical reasons, to counterbalance the order of presentation of the conditions. In a new experiment, we would take care to leave some time between the video and VR-IV in order to limit the possible impact of one visualization on another.

A first perspective to this study would be to enrich the set of questions to allow for a more explanatory characterization of urban streetscapes. Indeed, it has been found in [26] that direct questioning of participants about the emotion brought by various environments was not discriminative of places.

A second perspective could be to use a more diverse sample. Our study only included young participants with no particular mobility difficulties. Interviewing people who were less comfortable walking or cycling, such as the elderly, would no doubt alter the assessments made. Experimenting with a wider range of people would help to ensure more inclusive walkability.

Another interesting perspective for this work would be to include data relating to other sensory modalities in the evaluation. At present, the VR-IVs and the videos have been designed solely from a visual point of view. Numerous studies have highlighted the importance of bodily, auditory [32–34], and olfactory sensations [35,36] in the evaluation of an urban landscape. The auditory modality remains the easiest to integrate initially.

Future research could investigate the extension of the protocol for the comparison of two kinds of immersive environments: panoramic videos of the reality of a built environment in an HMD versus a virtual environment of the same streetscape in an HMD. It would be an opportunity to compare immersive 3D setups and to evaluate the eventual gains and drawbacks of the virtual environment versus the real environment. This could explain whether the differences observed in our study are linked to the lack of realism of virtual reality representations or to its more immersive nature.

Finally, a last perspective of this work is to compare the virtual visit with the reality tours once the district is built by asking questions to real residents. Previous studies compared reality scenes in street view images versus audits by local residents and onsite inspection [20]. We would like to compare the virtual environment in an HMD versus an onsite survey (instead of reality videos). It would be the opportunity to validate more extensively and enhance the use of immersive environments for the public auditing of existing or future built environments.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Model
HMD	Head-Mounted Display
PLOS	Pedestrian Level Of Service
PLOS-TQM	Pedestrian Level Of Service-Trip Quality Model
SUMI	Sustainable Mobility Indicator
SUMI-QPS	Sustainable Mobility Indicator-Quality of Public Space
VR	Virtual Reality
VR-IV	Virtual Reality-Immersive Visit

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Article

Video-Based Analysis of a Smart Lighting Warning System for Pedestrian Safety at Crosswalks

Margherita Pazzini , Leonardo Cameli , Valeria Vignali , Andrea Simone  and Claudio Lantieri 

Department of Civil, Environmental and Material (DICAM) Engineering, University of Bologna, 40136 Bologna, Italy; leonardo.cameli2@unibo.it (L.C.); valeria.vignali@unibo.it (V.V.); andrea.simone@unibo.it (A.S.); claudio.lantieri2@unibo.it (C.L.)

* Correspondence: margherita.pazzini2@unibo.it

Highlights:

What are the main findings?

- The presence of an integrated lighting warning system near crosswalks significantly increases yielding compliance and allows drivers to respect the stopping distance before a pedestrian crossing.
- Five-month continuous monitoring of different warning lighting systems proved that the combination of lighting with in-curb fixed LED strips, orange flashing beacons, and dedicated LED lighting reduces drivers' speed compared to standard street lighting systems.

What are the implications of the main findings?

- Smart lighting systems detecting pedestrians at night, both in urban and suburban areas, are a valid solution to increase safety near pedestrian crossings. These smart systems improve drivers' vision and significantly reduce the risk of accidents between vehicles and pedestrians.
- In-curb fixed LED strips and flashing beacons increase driver attention towards pedestrians, thus making drivers stop vehicles at crosswalks, yielding to pedestrians.



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Abstract: This study analyses five months of continuous monitoring of different lighting warning systems at a pedestrian crosswalk through video surveillance cameras during nighttime. Three different light signalling systems were installed near a pedestrian crossing to improve the visibility and safety of vulnerable road users: in-curb LED strips, orange flashing beacons, and asymmetric enhanced LED lighting. Seven different lighting configurations of the three systems were studied and compared with standard street lighting. The speed of vehicles for each pedestrian–driver interaction was also evaluated. This was then compared to the speed that vehicles should maintain in order to stop in time and allow pedestrians to cross the road safely. In all of the conditions studied, speeds were lower than those maintained in the five-month presence of standard street lighting (42.96 km/h). The results show that in conditions with dedicated flashing LED lighting, in-curb LED strips, and orange flashing beacons, most drivers (72%) drove at a speed that allowed the vehicle to stop safely compared to standard street lighting (10%). In addition, with this lighting configuration, the majority of vehicles (85%) stopped at pedestrian crossings, while in standard street lighting conditions only 26% of the users stopped to give way to pedestrians.

Keywords: pedestrian crosswalk; pedestrian safety; nighttime road safety; driver–pedestrian interaction; LED road lighting; road safety measures; lighting warning system

1. Introduction

In the European Union, pedestrians are involved in one out of five fatal road accidents. In 2019, 72% of fatal crashes occurred in urban areas and 20% involved pedestrians, reaching 4628 deaths [1]. This figure is considerably high when considering other vulnerable road users, such as motorcyclists, amounting to 16%, cyclists, to 9%, and mopeds, to 3%. In

Italy, the number of road victims in 2021 amounted to 471 pedestrians, with a 15% increase compared to 2020 [2]. The number of fatal road accidents increased further in 2022, while remaining below pre-COVID-19 levels [3]. Data show that since 2009 almost 90% of the increase in pedestrian casualties occurred at night [4,5], probably due to high vehicle speeds. High speed is one of the main causes of road accidents involving pedestrians, especially at night in the dark. In addition, late braking, left turns on two-lane roads, pedestrian crossings, lighting poles reducing road visibility, and unprotected pedestrian areas should be mentioned. Pedestrian safety research has long recognised that darkness is a major risk factor in road crashes involving pedestrians [6–8]. Night collisions are usually more severe than day crashes since lighting conditions have an important impact on pedestrian safety. Literature and research in the field provide clear evidence of this. Schneider (2020) [9] showed that the death rate of pedestrians in dark conditions has increased steadily since the late 1970s. Since the early 1980s, the death rate has risen from about 63% to 76% in 2018 [5]. The highest risk of death for pedestrians is between 3 a.m. and 6 a.m. [10]. Night crashes at intersections have an 83% risk of being fatal in the absence of street lighting, while falling to 54% with street lighting [11]. Studies focused on how darkness affects drivers' vision, determining driving speed and the ability to detect an obstacle, thus estimating the correct stopping distance [12,13]. Sullivan and Flannagan (2001) [14] identified high speed at night as a high-risk factor for pedestrians, compounded by excessive alcohol use, both by pedestrians and motorists.

Several studies also showed that the retroreflection of road signs, correct lighting, and bio-movement significantly increase the distance from which a driver can detect a pedestrian [15]. Other studies proved that age or any visual impairment can negatively affect the ability of drivers to distinguish pedestrians at night [16]. The increase in fatal accidents at night is also closely linked to the type of infrastructure. Unsigned pedestrian crossings increase fatalities by 80.8%; 40–45 mph roads are often responsible for 54.6% of serious accidents, five-lane roads for 40.7%, urban streets for 99.7%, and high-flow roads for 81.1% [17]. Extending the curb could be the first infrastructure solution to the problem. Bella and Silvestri (2015) [18] found that a curb extension leads drivers to maintain the most appropriate speed when approaching a pedestrian crossing. More than 80% of drivers perceived curb extensions as effective and showed a greater willingness to yield to pedestrians, since the pedestrian crossing was better visible.

Speed, age, and type of infrastructure may affect drivers' vision, but it is definitely better in light conditions. The first big difference in terms of visibility on the road is between day and night [19,20]. Alogaili and Mannering (2022) [21] showed that nighttime crashes have more severe consequences for pedestrians over time. Technologies that seek to reproduce conditions of daytime visibility even at night (improved lighting, infrared pedestrian detection, etc.) may bring significant safety benefits, even if the increase in vehicle speed plays an important role in causing accidents. High speed reduces the overall ability of a driver to see and perceive [22] because they tend to focus on the centre of the road rather than the sides, from which pedestrians usually come [23]. At night, drivers do not moderate their speed to compensate for reduced visibility, while pedestrians overestimate the ability of drivers to see them [24]. In addition, the extensive use of mobile phones and other distracting devices can cause further safety problems for both drivers and pedestrians [25,26]. Proper street lighting lowers the risk of fatal crashes for pedestrians [27,28], while mitigating road crashes under different driving conditions [29]. Focusing on pedestrian crossings, several countermeasures could be taken to increase visibility so that drivers can stop in time and yield to pedestrians.

Hakkert et al. (2002) [30] added in-curb flashing lights near a pedestrian crossing. The average speed of vehicles approaching the area decreased by 2 to 5 km/h, while the number of drivers giving priority to pedestrians increased accordingly. This resulted in a significant reduction in vehicle–pedestrian crashes, as well as in the number of pedestrians crossing outside the marked pedestrian zone. Hussain et al. (2023) [31] showed that both LED light and advanced variable message signal (VMS) were useful in increasing visibility by up to

98.4% and reducing vehicle–pedestrian conflicts. Both devices were effective in motivating drivers to reduce vehicle speed in advance. Vignali et al. (2019) [32] studied the inclusion of flashing beacons near unmarked pedestrian crossings. They showed that flashing beacons increased fixations of “Yield here to pedestrian” vertical signs and improved the distance at which drivers could detect the presence of a pedestrian crossing the road. Hoyer and Laureshyn (2019) [33] added the “SeeMe” light with automatic pedestrian detection to pedestrian crossing signs in residential areas. This lighting system on two-lane roads improved driver performance in areas with moderate motor vehicle volumes and speed limits of up to 50 km per hour. Shurbutt et al. (2009) [34] installed a rectangular side-mounted stutter-flash LED beacon system near a pedestrian crossing to increase the safe braking performance of vehicles toward pedestrians. Results showed a considerable increase in safety distances for a two-beacon system. Patella et al. (2020) [35] added white LED strips to evaluate drivers’ speed at night. Results showed that the average travel speed was reduced by about 7.8 km/h. Studies reported that rectangular rapid flash beacons (RRFBs) installed at crosswalks improved drivers’ braking performance and yielding rates at midblock crosswalks [36,37]. Goswamy et al. (2023) [38] demonstrated how rectangular rapid flashing beacons (RRFBs) reduce the severity of night crashes. Fitzpatrick and Park (2021) [28] showed that there were no substantial differences between daytime and nighttime driver-yielding performance with pedestrian hybrid beacons (PHBs), while rectangular rapid flashing beacons (RRFBs) were more effective at night.

Different light signalling systems have been extensively studied in the literature. However, few studies have analysed which configuration is the most effective for increasing the safety of weak road users at night near a pedestrian crossing. This study aims to assess the impact of integrated light warning systems on driver behaviour to identify the most effective configuration and increase the safety of vulnerable road users. The systems included a dedicated lighting vertical sign on both sides, side-mounted flashing beacons and in-curb LED strips for both warning and lighting pedestrian crossings. Seven different lighting configurations were studied and compared to current standard street lighting. Cameras installed near the pedestrian crossing monitored different lighting configurations continuously for five months. Compared to previous studies [39], continuous analysis of the lighting systems allowed users to be monitored without being aware of the experiment. The results obtained are evidence of the reliability of the integrated light warning system.

2. Materials and Methods

2.1. Pedestrian Crossing Lighting System

The pedestrian crossing chosen for the experimental system is located in Via Andrea Costa, in the Porto-Saragozza district of Bologna, Italy. This two-way road conveys the vehicles in the direction of the city avenues, and allows the flow both towards Bologna city centre and in the opposite direction, towards the nearest suburbs. In its current dual-strip configuration, the pedestrian crossing serves both pedestrians coming from and those heading to bus stops through the pedestrian safety island, as well as users swapping between the two existing pavements (Figure 1).

For the analysis of pedestrian crossings, a lighting system was introduced (Figure 2) consisting of the following:

- Movement sensor for the detection of pedestrians near the curb-side area.
- In-curb LED strips: Flexible in-curb LED strips of the Flexi-led line type, and adaptable to the desired shape, installed at both ends of the curbs near the pedestrian crossing. Two alternative activations for the LED system were studied: LED strips always on with constant light emission as the default state (fixed); LED strips lit with flashing light emission as the default state (flashing).
- Orange beacons: Made with a backlit LED panel, they were placed on both sides of the pedestrian crossing. Very-high-refraction film was applied above the panel, showing the symbol of the pedestrian crossing [40] and two pairs of highly bright amber flashing LEDs were specularly installed on it.

- Asymmetric enhanced LED lightning: A metal pole was installed on both sides of the pedestrian crossing, six metres high from the paved road. A die-cast aluminium lighting body was mounted on it with a white LED system and asymmetric optics focused on the zebra crossing.



Figure 1. Urban context of the experimental pedestrian crosswalk (source: Google Maps).

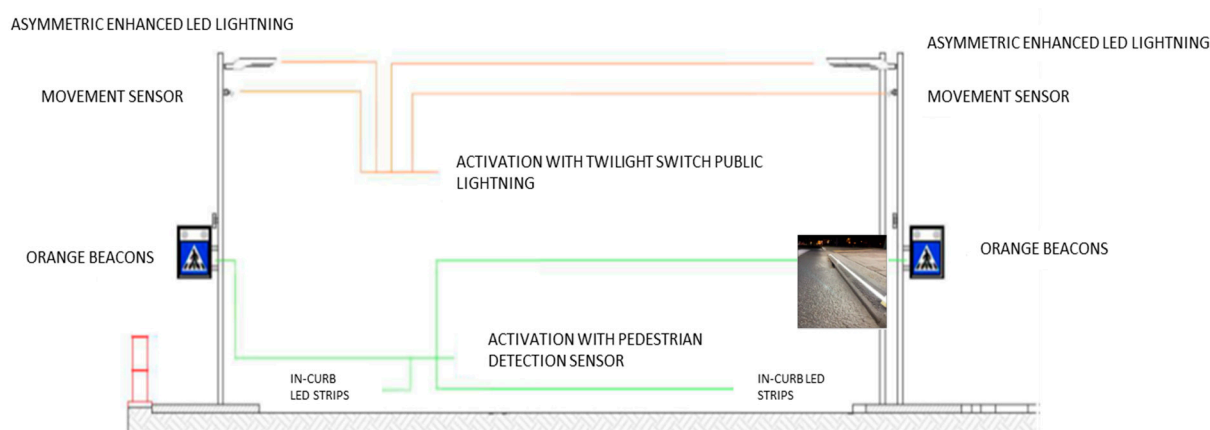


Figure 2. Section of the pedestrian crossing analysed with different lighting warning systems.

An autonomous mechanism was used as a monitoring system. The components used to operate the system were placed in a box installed on a pole of the lighting system connected to the new crossing technology. The video surveillance system consisted of two metal-optic cameras with a viewing angle of about 70 degrees, which allowed for recording colour video even in low-light conditions (Figure 3).

Through a network-switching device, surveillance cameras of the pedestrian crossing were connected to a DVR recorder with a memory capacity of about 140 GB, corresponding to seven days of video recording. The cameras and video recorder were active all night, according to the times imposed by public lighting. Both data and power were supplied and transmitted via a LAN cable.

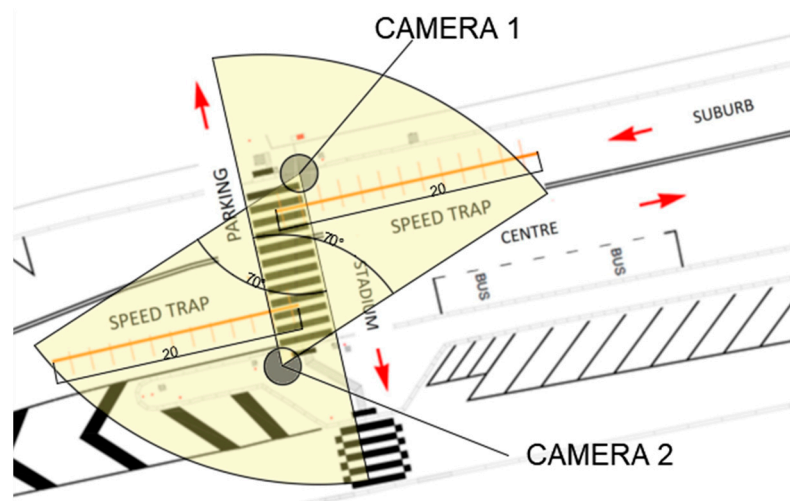


Figure 3. Crossing camera position and operating radius. The red arrows indicate the two road directions (suburb and centre), the parking area and the stadium.

The video surveillance system was placed on both sides of the pedestrian crossing to analyse the behaviour of all drivers in the seven different experimental lighting configurations of the crossing. Figure 4 shows the output of the monitoring system recorded during the night (from 7 p.m. to 6 a.m., considering seasonal fluctuations of 2 h).



Figure 4. Extracted frame showing vehicle–pedestrian interaction.

2.2. The Integrated Lighting Warning System and the Monitoring System

Figure 5 shows four phases of the study to evaluate different lighting warning systems. Starting from the standard street lighting configuration, phase 1 involved the evaluation of 7 different lighting configurations and the subdivision of smart lighting accordingly. In phase 2, the different systems were monitored continuously for five months. Phase 3 involved the analysis of video data collected to study vehicle speeds and braking distances. Finally, in phase 4 the 7 different lighting configurations were statistically compared to assess which was best suited to ensure pedestrian safety at night.

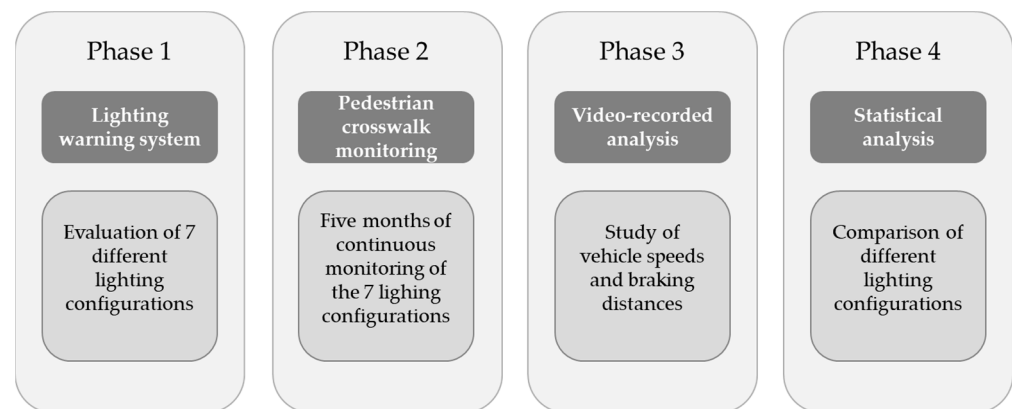


Figure 5. Steps of the study to evaluate different lighting warning systems.

Table 1 shows the seven different light configurations considered during the monitoring phase to assess the behaviour of drivers near the crossing.

Table 1. On–off status of the pedestrian crossing lighting systems in the seven conditions.

Configuration	Standard Road Lightning	Orange Beacons	Enhanced LED Lightning	In-Curb LED Strips—Fixed	In-Curb LED Strips—Flashing
0	On	Off	Off	Off	Off
1	On	On	Off	Off	Off
2	On	On	On	Off	Off
3	On	On	Off	On	Off
4	On	On	Off	Off	On
5	On	On	On	On	Off
6	On	On	On	Off	On

Equipped with a single standard streetlamp without any experimental lighting element, configuration 0 was considered the control configuration. The lighting was always active regardless of the presence of pedestrians and was the basic configuration for all subsequent experimental configurations. In configuration 1, orange beacons were added to the standard street lighting. They provided dedicated lighting with LED projectors operating only via pedestrian sensors. In configuration 2, enhanced LED lighting was added to the orange beacon system, providing an orange flashing illumination of the vertical pedestrian crossing signal. Configurations 3 and 4 reflected configuration 1 with the addition of in-curb LED strips. In configuration 3 the LED strips were fixed with constant emission (fixed). In configuration 4, the LED strips flashed (flashing). Configurations 5 and 6 resembled configuration 2 with the addition of fixed and flashing LED strips.

The first step was to define which type of pedestrian–vehicle interaction to analyse. Based on the monitoring carried out, pedestrians can be involved in different scenarios defined by the behaviour of the vehicle approaching the pedestrian crossing:

- Slowdown: once the pedestrian is detected, the vehicle slows down to allow crossing without stopping completely.
- Stop: the vehicle stopped completely to allow crossing.
- No priority: the vehicle did not stop or slow down, so the pedestrian was forced not to cross the road.

Vehicle slowing down and stopping scenarios were taken into consideration in order to obtain the following indicators:

- Speed of vehicles approaching the pedestrian crossing.
- Number of crossings, diversified by categories of users (pedestrians, cyclists).
- Percentage of correct interactions, in relation to crossing settings.

Pedestrian–vehicle interactions were monitored for five months, without considering the separate direction of vehicle flows. In order to correctly position some of the infrastructure for speed analysis, a part of the lane length was identified for each direction of travel. The time taken by vehicles to travel that section of road was measured to obtain the instantaneous speed. Considering the field of view of the camera and the results of the survey, two points on the road platform, at a distance of 20 m from the zebra crossing line, were identified for measurements. Once the reference road section was identified, the video metadata were analysed. The sampling rate used was 15.00 frames per second, equivalent to a time interval of 0.0667 s between each frame (Figure 6).

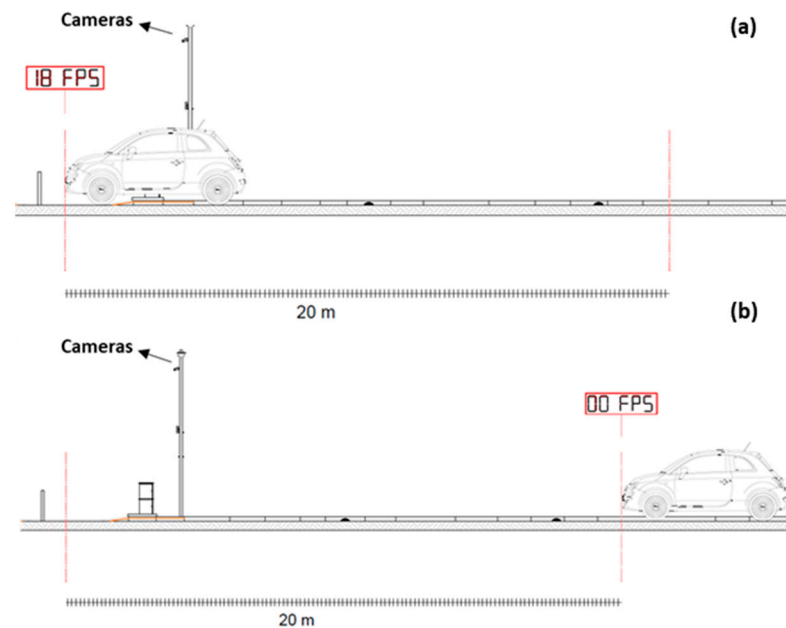


Figure 6. Detection technique for speed estimation: (a) entrance zone of the reference section; (b) exit zone of the reference section with the number of frames per second detected.

Once the time interval for each frame was identified, measurements of all pedestrian crossings with pedestrian–vehicle interaction were taken for each vehicle. The number of frames needed to cover the reference section of 20 m in the direction of travel of the vehicle was recorded. The instant speed formula was then applied, provided by the ratio between the length of the reference stroke (equal to 20 m) and the number of detected frames (fps), with the time interval between each frame equal to 0.0667 s.

The curve of the speed of approach to the pedestrian crossing was calculated using the formula of the Italian Ministerial Decree DM 2001 (MIT, 2001) [41] (1), which depends on the space covered in time τ (D_1), the braking distance (D_2), the vehicle speed at the start of braking and the final speed (V_0), final speed of the vehicle, where $V_1 = 0$ in case of stopping, the resistance forces (aerodynamics (R_a), coefficient of surface adhesion (f_i), track slope (i), gravitational acceleration (g), and vehicle mass (m)), and the total reaction time (τ) (perception, reflection, reaction, and actuation).

$$D_A = D_1 + D_2 = \frac{V_0}{3.6} \times \tau - \frac{1}{3.6^2} \int_{V_0}^{V_1} \frac{V}{g \times \left[f_i(V) \pm \frac{i}{100} \right] + \frac{R_a(V)}{m} + r_0(V)} dV \quad [m] \quad (1)$$

Five months of video was analysed by five independent researchers who examined the experimental crossing for all seven configurations (considering the standard configuration, 0). Every light configuration was present for 20 days. The raters were not blind to the conditions they were examining. They watched the videos and detected the speed of the vehicles approaching the reference point of 20 m. They did not participate in the choice

of lighting configurations and in the final comparison of the data obtained. When the driver–pedestrian interaction met the conditions to be considered valid (i.e., the correct approach to the crossing perpendicular to the sidewalk), the type of interaction and speed were studied with the method described above.

3. Results

The analysis of the seven configurations defined the number of vehicle–driver interactions and their approach speeds. The speed of vehicles recorded at the experimental pedestrian crossing, according to the different configurations, is analysed in Table 2.

Table 2. Descriptive statistics of the speed data for the seven configurations.

Configuration	N of Interactions	Minimum Speed (km/h)	Maximum Speed (km/h)	Average Speed (km/h)		Standard Deviation	Variance
	Statistics	Statistics	Statistics	Statistics	SD	Statistics	Statistics
0	42	17.41	59.97	42.96	1.53	9.94	98.86
1	27	14.20	56.81	28.24	2.07	10.74	115.33
2	50	14.39	59.97	35.69	1.61	11.39	129.80
3	59	8.24	59.97	34.08	1.78	13.70	187.70
4	136	7.29	56.81	31.41	1.19	13.93	194.02
5	117	6.50	59.00	20.37	1.04	11.22	125.99
6	90	12.71	60.00	40.32	1.27	12.08	146.03

For each configuration, the number of interactions changed accordingly. This depended on the period of the year in which the interactions were recorded and the number of crossings that insisted on the configuration considered in the period analysed. Table 2 shows that the average speeds of configurations 1, with orange beacons (28.24 km/h), and 5, with flashing led strips (20.37 km/h), allow for a safe pedestrian crossing. A decrease in speed is evident for all configurations compared to condition 0 (standard road lighting), which has no innovative crossing elements, except for configuration 6, where the average speed is 40.32 km/h. Changes in speed data were reported for each configuration. Standard deviations show low variability in speed data between different configurations, without abnormal values. This confirms that all users, in the absence of the new lighting systems described above, were proceeding at speeds very close to the average of 42 km/h.

The speed recorded on the road under analysis was always below the 50 km/h limit. The aim of this study was to verify whether the actual speed maintained by drivers was adequate to allow safe passage for vulnerable users. The speed calculated for each pedestrian–vehicle interaction was compared to the speed vehicles should maintain to yield to pedestrians. A safe stop manoeuvre would start 20 m before the central line of the pedestrian crossing at a speed of 7 m/s (25 km/h). This condition would give a driver time to perceive the pedestrian crossing, assess the emergency manoeuvre to be performed, and safely stop within the available space. Percentages of events involving vehicles with speeds between 25 km/h and over 45 km/h analysed for each configuration are given below (Figure 7).

As shown in Figure 7, under all conditions, a higher percentage of vehicles maintain a speed of 25 km/h or even lower than the standard condition without innovative equipment. The results also show that conditions 1 (orange beacons) and 5 (enhanced LED lighting, orange beacons, and in-curb fixed LED) recorded more vehicles with speeds within the acceptable range to detect a pedestrian and to brake accordingly. From the calculation given by Formula (1), three speed classes were defined within which a driver is able to perform complete manoeuvres, partial manoeuvres, or no manoeuvres in order to stop the vehicle and let a pedestrian cross. With a speed of up to 25 km/h, a driver can perceive a user at a pedestrian crossing, assess any emergency manoeuvres to be made, and stop the vehicle safely within the available space. For speeds between 25 km/h and 35 km/h, a driver can only perceive the pedestrian crossing, assess the emergency manoeuvre to be carried out,

and activate the emergency braking without completing the transitional braking phase. Finally, for speeds above 35 km/h, the driver of a vehicle is not able to perceive a user crossing the road and implement the emergency manoeuvre, since the required journey time is less than the psychophysical reaction time set at 2.10 s [18]. Figure 7 shows that, for the 25–35 km/h range, configuration 1 has the highest event rate of 34% compared to other light configurations. Although configuration 2 has a percentage of events equal to condition 6, it shows peak values in the range 35–45 km/h. In the next stage, a series of statistical tests were carried out to validate the analysed samples. As shown in Table 2, the highest speeds are in configurations 0 and 6, where the highest percentage of events occur in the range > 45 km/h (Figure 7).

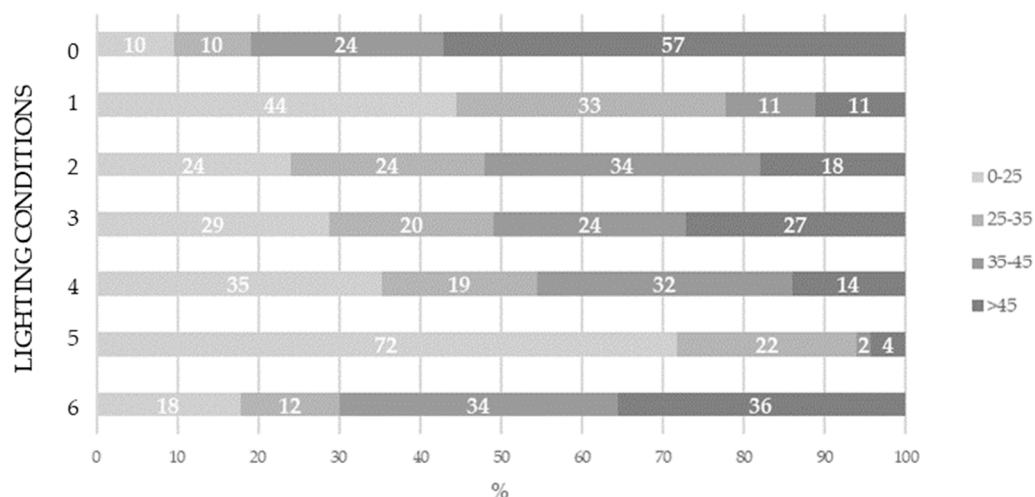


Figure 7. Percentage of events in the different speed ranges for each condition.

A one-way ANOVA was run with the seven configurations as the independent variable. This test statistically confirmed that there were significant differences among the seven configurations' average speeds. Table 3 compares all of the different configurations to find statistically significant differences that allow for the effectiveness of new experimental lighting systems in relation to speed to be validated. It has been suggested that adding a feature to the system will reduce speed. Table 3 summarises the comparison between the seven conditions, reporting the ANOVA result.

Table 3. Single-way ANOVA among the different configurations.

ANOVA	Sum of Squares	df	Mean Square	F	Sig.
Between groups	28,467.52	6	4744.58	31.22	0.000
Within groups	78,104.55	514	151.95		
Total	106,572.07	520			

The results of the ANOVA showed a significant difference between the speed of the seven configurations ($F(6, 514) = 31.22, p < 0.001$). To further investigate the correlation among the different configurations in terms of speed, a Scheffe post hoc analysis (Table 4) was carried out. Configuration 0 showed significant differences with almost all of the others. From configurations 0 to 5, adding new light devices, there were significant differences. By increasing the light signalling devices, the average speed decreased significantly compared to other configurations. Configuration 6, with flashing in-curb LED strips, showed an unusual trend as it did not have substantial changes compared to configuration 0. In configuration 5 ($n = 117, M = 20.37, SD = 1.04$), there is a significant difference in average speed compared to all of the configurations (not for configuration 1).

Table 4. Scheffe post hoc analysis.

(I) Condition		Mean Difference (I–J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
0	1	14.72 *	3.04	0.000	5.44	24.01
	2	7.26	2.58	0.106	−0.61	15.15
	3	8.88 *	2.49	0.008	1.28	16.48
	4	11.54 *	2.18	0.000	4.90	18.19
	5	22.58 *	2.22	0.000	15.82	29.36
	6	2.63	2.30	1.000	−4.39	9.67
1	0	−14.72 *	3.04	0.000	−24.01	−5.44
	2	−7.45	2.94	0.244	−16.44	1.53
	3	−5.84	2.86	0.881	−14.58	2.90
	4	−3.17	2.59	1.000	−11.11	4.75
	5	7.86	2.63	0.062	−0.17	15.90
	6	−12.08 *	2.70	0.000	−20.34	−3.83
2	0	−7.26	2.58	0.106	−15.15	0.61
	1	7.45	2.94	0.244	−1.53	16.44
	3	1.61	2.37	1.000	−5.62	8.85
	4	4.28	2.04	0.764	−1.94	10.50
	5	15.32 *	2.08	0.000	8.96	21.68
	6	−4.63	2.17	0.706	−11.27	2.01
3	0	−8.88 *	2.48	0.008	−16.48	−1.28
	1	5.84	2.86	0.881	−2.90	14.59
	2	−1.61	2.37	1.000	−8.85	5.62
	4	2.66	1.92	1.000	−3.20	8.53
	5	13.71 *	1.97	0.000	7.69	19.72
	6	−6.25	2.06	0.055	−12.55	0.059
4	0	−11.55 *	2.18	0.000	−18.19	−4.90
	1	3.18	2.59	1.000	−4.75	11.11
	2	−4.28	2.04	0.764	−10.50	1.95
	3	−2.66	1.92	1.000	−8.53	3.20
	5	11.04 *	1.55	0.000	6.29	15.79
	6	−8.91 *	1.67	0.000	−14.02	−3.79
5	0	−22.59 *	2.22	0.000	−29.36	−15.82
	1	−7.87	2.63	0.062	−15.90	0.17
	2	−15.32 *	2.08	0.000	−21.68	−8.96
	3	−13.71 *	1.97	0.000	−19.72	−7.70
	4	−11.04 *	1.55	0.000	−15.79	−6.29
	6	−19.95 *	1.72	0.000	−25.23	−14.68
6	0	−2.64	2.30	1.000	−9.67	4.39
	1	12.09 *	2.70	0.000	3.83	20.34
	2	4.63	2.17	0.706	−2.01	11.27
	3	6.25	2.06	0.055	−0.058	12.55
	4	8.91 *	1.68	0.000	3.79	14.02
	5	19.95 *	1.723	0.000	14.67	25.23

* The mean difference is significant for a p -value less than 0.05.

Significant changes were found among the configurations, especially between configuration 0 and the others, with a significant difference when compared to configuration 5 ($p < 0.001$), according to the ANOVA with the Scheffé post hoc analysis. Configuration 6 is distinct from a number of the other configurations in an important manner. The addition of the dedicated enhanced LED lighting and the fixed-in-curb LED device shows that the difference between configurations 0 and 5 was significant in terms of speed. This suggests that the use of all of the smart instrumentation has real effectiveness in decreasing speed.

The addition of dedicated enhanced LED lighting and a fixed in-curb LED device showed significant speed differences between conditions 0 and 5. This means that the use

of smart devices had a real effectiveness in reducing speed. The use of orange beacons (configuration 1) or enhanced LED lighting, orange beacons, and a fixed in-curb LED device (configuration 5) proved to be the best for reducing speed. In any case, they did not show a significant difference in the average values. For this reason, results were interfaced with two other factors: the number of stops made or not made by drivers at the pedestrian crossing. Figure 8 shows the different types of interaction as “Stop” and “No-Stop” manoeuvres of drivers.

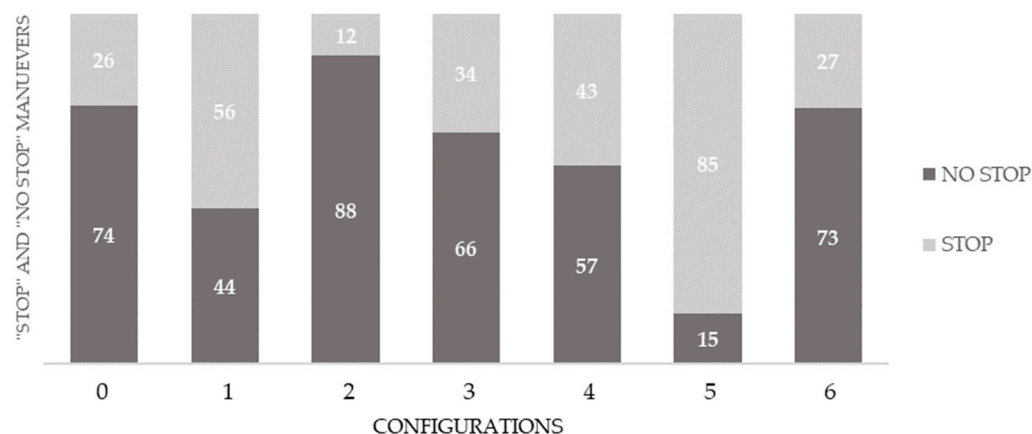


Figure 8. Percentage of vehicles’ manoeuvres approaching the pedestrian crossing.

The analysis was carried out by observing the videos when drivers yielded to pedestrians crossing the road. The number of stops did not increase with the addition of innovative signalling elements near the pedestrian crossing. However, for condition 5, 85% of vehicle–pedestrian interactions allowed the pedestrian to cross, while in condition 1 only 56% were able to do so. The statistically significant speed difference previously recorded by the one-way ANOVA was due to the greater number of “stops” recorded in the interactions analysed.

4. Discussion

This study presents the analysis of data collected over five months from monitoring a pedestrian crossing. The “natural” interaction between pedestrians and vehicles was evaluated to assess which lighting configuration was the best for vulnerable road users’ safety. Since neither pedestrians nor drivers were aware of participating in this study, their behaviour was not influenced by the characteristics of demand. Seven lighting configurations were analysed, including condition 0 with only standard street lighting. Configurations differed only for the activation of a different device or the specific feature of a device, such as the continuity of light emission for in-curb LED lighting.

Based on the established parameters, analysis of the collected data shows that, during the 5-month observation period, the total number of recorded crossings amounted to 519. The distribution of these crossings was not homogeneous, because both pedestrian flow and hours of darkness affected the number of observations. The average speed and standard deviation were calculated for each configuration. Speeds were always lower than that of configuration 0 (only standard road lighting and all innovative devices switched off) and the speed limit imposed on the road. The slowest speeds were reached in configuration 1 with orange beacons ($n = 27$, $V_{\text{mean}} = 28.24$, $SD = 2.07$) and configuration 5, with a fixed in-curb LED system ($n = 117$, $V_{\text{mean}} = 20.37$, $SD = 1.04$). An average speed of 40.32 km/h was recorded for configuration 6 only, similar to configuration 0. With all devices on and an in-curb flashing LED system, drivers felt safe and able to detect any passing user. For this reason, they did not slow down and maintained speeds similar to those of configuration 0. This result can also be seen in Figure 8, which shows that the percentage of vehicles stopping at the pedestrian crossing is 27%, as well as for configurations 0 and 6. The presence of lighting warning systems reduced vehicles’ speed in configurations 1, 2, 3, 4,

and 5, analysed compared to the standard road configuration, 0 [42,43]. Despite the different number of samples analysed for each configuration, the data show a comparable variance.

After this, it was assessed whether a driver was able to stop the vehicle at a distance of 20 m from the pedestrian crossing in relation to the driving speed maintained in the presence of a pedestrian crossing the road. Considering the braking distance, at a speed below 25 km/h a driver should be able to stop the vehicle to let a pedestrian cross the road. The results show the trend at average speeds. For each condition, there is a percentage of vehicles travelling at speeds lower than 25 km/h. This speed was higher in configurations 0 and 6.

Analysing the different lighting combinations, the use of orange beacons (configuration 1) or enhanced LED lighting, orange beacons, and fixed in-curb LED strips (configuration 5) are those able to guarantee a greater degree of road safety in terms of the speed of approach. Again, configurations 5 (72%) and 1 (44%) show a greater number of vehicles able to stop in time at the pedestrian crossing.

A one-way ANOVA test was used to validate the effectiveness of the best lighting configurations in reducing vehicle speed. The ANOVA test with a Scheffe post hoc analysis showed a significant difference among the seven configurations. This confirmed that the road lightning system influenced the speed of the drivers. This study confirmed that configuration 5 showed a significant difference with all other configurations except for configuration 1. The comparisons between these two configurations were investigated by analysing vehicle–pedestrian interactions. The percentages of “stop” and “non-stop” vehicles were evaluated. This analysis concluded that configuration 5 with 85% stops allowed more crossings than configuration 1 with only 56%.

The results obtained are in line with those of Carrese et al. [44], which show that an integrated LED lighting system generates a significant speed-reducing effect on vehicles, improving pedestrian safety at pedestrian crossings. Pena-Garcia et al. [45] also found that well-lit streets (i.e., where lighting is uniform) with improved levels of illumination make people feel safer. By inserting fixed in-curb LED strips, which are activated only when a pedestrian crosses the road, the crossing is even more visible and therefore safer.

5. Conclusions

In all cities, more attention is being paid to pedestrian safety and strengthening measures have been taken to achieve Vision Zero targets for road traffic fatalities or serious injuries [44]. In Italy, the number of pedestrians killed in road accidents was 17% (534 victims) of total road accidents in 2019 [45]. The enhanced intensity of smart street lighting increases the visibility of pedestrians at night, especially near pedestrian crossings. This type of intervention was associated with a significant reduction in night pedestrian accidents. This research analysed the impact on pedestrians of an experimental smart lighting warning system placed near a pedestrian crossing to increase road safety. The pedestrian crossing was equipped with different signalling systems controlled by pedestrian detection sensors or flashing devices: in-curb LED strips, orange beacons, and enhanced LED lighting. Two video surveillance cameras were installed on the two poles of the enhanced LED lighting system, placed at the two ends of the pedestrian crossing. With a viewing angle of about 70 degrees and a high-resolution 1920 × 1080 colour format, these cameras detected the pedestrian crossing and the part of the road platform that approaches it even in poor-visibility conditions. As streetlamps are operated by a twilight switch adjusting the voltage only at night, a 12/24 volt battery with a charger was installed in the orange beacon system with pedestrian presence detectors even during the daytime. Vehicles approaching the pedestrian crossing could see it thanks to the light beam projected by the enhanced LED lighting system and the light of the backlit panels with the symbol of the crossing. In addition to these devices, vehicles were also able to detect pedestrians entering the crossing by flashing LED orange beacons and in-curb LED strips. This articulated system appropriately warned drivers approaching a pedestrian crossing of pedestrians already engaged or about to cross it, so that they could safely adjust their speed by means of appropriate devices. For

the evaluation of the best-integrated lighting system, each device was evaluated in relation to the approaching driver's behaviour. The smart lighting warning system, in combination with both orange flashing beacons and in-curb flashing LED lighting, resulted in being particularly effective in reducing the speed at night [28,38]. This research confirmed the validity of previous studies using mobile eye tracking [39,46–48]. Again, the use of enhanced LED lights, orange beacons, and in-curb LED strips (configuration 5) showed a higher percentage of permitted crossings (85%) [49]. A video (S1) of the present configuration (configuration 5) of the pedestrian crossing lighting warning system was added to the Supplementary Materials. This research also showed how lighting conditions affect vehicle performance regardless of driving or environmental conditions. The calculation of the stopping distance did not consider other factors that may affect a driver, such as pedestrian clothing, fatigue, and age of the driver. Future analyses should predict how these elements affect the stopping distance. Finally, to improve road safety, there is a need for in-depth studies on aspects closely related to pedestrian crossings, such as location, traffic volume, vehicle speed, number of pedestrians, width of the pavement, and distracting elements on the side of the road.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/smartcities7050114/s1>, Video S1: The pedestrian crossing lighting warning system.

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