GEO-VISUALIZATION OF CHILD-FRIENDLY URBAN MOBILITY: DESIGN AND IMPLEMENTATION OF A VISUALIZATION TOOL

MASTER'S THESIS

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PARIS-LODRON UNIVERSITY SALZBURG (PLUS)

Faculty of Digital and Analytical Sciences

Department of Geoinformatics

and

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With the support of Erasmus+ programme of the European Union. This Master's Thesis has been developed in the framework of the Erasmus Mundus Joint Master Degree (EMJMD) "Copernicus Master in Digital Earth", jointly coordinated by Paris-Lodron University Salzburg, Department of Geoinformatics, Austria together with University of South Brittany, Computer Science Department, France and Palacký University Olomouc, Department of Geoinformatics, Czech Republic.

The primary objective of this research is to design and implement an interactive geo-visualisation tool for communicating child-friendly urban mobility (I). To achieve this, the open-source NetAScore framework for the assessment of walkability and bikeability is adapted to develop **NetAScore4Teens,** by integrating child-friendly mobility indicators identified through a literature review and participatory workshops with young adolescents (II). The resulting input and output data are used to build an interactive web-based dashboard for exploring street-level walkability and bikeability. The proposed workflow is demonstrated in Salzburg, Austria, and its transferability is checked in Olomouc, Czechia. Finally, the developed geo-visualisation tool is evaluated through user testing to assess its functionality, usability, and user experience.

KEYWORDS

Active Mobility; Bikeability; Child-Friendly Cities; Children's Independent Mobility; Geo-Communication; Geo-Visualization; NetAScore; Participatory Methods; Walkability.

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This thesis has been composed by *Amna Azeem* for the Erasmus Mundus Joint Master's Degree Program in Copernicus Master's in Digital Earth for the academic years 2024/2025 and 2025/2026 at the Department of Geoinformatics, Faculty of Digital and Analytical Sciences, Paris Lodron University Salzburg, and Department of Geoinformatics, Faculty of Science, Palacký University Olomouc.

Hereby, I declare that this piece of work is entirely my own, the references cited have been acknowledged, and the thesis has not been previously submitted to the fulfilment of the higher degree. I take full responsibility for the integrity, accuracy, and entire content of this master's thesis.



29.07.2026, Salzburg

Signature of a student

*Here is to the **parents**,*
For being my greatest support system,
*To the **supervisors** & **teachers,***
For planting the seed of curiosity & motivation
*To the **mentors** & **friends**,*
For guidance & support
*To the **children**, **teens**, and **communities**,*
For their stories & voices
The heart of this work.

First and foremost, I would like to remember my late childhood friend and neighbour. Your memory has remained with me throughout this journey, and I wish you were here to celebrate this moment with me. This is for you.

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ASSIGNMENT OF DIPLOMA THESIS

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Theses guidelines

The aim of this master's thesis is to design and implement an interactive geovisualization tool for presenting child-friendly urban mobility. The thesis builds on a previously developed model for assessing urban mobility from a child's perspective. Emphasis is placed on the transferability of the methodology and the potential use of various types of geospatial data, including Copernicus data. The objective will conduct a review of existing concepts related to child-friendly mobility and focus on the visualization of the model's results. It is foucused on a concept for an interactive geovisualization tool that enables clear and meaningful interpretation of both input and output data of the model. This concept will then be implemented using a suitable software environment (e.g. a web-based mapping application). The tool's functionality will be user-tested in two case studies. The main outcomes of the thesis will include a newly developed interactive geovisualization tool for the child-friendly mobility model, comprehensive documentation including the visualization methodology, and a critical evaluation of the tool's benefits and limitations.

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Recommended resources:

1. Al-Kodmany, K. (2001). Visualization tools and methods for participatory planning and design. Journal of Urban Technology, 8(2), 1-37.
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LIST OF ABBREVIATIONS

Abbreviation	Meaning
API	Application Programming Interface
CFCs	Child Friendly Cities
CGCI	Child Friendly Cities Initiative
CIM	Children's Independent Mobility
GDCI	Global Designing Cities Initiative
GeoJSON	Geographic JavaScript Object Notation
GIS	Geographic Information System
i-mobyl	Inclusive Mobility Interventions for Young Adolescents and Livable Urban Spaces
MIT	Motorized Individual Transport
NACTO	National Association of City Transportation Officials
OSM	Open Street Map
PGIS	Participatory Geographic Information System
PMTiles	Protomaps Tiles format
PGIS	Participatory Geographic Information System
UN-HABITAT	United Nations Human Settlements Programme
POI	Point of Interest
PPGIS	Public Participation Geographic Information System
SDGs	Sustainable Development Goals
SQL	Structured Query Language
STL	Street Tree Layer
UI	User Interface
UN	United Nations
UNICEF	United Nations International Children's Emergency Fund
UX	User Experience
YA	Young Adolescents

INTRODUCTION

Urban mobility plays a central role in shaping the spatial structure of cities and influencing equitable access to opportunities, public services, and education. It comprises various modes of transport such as walking, cycling, public transport, and private cars, used by diverse groups of people, such as women, elderly people, young adults, persons with disabilities, and children. Children and young adolescents are important users of everyday urban life; however, their needs and aspirations are often overlooked in mobility planning. The result is unsafe streets, inadequate infrastructure, and a lack of play spaces. Children and young adolescents have diverse needs and perceptions compared to the normative adult population. First, Children and young adolescents account for a high proportion of public transit journeys (Jones et al., 2012), particularly for school travel (Hensher, 2017); second, they have particular travel needs and aspirations (e.g., to achieve greater independence) (Kullman, 2010). Children and young adolescents take trips each day across multiple modes of transportation yet face mobility constraints. They are particularly vulnerable to road safety issues. **(**UNICEF, 2025). Relatively few urban transportation policies or plans (e.g., road or public transport) take any of this into account when planning infrastructure, routes, levels of service, or include children and young adolescents in planning. Alongside the lack of data on children and young adolescents' mobility from urban areas in both developed and developing countries, there is also a lack of consideration for the needs of young children and caregivers in broader urban infrastructure and policy design (Beck & Kaune, 2025). While there is growing attention to child-friendly urbanism, a study by Hennig (2019) identifies a lack of practical tools and assessment methods to meet the needs of children and young adolescents and suggests using OpenStreetMap as a useful, accessible geospatial dataset for assessing child-friendly mobility (Hennig, 2019). This study develops a geo-visualisation tool for walkability and bikeability assessment from children's and young adolescents' perspectives, to address the gaps within existing mobility models. Hence, building on the previously developed indicators-based NetAScore model for walkability and bikeability, this research adapts the model and develops the NetAScore4Teens version. The research is centred on young adolescents, gathering rich qualitative data through participatory workshops and translating those insights into indicators, ultimately integrating them into the NetAScore4Teens version. Based on these adolescent -informed inputs, the model will produce an output reflecting the factors that young adolescents value in their everyday mobility, such as safety, comfort, and enjoyment, and will then evaluate whether the existing infrastructure adequately meets those needs. A resolved situation is one in which children's mobility requirements are evaluated using the model, with direct participation and input from children. The objective of the tool is to visualise input and output data of the model in the form of walkability and bikeability scores by developing a user-friendly and intuitive dashboard for planners, researchers, and policymakers alike. This will shed light on where children's mobility gaps exist, thereby supporting evidence-based and child-centred decision-making. Ultimately, it will equip urban planners, researchers, policymakers, and others to evaluate and plan safer routes for children and to create more inclusive environments that support their independent mobility.

1 OBJECTIVES

The objective of the study is to design and implement an interactive visualisation tool to assess and communicate child-friendly urban mobility. This study implements the NetAScore4Teens, a child-adapted version of previously developed NetAScore, which evaluates walkability and bikeability at street segment level. To achieve the main objective, three sequential sub-objectives are defined as follows:

Sub-objective 1: Conceptual and Literature Background

a) Review and analyse literature on child-friendly mobility.

b) Identify existing geospatial methods and tools for assessing children's mobility.

c) Identify indicators and variables contributing to children's mobility.

Sub-objective 2: Design and Implementation of the Tool

a) Adapting the NetAScore4Teens model, implementing the design and user interface of geo-visualisation tools.

b) Building a dashboard using the input and output data from NetAScore.

Sub-objective 3: User Testing and Evaluation

a) Conduct user testing of the dashboard to test the tool's functionality, effectiveness, and usability.

b) Evaluate performance, benefits, and limitations of the tool based on user feedback.

The research will deliver an interactive dashboard and a comprehensive thesis report documenting the literature, methodology, software implementation, results, and user-testing evaluation of the tool.

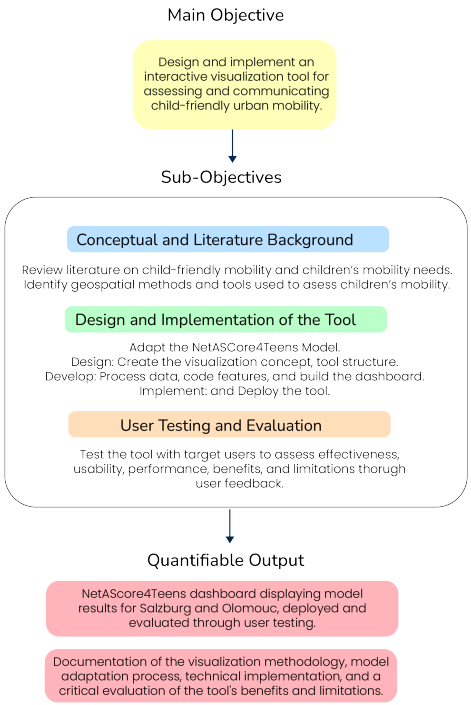


Figure 1. Research Objectives

2 STATE OF THE ART

The current urban planning practices dominantly represent adult-centric values and needs, discouraging walking, cycling, and outdoor play among children (Michail et al., 2025), limiting their freedom to enjoy public spaces (Frohlich and Collins, 2024). Children are distinct users of urban mobility. Unlike adults, their mobility needs extend beyond movement, safety and efficiency to include places of pause, play, and exploration that can support their cognitive development (Michail et al., 2025). However, urban design and transportation infrastructure do not always fully consider their needs. This leaves children with shrinking opportunities to walk, bike and move freely and safely. Children's active and independent mobility is an increasingly studied area within this context (Hoelzel & Scheiner, 2026). Active mobility, also known as non-motorised mobility, primarily includes walking and cycling; however, kick scooters, skateboards, other wheeled devices, manual wheelchairs, and hand-cycles are also recognised as active transport modes (Reimers & Demetriou, 2024; Cook et al., 2022). The extent to which children can experience the use of non-motorised modes such as walking in an autonomous and exploratory manner is captured by the concept of Children's Independent Mobility (CIM); defined as children's freedom to get around their neighbourhood or city without adult supervision, a term introduced by Hillman et al. (1990). Active mobility has proven to have environmental and health benefits that positively impact children's well-being (Stark et al., 2025; Yuan et al., 2023; Jones et al., 2020). Higher levels of physical activity, sociability and improved mental wellbeing are associated with the ability of children to play outdoors with freedom (CIM), and use of walking and cycling to move around (Active mobility) (Brown et al., 2019; Stanley et al., 2015; Page et al., 2009; Schoeppe et al., 2013; Schoeppe et al., 2014). Children benefit from independent mobility, with autonomy to walk, cycle, and take transit, and they should feel safe using streets (Global Designing Cities Initiative [GDCI], 2020). Research also proves that independent travel at a young age enhances physical fitness and promotes interaction with other children (Fyhri & Hjorthol, 2009), while the negative impacts of low levels of active mobility in children can range from children's physical health to psychological, cognitive, social, and economic well-being (Waygood et al., 2020). Despite the benefits, there is a significant decline in children's active and independent mobility, which negatively impacts their mental health (Gray et al., 2023). Two distinct factors;one social, one environmental have contributed to the decline of children's independent mobility. Lopes et al. (2014) report a general decline due to restricted parental autonomy for children to move around in urban settings. This decline in CIM is also closely linked to unsupportive built and social environments, which independently resulted in changes in mobility patterns (Riazi et al., 2022). Street design plays a significant role in this second factor. Streets with sources of risk and unhealthy stress, and traffic-related safety concerns threaten children and caregivers with dangerous conditions, limit independence, and reduce everyday opportunities for learning and building healthy relationships (Gong, van den Berg, & Arentze, 2024; GDCI, 2020; Tranter & Pawson, 2001). On the other hand, streets and public spaces that prioritise active travel and keep motorised traffic separate enhance children's safety and enable cycling and walking (Brown et al., 2019). However, current urban design practices often fail to recognise streets as social and inclusive spaces, overlooking the benefits of walkable neighbourhoods and public spaces (Michail et al., 2025). At the level of urban infrastructure and policy, the specific needs of young children and caregivers are rarely considered. A research survey conducted by Beck & Kaune (2025) ranks mobility as the second biggest challenge for babies, toddlers, and caregivers in their city, where children's

well-being in urban spaces remains an often-overlooked demographic in urban planning and design (Pia & Bezboruah, 2025). Hence, there is an urgent need to consider urban mobility an important determinant of children's well-being and quality of life, and to support their cognitive development, well-being, and health.

2.1 Theoretical Background: Child-friendly Cities and Urban Planning

Many cities remain inadequately designed for children, and there is a need to address children's specific needs and rights (Palmas et al., 2024; Riggio, 2002; United Nations Children's Fund [UNICEF], 2006). When the urban environment is child-friendly, children, caregivers, and society as a whole benefit. Child-friendly urban spaces are essential not only for children's healthy development but also for the well-being of caregivers and society (Krishnamurthy et al., 2018; van Vliet & Karsten, 2015), offering socio-economic benefits with healthy urban conditions for all. (Freeman & Tranter, 2024; Gill, 2021). In this context, child-friendly urban planning makes the case for cities to be good, healthy places for children to live, play, and grow up (Tim Gill, 2021), offering a broader framework for rethinking how cities should support their everyday movement, safety, learning, rest, and opportunities for play (Gill, 2021; Krishnamurthy, Steenhuis, Reijnders, & Stav, 2018; UNICEF, 2018; Kyttä et al., 2012; Malone, 2015). Urban Mobility is an essential aspect of a child-friendly city, given that children need healthy, green, walkable, and smart environments for their development (Cordero-Vinueza et al., 2023), where limited options for walking, playing, and connectivity are linked to unhealthy, unsafe and unplanned environments for children (Aerts, 2018). Marketta Kyttä's framework in this context provides a conceptual bridge between urban mobility and child-friendly cities, demonstrating children's everyday freedoms in two dimensions: 1) children's mobility, meaning their ability to move independently and get to spaces and facilities on their own, and 2) availability of affordances in the environment, meaning the spaces and facilities that invite or support activity (Kyttä, 2004). The framework provides a conceptual basis for measuring urban mobility and meaningfully connects the idea that children's independent mobility is achieved by providing certain favourable conditions of the built environment, shaping neighbourhoods, streets, and public spaces so that children can move safely and access meaningful destinations. See Figure 1.

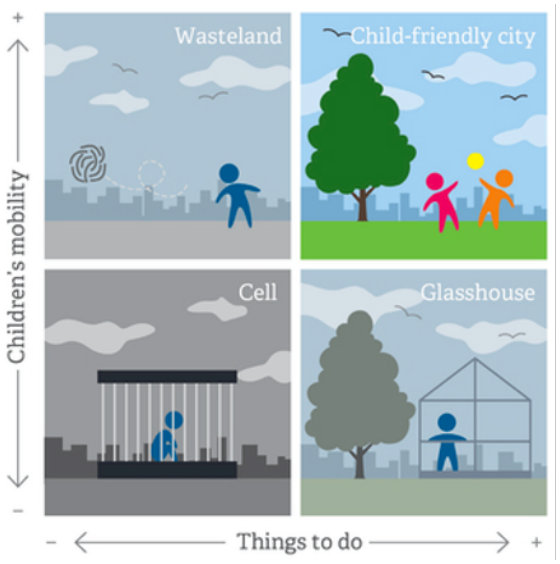


Figure 2. Kyttä's Framework for Child-friendly cities (Source: Gill, 2021)

2.2 Global Agendas and Frameworks

With more than one-third of children worldwide living in urban areas, the call for child-friendly cities (CFCs) has grown in urgency (Cordero-Vinueza et al., 2023). Child-friendly mobility and urban planning have gained theoretical importance in recent years, and global agendas and policies have focused on designing inclusive cities for all, including children. Moving beyond traditional frameworks, these approaches emphasise treating children as active users of urban spaces and seek to reframe cities as places that support their rights, safety, and independent mobility. An important foundation in this case was laid by the United Nations Convention on the Rights of the Child (1989), establishing children's rights to participation, safety, play, and access to supportive environments (United Nations,1989). Broader international frameworks emerged later, such as the Child-Friendly Cities Initiative (CFCI), which declared the well-being of children an indicator of a healthy habitat (UNICEF & the United Nations Centre for Human Settlements [UNCHS-Habitat], 1997). One of the United Nations' Sustainable Development Goals, also known as Agenda 2030, is Sustainable Cities and Communities (Goal 11), which focuses on providing access to safe, affordable, accessible, and sustainable transport systems for all, including children (United Nations, 2015). The New Urban Agenda (Habitat III, 2016) reinforces these global commitments toward inclusive and people-centred urban mobility (United Nations, 2017). Following these global frameworks, several other initiatives focused on children have gained importance; Urban95 by the Bernard van Leer Foundation takes its longstanding focus on young children into the realm of urban planning (Vincelot, 2018). Its emerging intervention model is the 'Children's priority zone', illustrated in Figure 2. Where "mobility" is an essential part (Gill, 2021).

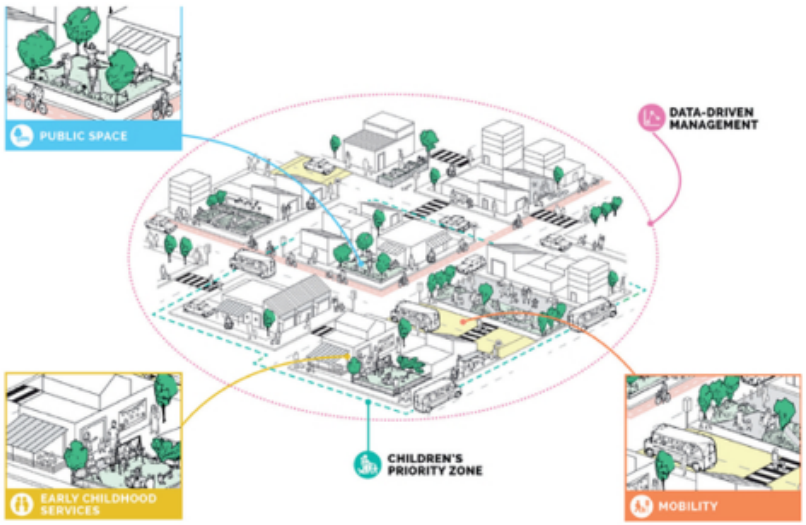


Figure 3. Child-priority Zones with Urban Mobility as an essential component (Source: Gill, 2021)

The UNICEF-published handbook by Aerts (2018) sets out substantive measures to flesh out its Child-Friendly Cities programme, where "**Improved Children's Independent Mobility**" is explicitly mentioned under CFCI Theory of Change (Aerts, 2018). These principles have been translated into more child-focused street guide measures by the National Association of City Transportation Officials' guide "Designing Streets for Kids",

setting a global standard for designing urban streets that prioritise safety, walkability, and accessibility for children and caregivers (GDCI, 2020). More recently, the Proximity of Care framework, developed jointly by ARUP and Urban95, emphasises the importance of designing neighbourhoods that support children's everyday movement, accessibility, and independent mobility (Newton & Candiracci, 2020). Together, these global agendas provide important policy and conceptual background for addressing the issues of child-friendly urban mobility; however, a gap exists in translating these policy commitments into measurable, spatially explicit assessments that are representative of children's mobility conditions.

2.3 European Initiatives

Some cities across Europe are beginning to take concrete interventions in pursuits of child-friendly mobility, though such interventions remain isolated examples rather than widespread practice. At street level, school streets are increasingly being implemented. Paris, for instance, has pedestrianised 13.5 km of streets around schools, yielding both open space and measurable cooling effects (Moran, 2025), sustained through local leadership and community engagement identified in a qualitative study of a recurring Parisian play street (Alexander, 2026). In Catania, Italy, stakeholder co-creation was found central to the success of two School Street case studies (Distefano et al., 2025). At the neighbourhood scale, the EU Horizon 2020 Metamorphosis project trialled child-led transformations of car-oriented streets across seven European cities, including Graz and Southampton (van Apeldoorn, 2019; Wong et al., 2020). Several cities have also developed mapping-based tools to support safe routes for children. An example in Austria is the Schulwegplan initiative jointly run by AUVA and KFV, which maps assessed school routes (AUVA & KFV, n.d.). A similar model by the City of Olomouc's Bezpečná cesta do školy (safe route to school) mapping tool enables identification of safe routes to school through a web map (City of Olomouc, 2023). These examples, while demonstrating that meaningful change is possible, they remain concentrated in specific cities and contexts, rather than reflecting a systemic shift in how urban environments are designed for children more broadly.

2.4 Built Environment Determinants of Children's Mobility

Translating global agendas into practice requires an understanding of the built environment and spatial features that shape children's mobility. Research has expanded on the role of urban environments in shaping children's lives (Cordero-Vinueza, Niekerk, & van Dijk, 2023). Children, due to their age and developmental stage, are slower, smaller, and more vulnerable to traffic and environmental hazards than adults. The physical environment continuously affects children's health and well-being (Brown et al., 2019; Palmas et al., 2024), especially when their exposure to hazards such as air and noise pollution and traffic accidents is high (Palmas et al., 2024). GDCI's Designing Streets for Kids guide identifies three pillars of child-friendly streets that shape children's mobility. The first pillar is safety and includes physical infrastructure to protect against traffic hazards. The second pillar is comfort and covers features to make the mobility experience pleasurable. The third pillar is inspirational, meaning spaces that offer play and learning opportunities for imagination. Safe street infrastructure is therefore essential to enabling children's independent mobility. Features like barrier-free sidewalks, accessible crossings, and adequate lighting reduce exposure to traffic accidents, enabling children to walk safely while supporting unsupervised mobility (WHO,

2023; GDCI, 2020; NACTO, 2013). Another deterrent to children's independent mobility is traffic speed and volume. WHO (2023) identifies traffic calming measures as critical to reducing the risk of road traffic injuries caused by high traffic speed and volume, which in turn is a leading cause of death for children and young adolescents aged 5–29 years. Speed bumps, speed tables, and raised crossings are important traffic-calming strategies to reduce speeds in areas with unsignalized crossings and high volumes of children and caregivers. (GDCI, 2020). Alongside the safety infrastructure, green infrastructure offers additional benefits for children and caregivers in urban areas: improving air quality, reducing the urban heat island effect, and providing natural shade and comfort while walking and biking. (Larsen et al., 2009; Lovasi et al., 2011; GDCI, 2020; Clement & Waitt, 2018), consistent with global frameworks that recognise access to green space as a core criterion of child-friendly cities (UNICEF, 2018). To further aid an encouraging environment for walking and cycling for children and caregivers, streets should include comfortable and convenient street furniture such as benches, rest areas, legible wayfinding and schedules, shaded transit stops, and facilities like restrooms and drinking fountains (GDCI, 2020). Finally, alongside safety and comfort, play is a critical determinant of children's mobility. Acknowledging streets as public spaces can ensure they are not only places to move through, but spaces to pause and spend time. For children and caregivers, streets can provide opportunities for outdoor play, inspiration, personal development, and interpersonal connections (GDCI, 2020; Michail et al., 2025). Increasing physical activity and play encourages socialising and creativity, contributing to children's healthy development (Brown et al., 2019; Gill, 2021). The availability of meaningful destinations, facilities, and play spaces along travel routes contributes to children's independent mobility (Krysiak, 2023; Brown et al., 2019).

2.5 Children's Participation in Mobility Planning

Children constitute a growing proportion of the urban population worldwide, yet scholars and practitioners face a roadblock in incorporating their views and perceptions of daily mobility (Humberto et al., 2022), as limited evidence exists on children's travel experiences and neighbourhood preferences (Egli et al., 2019; Wilson et al., 2018). Children and young adolescents remain an overlooked and vulnerable segment in urban transport. (McMillan,2013). The missing perspectives from children are important to incorporate to ensure that urban mobility truly reflects children's needs. This requires considering children as legitimate urban stakeholders (Aerts, 2018). A growing body of research supports community participation; however, evidence specifically on the outcomes of children's engagement in street design is lacking (GDCI, 2024). Children are active users of mobility systems, and integrating their perspectives can offer unique insights on built environments to inform policies aimed at promoting walkable and child-friendly cities (Michail et al., 2025). Children's participation can provide an in-depth understanding of the local context, leading to more humane and child-friendly streets (GDCI, 2024). This can bridge the gap between generations and understanding children's and communities' needs (GDCI, 2024). The social-ecological conceptualisation of children's mobility by Mitra and Manaugh (2020) suggests the need to incorporate children's perspectives to achieve a comprehensive understanding of the relationship between urban environments and their travel behaviours. Although children's participation is increasingly advocated, Wilson et al. (2018) argue that most of the evidence on children's mobility is based on objective assessments that tend to omit children's actual urban mobility experiences. To fill these gaps, researchers increasingly turn to participatory mapping and tools that enable children to express their concerns

(Preto et al., 2016), providing valuable insights into their everyday mobility (Freeman et al., 2017).

2.6 Participatory Approaches to Understanding Children's Mobility Needs

Participatory approaches to understanding children's everyday mobility have gained importance in recent studies. Michail et al. (2025) used a map-based focus group approach to explore children's perceptions of active school travel and suggested that understanding children's travel experiences through a participatory approach can provide valuable insights into walkable cities and neighbourhoods. Safe public spaces, sociable spaces, and pedestrian-friendly streets are highlighted as key factors for active school travel among children, while footpaths, cycling paths, and safe crossing are preferred by children for walking and cycling. The study also highlights heavy traffic, poorly maintained public spaces, and antisocial behaviours as barriers to child-friendly and walkable neighbourhoods. Many studies have expanded conventional understandings of mobility indicators, revealing emotional, sensory, social, and experiential dimensions of children's everyday movement. Corvalán and Ther-Ñancuvilú (2025) employed highly participatory, sensory-based methods, highlighting the experiential, social, and emotional dimensions of children's mobility on islands. Similarly, drawing-based visual methods used by Agarwal et al. (2021) allowed children to be creative, revealing emotional, perceptual, and cognitive dimensions of urban spaces, such as greenery, opportunities for exploration, cleanliness, a sense of safety, and spaces for social interaction. Various methods, such as co-design, storytelling, and mapping, have been employed by various researchers. Carrión et al. (2024) use a fictional narrative technique to evaluate children's safer routes to schools, highlighting the importance of using tailored methods to develop evidence of children's perceptions of urban environments, revealing a contrast between adult metrics (traffic flow, efficiency, and functionality) and what children prioritise: safety, freedom, enjoyment, experience and social interactions. Similarly, a scale-based approach developed by Sapsağlam & Eryılmaz (2024) to measure a city's child-friendliness, grounded in children's actual experiences of urban environments, identifies play opportunities, safety, comfort, and emotional experiences as important indicators of supportive urban environments for children's healthy development. Furthermore, mapping techniques such as PGIS (Participatory GIS) for translating children's perceptions and identifying risky places along children's daily routes have revealed important dimensions of children's mobility, including spatial familiarity, traffic exposure, social and environmental risks, and unsafe crossings (Freeman et al., 2017; Preto et al., 2016). Together, these research findings from participatory methods with children not only capture the children's mobility dimensions that are often missing in traditional planning approaches but align well with the Global Designing Cities Initiative's (GDCI) design guide "Designing Streets for Kids", a global standard and practical guide for walkable, safer, and healthier streets for kids. (GDCI, 2020).

2.7 Children's Mobility Assessment Approaches

While participatory approaches help capture children's perceptions, there remains a need to integrate these insights into mobility frameworks representative of child-centred metrics. Urban paradigms, such as 15-minute cities, have gained attention in recent years. While these models focus on proximity, walkability, and inclusivity, there is a need to research how adequately these models capture children's mobility indicators. This

section particularly focuses on measurable variables and indicators used in previous studies to include various dimensions of children's mobility. Children's Independent Mobility in particular, has been measured by Moura, Rosa, & Barros (2024) using 15 indicators under three categories: environment, place and mobility to measure safety and attractiveness of urban environments by employing GIS, thematic mapping, multi-criteria analysis techniques while Bhosale et al. (2017) capture children's independent mobility using access to specific destinations and activity spaces demonstrating web-based mapping as a way to provide spatially explicit and standardized way to quantify CIM. Torun et al. (2024) use qualitative GIS analysis combined with participatory mapping to analyse children's everyday activity spaces, including places for walking, cycling, and playing, integrating experiential determinants of child-friendly mobility. An optimised child-friendly pedestrian pathway network through a GIS-based planning tool was developed by Fang, Azizan, & Huang (2024) that identifies safe and connected walking routes for young children. Diverse indicators covering effective walking, spatial connectivity, pedestrian obstructions, crossings, traffic flow, road network density, and intersection density are used by Zhao et al. (2021) to evaluate the walkability of children's school travel routes. Mizen et al. (2020) model children's daily mobility, focusing on walking routes to school and employing GPS-informed weighted GIS networks that incorporate built-environment features such as road type and physical environment. Ikeda et al. (2019) introduced the potential of data modelling for active school travel and daily journeys, integrating objective GIS-based modelling with participatory, child-centred data. Some relevant studies do not directly measure children's mobility but instead evaluate urban conditions that support child-friendly movement and activity. For instance, Zhang, Song, & Zhao (2024) developed a composite child-friendliness scoring framework using multi-source data (POIs: schools, parks), NDVI, street-view image features, and GIS integration. Evaluation of the child-friendliness of urban environments and children's everyday spatial behaviour is conducted by Mansournia et al. (2024, 2025) using Public Participation GIS (PPGIS), polygon-based digital mapping, and geo-visualisation s, employing metrics such as activity spaces, outdoor places, visit frequency, and proximity. Wang, Wong, & Cheng (2025) developed a dynamic walkability assessment framework using BIM-GIS integration, while Jeong et al. (2023) conducted a comprehensive walkability evaluation of pedestrians' access to destinations within a 15-minute city framework using spatial analysis, Urban Network Analysis, and composite index computation. Badland et al. (2013) used open-source GIS to model walkability and accessibility of neighbourhoods using indicators such as residential density, land-use mix, street connectivity, and accessibility to neighbourhood destinations, as well as simulated pedestrian movement and estimated walking trips. Finally, Werner et al. (2024) developed an open-source framework, NetAScore, to assess walkability and bikeability; indicators include pedestrian infrastructure, road width, number of lanes, noise, water, and greenery. By default, it uses OpenStreetMap data to derive indicators such as cycling infrastructure, speed limits, and greenness, and combines them into a joint suitability index for each road segment. The indicator-based approach is adaptable; additional datasets can be integrated, and the framework can be extended with new indicators, making it suitable for context-specific applications. In addition, the walkability profile of the model by Stutz et al. (2025) evaluates pedestrian infrastructure, road and environmental conditions. However, designed for the general pedestrian and cyclist population, these assessment frameworks do not incorporate child-specific dimensions such as crossing safety, traffic calming measures, play spaces or shade, limiting their direct applicability to children's independent mobility assessment.

2.8 Geo-visualisation and geo-communication of Children's Mobility

Within the existing mobility assessment frameworks and modelling, there is also an increasing need among planners, researchers, and decision-makers to enable the communication and interpretation of these spatial assessments through visual and interactive interfaces to wider audiences. For this purpose, geo-communication and geo-visualisation dashboards allow the translation of complex data into an interpretable form. Different geo-communication tools have been used by different researchers in mobility research. The reviewed mobility assessment approaches and frameworks can be grouped into 5 broader geo-communication tools, each with its own limitations, highlighting the need for the present study.

The most common approach used by researchers involves participatory and hand-made maps (Corvalán and Ther-Ñancuvilú, 2025; Freeman et al., 2017; Derr and Tarantini, 2016). While these studies capture children's spatial and mobility experiences, the communication outputs remain qualitative and require digitisation or planner-ready formats. A digitally advanced platform known as Participatory Geographic Information System (PGIS) and PPGIS is employed by researchers to bridge children's input into spatial data through geo-referencing (Mansournia 2024, 2025; Torun et al., 2024; Preto et al., 2016). While they capture children's perceptions, quantifiable street-level walkability indicators are still missing. A static map is a common geo-visualisation output (Moura et al., 2024; Fang et al., 2024; Zhang et al., 2024; Jeong et al., 2023; Mizen et al., 2020) used to present results from advanced spatial analysis and modelling frameworks. The limitation of a static map is that it compresses multiple indicators into a single layer, which limits filtering, querying, and exploration for more informed decision-making by planners and decision-makers, making it hard to analyse underperforming indicators. Interactive web maps focused on participation are used in studies by Bhosale et al. (2017), Badland et al. (2013), and Hennig and Vogler (2016); however, these studies do not include any mobility-specific scoring or communication framework. Finally, geo-visualisation dashboards have emerged at the neighbourhood or city-block scale (Zhang et al. 2024; Mansournia 2024, 2025), but no tool exists that combines street-segment-level scoring based on child-informed indicators. Across all geo-visualisation outputs produced by different GIS analyses, participatory methods, and advanced modelling, a consistent gap emerges: no tool combines child-informed indicators from direct engagement with a segment-level scoring model presented through an interactive dashboard that can enable urban planners to support decision-making.

3 METHODOLOGY

This study uses an open-source walkability and bikeability assessment model, NetAScore (Werner et al., 2024), to develop NetAScore4Teens, a child-oriented adaptation of the model and an interactive visualisation tool using the model's input and output data. The research involves a literature review and participatory workshops to identify and validate child-specific indicators for inclusion in the mobility assessment model. The model is then implemented, resulting in a child-informed, indicator-driven assessment framework, the results of which are visualised through an interactive dashboard supporting the interpretation of child-friendly mobility. Finally, user testing of the dashboard is conducted to evaluate its functionality and usability. The study combines GIS research, data-driven modelling, and participatory qualitative research to ensure that the model is technically rigorous and grounded in the lived experiences of the user group, i.e., children and young adolescents. The model's generic approach and its ability to be used with open data ensure reproducibility, adaptability, and scalability (Stutz et al., 2025), properties that are leveraged in implementing NetAScore4Teens within the case study of the City of Salzburg, Austria. Salzburg is a medium-sized and fourth-largest Austrian city, with a population of 155,000, where 40% of all trips are shorter than 2.5 km and 70% are shorter than 5 km (Stadt Salzburg, 2021), making it a good case for active mobility (Stutz et al., 2025).



Figure 4. Location of Salzburg, Austria (Source: Wikipedia)

To explore the performance of the model beyond the primary case study area, the technical pipeline was executed for Olomouc, Czechia. Olomouc is also a medium-sized city in Czechia with approximately 100,000 inhabitants (Czech Statistical Office, 2025) and a large (25,000) student population (Palacky University Olomouc, 2025). Its flat topography and compact size also make a relevant case for active mobility.

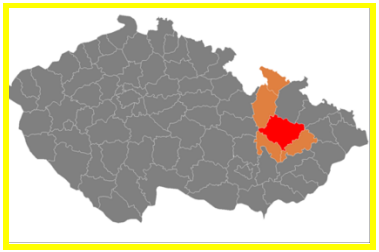


Figure 5. Location of Olomouc, Czechia (Source: Wikipedia)

The research is conducted within the framework of i-mobyl, a European-funded research and innovation project focusing on the co-creation of mobility interventions with young adolescents aged 11–15 (i-mobyl, n.d). The methods used in the research are discussed below, step by step:

3.1 Identification of Child-Friendly Mobility Indicators

The research began with the identification of indicators through a systematic review of academic literature and global guides, such as the GDCI Designing Streets for Kids guide and NACTO Urban Street Design Guide. Existing NetAScore indicators were evaluated for their relevance to children and either retained, adapted, or assigned updated weights. New child-specific indicators were added where gaps were identified.

3.2 Participatory Workshops with Teens

Participatory workshops with 13–14-year-old students from the 4th year of Gymnasium at English-speaking SALIS Salzburg International School were organised to understand whether the existing and new indicators truly represent children's mobility needs. A total of 50 students participated, across two classes of 25 students each. Research access and permission for conducting the workshops were authorised by the school administration and participating teachers; as the workshops formed part of regular classroom activities, individual student participation was not opt-in, and all students in the two participating classes took part as part of their normal lesson. The objective of the workshops was to capture their experiences, aspirations, needs, and perceptions of everyday mobility and integrate those insights into the model. In total, 4 workshops (2 indoor and 2 outdoor) for both classes were conducted as part of their regular classroom activities; hence, separate formal ethical approval was not sought for this stage of the research. Students were instructed not to disclose any personal information during the activities, and participating teachers monitored responses to ensure this guidance was followed. All data collected, written responses, sketches, and group notes, were anonymised at the point of collection, with no names or other identifying information recorded or retained. Full workshop findings are documented in a standalone report (Mobility Lab Salzburg, 2025). The tools and activities for the workshops were adapted from the GDCI Designing Streets for Kids Guide and the Urban Foxes Placemaking Inclusion Cookbook (GDCI, 2024; Urban Foxes, n.d.).

3.3 NetAScore4Teens Model Development

The findings from workshops were used to inform the NetAScore4Teens model using the original NetAScore (Werner et al., 2024), an indicator-based, segment analysis of walkability and bikeability infrastructure. It is a Python-based model with a PostgreSQL database and the PostGIS extension. The model uses a weighted average formula to compute the indicators for each road segment, resulting in a metric adhering to the unit interval [0, 1], where 0 indicates poor, and 1 indicates excellent walkability/bikeability. For example, segment-based walkability $w(e)$ for a graph consisting of vertices and edges $G(V,E)$ is defined as:

$$w\,(e) = \frac{\sum_{k=1}^{n} w_k i_k\,(e)}{\sum_{k=1}^{n} w_k}$$

for $e \in E$ and n indicators, where w represents indicator weights, and i refers to numerical indicator value (Werner et al., 2024). Firstly, the model's generic approach and the ability to be used with open data ensure its reproducibility, adaptability, and scalability. Stutz et al. (2025) allowed easy adaptation for our specific context, i.e., teens. Secondly, flexible parametrisation of the model allowed defining model parameters, where additional

indicators were introduced, and weights were adjusted for children's context. The weights of indicators were established in three stages: an initial set of weights derived from the literature review, followed by validation through workshops with young adolescents, and final adjustment through an internal weighting workshop. The weights are defined within the NetAScore pipeline through mode profile weights, and indicator mappings are defined within NetAScore's mode profile files (YAML configuration files specifying model parameters per travel mode). Hence, for the teen's version, new indicators derived from literature and informed from workshops and existing indicators were checked, retained, and updated with weights based on their relevance to children. Finally, the issue of the weighted average not adequately capturing walkability for certain indicator combinations was dealt with by using rule-based overrides that NetAScore offers.

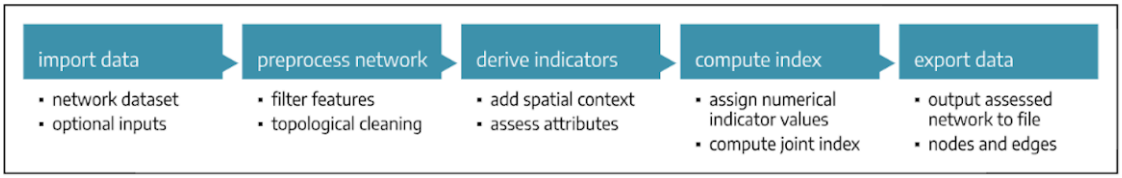


Figure 6. NetAScore Workflow (Source: Werner et al., 2024a)

3.4 Model Execution

The model execution follows the NetAScore workflow (Werner et al., 2024a; NetAScore v1.1.1, Werner et al., 2024b), which computes walkability and bikeability indices in five processing steps. The first, Import Step, imports network data either from local files or directly from OpenStreetMap via the Overpass API, with the option of including additional data layers. For this study, OpenStreetMap data for Salzburg are retrieved automatically through the NetAScore import configuration using a place-name query with the administrative boundary and a 1,000 m buffer. For Olomouc, OpenStreetMap data are obtained from the Geofabrik Czechia extract and clipped to the administrative boundary (admin_level = 8) before model execution. The second, Network Step, creates network datasets according to the selected input source. For OSM data, relevant road-network features and attributes are extracted, followed by topological cleaning. Next, the Attribute Step derives the attributes and indicators required for routing applications and index calculation from the processed network dataset and optional supplementary datasets. Contextual indicators, such as greenness and crossings, are computed using the default NetAScore parameterisation, including spatial buffers of 10–30 m (Werner et al., 2024a). The Index Step then computes the walkability and bikeability indices as weighted averages of all available indicators for each road segment. Finally, the Export Step generates a GeoPackage containing the network edges and nodes. The same technical workflow is subsequently applied to the second case study area, Olomouc, Czechia.

3.5 Plausibility Check

Given the large number of street segments generated by the model within the case study area, a thorough validation of all street segments by on-site inspections was beyond the scope of this thesis. Instead, a stratified sampling approach was used, and 10 road segments were checked. Centroid coordinates for each road segment were extracted and used to generate a direct Google Street View link, allowing each segment to be visually cross-checked against its assigned score. Apart from 10 randomly selected segments, a targeted check for 2 street segments around SALIS International School located on Zaunergasse was done. It is the area where outdoor street evaluation activity was done as part of the workshops. The location was directly observed and evaluated by teen participants of the workshop; this comparison offered a valuable opportunity to assess

the model's computed scores against children's own first-hand assessment of the same streets.

3.6 Data Preparation for Visualisation

The output of NetAScore4Teens was generated in the form of a GeoPackage file comprising all the geometries and attributes. To check the results, the GeoPackage was first visualised in QGIS and ArcGIS Pro, and static maps for both walkability and bikeability were generated. For interactive visualisation of the results, the GeoPackage file was first converted into GeoJSON, then converted into vector tiles using Tippecanoe, and packaged into PMTiles format. A similar method was applied for supplementary contextual datasets (Copernicus Street Tree Layer and Urban Atlas Land Use, 2021) and point-of-interest data**.** The process was repeated for a second city, Olomouc, Czechia.

3.7 Development of Geo-visualisation Tool

The input and output data of NetAScore4Teens and supplementary contextual data mentioned above are visualised in the form of an interactive dashboard for planners, researchers, and decision-makers alike. For the rendering of an interactive vector-tile map, open-source MapLibre GL JS is used. It efficiently renders score-based styling, layer management, filtering, and other interactive functions. The surrounding dashboard interface is developed in vanilla JavaScript, HTML, and CSS. The purpose of the dashboard is to enable users to explore walkability and bikeability scores at the street segment level, identify low- to high-scoring segments, and help identify the roads least supportive of children's mobility. The main idea is to translate the model's multi-indicator complexity into an accessible, interactive, and intuitive tool to identify gaps in the mobility infrastructure. To provide contextual environmental and land-use information alongside the NetAScore4Teens walkability and bikeability indices, the dashboard integrates the Copernicus Street Tree Layer and the Urban Atlas Land Use dataset (2021) and Point-of-interest (POI) data fetched from OSM (OSM data last updated on July 24, 2026).

3.8 User Testing of Geo-visualisation Tool

To evaluate the usability, functionality, and usefulness of the dashboard, user testing was conducted with 10 participants comprising researchers and urban planners. The approaches used for the user testing were moderated think-aloud sessions. The experiment was designed to gather valuable feedback given the time constraint. All participants took part in a moderated think-aloud session lasting 15–20 minutes; six of these were conducted in-person, and four were conducted online. Each session began with a brief introduction explaining the purpose of user testing, after which participants explored the dashboard while verbalising their thoughts, reactions, and real-time difficulties faced while using the tool. All feedback was noted down during the session. Across all sessions, the aim was to assess the dashboard's UI and UX design and to understand whether the information it presents is well perceived by users. The findings from the user testing provided valuable insights, with participants offering feedback on the current design and identifying areas for future refinement.

3.9 Used data

The NetAScore4Teens model uses data from OpenStreetMap (latest updated July 3, 2026) to compute the walkability and bikeability index for the City of Salzburg, Austria, and for the second case study, Olomouc, Czechia (latest updated July 24, 2026). Qualitative data gathered through a participatory workshop was used to understand mobility perception and needs of children and translated into measurable/quantifiable indicators (OSM attributes/keys indicators), informing the model. The dashboard uses the computed data resulting from the model, visualised alongside POIs data from OSM (last updated July 24, 2026), Copernicus Urban Atlas Land Use (2021) and Street Tree Layer data. See table below:

Table 1. Data Used for the Study

Data	Purpose	Parameters
Qualitative data	Inform Indicators	50 students, SALIS, 4 workshops
OpenStreetMap	Network & Indicators, POIs	Overpass API, extracted 3 Jul 2026 (Salzburg), 20 Jul 2026 (Olomouc), 1000 m buffer, POIs extracted: 20 Jul 2026
Copernicus Urban Atlas Land Use (2021)	Contextual land-use layer for dashboard	Vector, 19 urban classes, MMU 0.25 ha, 2–4 m VHR + Sentinel-2 imagery, 2021 reference year
Street Tree Layer (2021)	Contextual green-infrastructure layer for dashboard	Vector, tree patches ≥500 m² with ≥10 m width, mapped within Functional Urban Areas, 2021 reference year

3.10 Used software

A range of software tools are used throughout the research. MS Excel is used for the processing of qualitative data from workshops, while Adobe Illustrator is used for generating graphs and visualising workshop outputs. The implementation of the model is done in Python, with PostgreSQL and the PostGIS extension serving as the spatial database for data storage and spatial queries. The final maps of walkability and bikeability index are prepared in QGIS and Adobe Illustrator. Vector tiles for the dashboard were generated using Tippecanoe (v2.79.0), which outputs directly in PMTiles format. MapLibre GL JS is used to render the interactive vector-tile map, including score-based styling, filtering, and layer management, while the surrounding dashboard interface is developed in vanilla JavaScript, HTML, and CSS. Claude (Anthropic) was used to assist with code implementation and debugging.

Table 2. Software Used for the Study

Software	Version	Purpose
NetAScore	v1.1.1 (commit 24a5107)	Open-source framework for computing walkability and bikeability indices
Python	3.12.7	Implementation of NetAScore4Teens
PostgreSQL	18.1 (Postgres.app)	Storage and management of geospatial data for NetAScore4Teens
PostGIS	3.6	Spatial processing extension for PostgreSQL
QGIS	3.44	Visualization of Static Maps for the Walkability and Bikeability
GDAL (ogr2ogr)	3.8.5	Conversion of GeoPackage output into GeoJSON format
Tippecanoe	v2.79.0	Generation of vector tiles (PMTiles format) from GeoJSON data for dashboard rendering
MapLibre GL JS	v3.21	Rendering of vector tiles; score-based styling, filtering, and layer management for the interactive map
PMTiles (JS library)v3.0.6	)v3.0.6	Client-side reading/serving of PMTiles vector tiles to MapLibre GL JS in the browser
Node.js	18+	Running the POI data-fetching script (fetch-poi-data.mjs)

HTML, Vanilla JavaScript, CSS	-	Front-end development and dashboard interface design.
Chart.js, Tabler Icons, SVGs	v4.4	Dashboard charts, visual elements, and user interface components.
Adobe Illustrator, MS Excel	2021	Data Visualizations, Map Layouts

The overall methodological workflow is illustrated in the figure below:

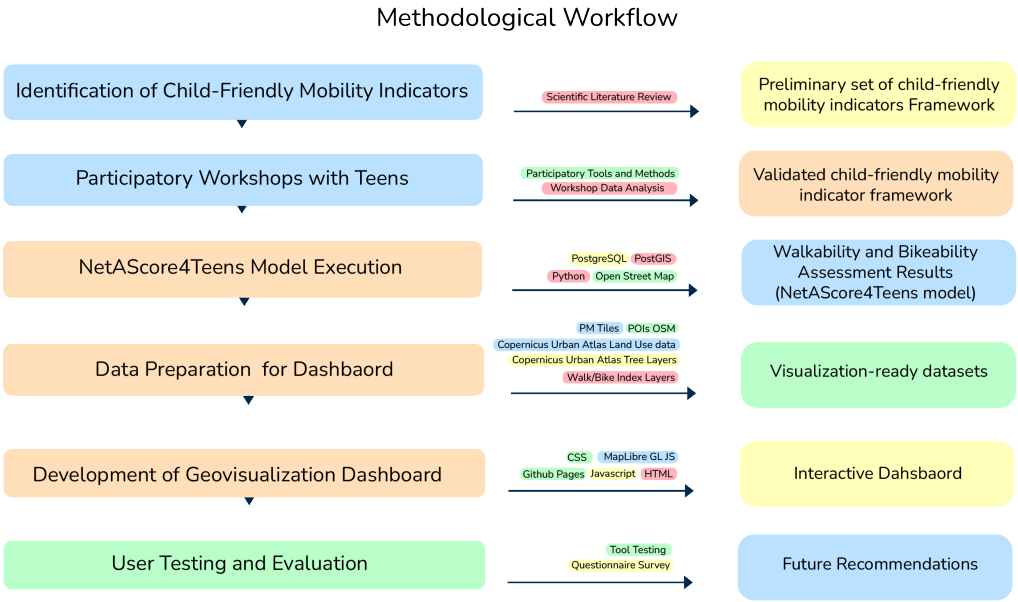


Figure 7. Methodological Workflow

4 DEVELOPMENT OF NETASCORE4TEENS

This section of the report includes details of the step-by-step workflow for the development of the NetAScore4Teens model.

4.1 Identification of Child-Specific Indicators

This section outlines the process for identification and selection of indicators for the NetAScore4Teens model, combining insights from academic literature, international design guidelines, and participatory workshops with adolescents.

4.1.1 Literature Review and Mind-Mapping

To develop a meaningful, child-specific mobility scoring framework, it is important that the results truly reflect the walkability and bikeability needs of children. For this purpose, a literature review was conducted on children's mobility, child-friendly cities, active mobility, play, and street design. The findings from the literature were synthesised through a mind-mapping exercise to identify emerging themes and dimensions influencing children's mobility. These themes include environmental, social and physical aspects of urban environments, and were specifically reviewed keeping in view the scale and vulnerabilities of the target user group, i.e., children. The mind-mapping exercise helped to connect various aspects of urban spaces to understand which variables and which dimensions to capture. See figure:

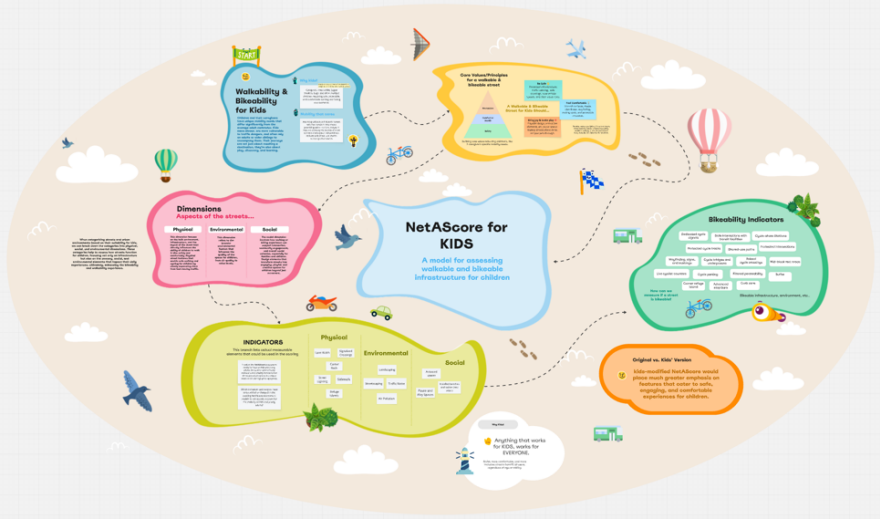


Figure 8. NetAScore4Teens mind mapping (Source: Author https://miro.com/app/board/uXjVI_5xRDo=/)

The result of this mind mapping exercise was a broader dimension of urban variables that were divided into three groups:

Table 3. Thematic Grouping

Physical	Physical street features that enable safe walking and cycling for children by clearly separating them from fast-moving traffic.
Environmental	refers to the broader environmental factors that influence the quality of the space for children, from air quality to noise levels.

Social	Design elements that transform streets into engaging, playful, and creative spaces for children beyond just movement.

These three dimensions were further analysed, connecting to the GDCI Streets for Kids Guide that identifies three key pillars of child-friendly streets that shape children's mobility. The first pillar is **safety** and includes physical infrastructure to protect against traffic hazards. The second pillar is **comfort** and covers features to make the mobility experience pleasurable. The third pillar is **inspirational**, meaning spaces that offer play and learning opportunities for imagination. (GDCI, 2020). These principles were translated into a three-tiered pyramid for NetAScore4Teens, starting with Safety as the essential and foundational requirement for children's mobility and then building on top of it layered by comfort and inspiration.



Figure 9. Framework for Indicators Identification (Source: Author)

This conceptual framework was used to define measurable indicators for the NetAScore4Teens across three themes: Safety, Comfort and Inspiration. The existing indicators were reevaluated for the children's context, and additional indicators were introduced. GDCI Designing streets for kids guide (GDCI, 2020) was proven to be a key guiding document for the identification of child-specific indicators alongside scientific literature. For instance, the recommended actions to improve streets for children depicted in the figure below were translated into children's mobility metrics.

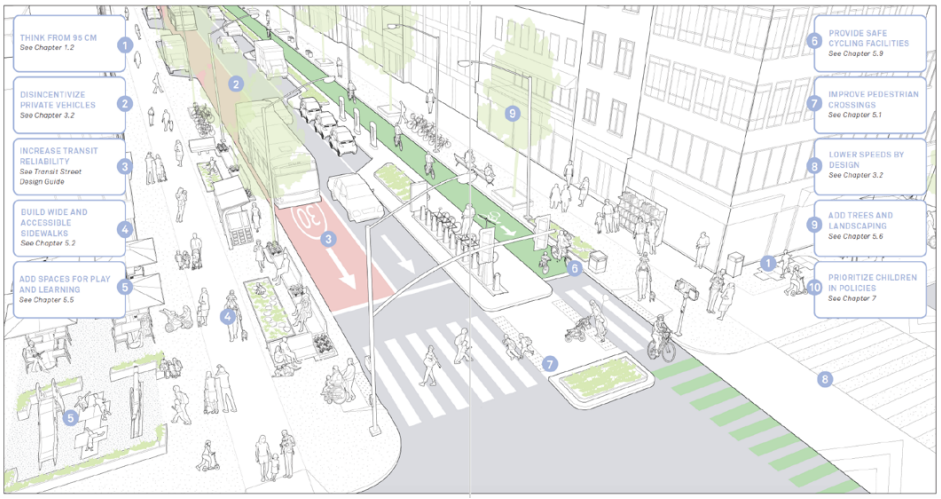


Figure 10. Street Design for Child-friendly Street (Source: GDCI, 2020)

As a result, a list of indicators was established for both walkability and bikeability, which was then cross-checked with the already mapped NetAScore indicators, with a focus on how the indicators are defined and weighted. Table 4a and 4b show a preliminary list of indicators for both walkability and bikeability with recommended weights understood through a detailed literature review.

Table 4. Walkability Indicators

Indicator	**Core Value**	**Existing Weight**	**Recommendation Weight**	**Justification & Citation**
Pedestrian infrastructure (sidewalk)	Safety	0.4	Keep same weight; individual value mappings adjusted	Essential for safe walking (GDCI, 2020; Banerjee et al., 2012; WHO, 2023)
Road category	Safety	0.3	Keep same	Proxy for traffic exposure (WHO, 2023)
Max speed	Safety	0.3	Keep same	Lower speeds critical for safety (GDCI, 2020; WHO, 2023)
Gradient	Comfort	0.3	Keep same	Affects walking comfort and accessibility
Number of lanes	Safety	0.1	Keep same	Increases traffic complexity and crossing risk
Destinations / facilities (general concept)	Comfort/Inspiration	0.3	Suggested to increase weight/ disaggregated	Encourages activity and independence (Speck, 2013)
Greenness	Comfort/Inspiration	0.3	Suggested to increase weight	Linked to children's physical activity and wellbeing (Larsen et al., 2009; Lovasi et al., 2011; GDCI, 2020)
Water bodies	Comfort/Inspiration	0.4	Keep same	Contributes to pleasant walking environment
Noise	Comfort	0.3	Keep same	Undermines comfort and wellbeing (GDCI, 2020)
Crossings	Safety	0.2	Suggested to increase weight	As important as sidewalks for safety (Kostanjsek & Lipar, 2007; GDCI, 2020)
Pavement	Comfort	-	Keep same	Bikeability indicator, affects cycling comfort and accessibility
Buildings	-	0.1	New; to assign weight, subject to data availability	Contributes to enclosure and perceived safety
Lane width	Safety/Comfort	(unweighted in original)	Existing NetAScore attribute, unweighted in original; assign weight	Increases pedestrian crossing exposure (NACTO, 2013)
Parking	Comfort	-	Existing NetAScore attribute,	Linked to child pedestrian injury risks

Indicator	Core Value	Existing Weight	Recommendation Weight	Justification & Citation
			unweighted in original; assign weight	
Shades	Comfort	-	New; to assign weight, subject to data availability	Supports thermal comfort (GDCI, 2020; Banerjee et al., 2012)
Rest areas / benches	Comfort	-	New; to assign weight, subject to data availability	Supports comfort for children/caregivers (Brown et al., 2019; GDCI, 2020)
Street lighting	Safety	-	New; to assign weight, subject to data availability	Vital for street safety
Wayfinding & signage	Comfort	-	New; to assign weight, subject to data availability	Supports navigation
Pause & play spaces	Inspiration	-	New; to assign weight, subject to data availability	Need for rest and play points (Brown et al., 2019; GDCI, 2020)
Air quality	Comfort/Health	-	New; to assign weight, subject to data availability	Children more physiologically vulnerable to pollution
Traffic volume	Safety	-	New; to assign weight, subject to data availability	Linked to child pedestrian injury risk (Agran et al., 1996; Appleyard, 1981)
Speed table / speed hump (traffic calming)	Safety	-	New; to assign weight, subject to data availability	Traffic-calming measure (NACTO, 2013; Ewing, 2001)

Table 4b. Bikeability Indicators

Indicator	Core Value	Existing Weight	Recommendation	Justification & Citation
Designated route	Safety	0.1	Keep same	Supports wayfinding and route confidence
Bicycle infrastructure	Safety	0.2	Suggested to increase weight	Spine of child-friendly cycle network (GDCI, 2020; NACTO, 2013)
Road category	Safety	0.3	Keep same	Proxy for traffic exposure
Motor vehicle speed	Safety	0.1	Suggested to increase weight	Strong risk factor for child cyclists (NACTO, 2017)
Gradient	Comfort	0.1	Keep same	Affects cycling comfort and effort
Pavement	Comfort	0.1	Suggested to increase weight	Affects cycling safety and comfort
Parking	Comfort	0.1	Keep same weight; category mapping	Affects cycling safety and route choice

Indicator	Core Value	Existing Weight	Recommendation	Justification & Citation
			adjusted (binary → 3-tier)	
Facilities (general concept)	Comfort	-	Suggested to increase weight; disaggregated	Supportive cycling environment
Shades	Comfort	-	New – to assign weight, subject to data availability	Supports thermal comfort during cycling (GDCI, 2020; Banerjee et al., 2012)
Rest areas / benches	Comfort	-	New – to assign weight, subject to data availability	Supports comfort on cycling routes (Brown et al., 2019; GDCI, 2020)
Existing indicators not retained for cycling (number of lanes, greenness, noise, buildings)	-	-	Not assigned in final bike profile	Considered from the original model but not weighted for the cycling mode in the final profile
Additional cycling infrastructure identified in literature (lane width, cycle-share stations, cycle bridges/underpasses, cycle parking, raised crossings, mid-block rest areas, curb zone, buffer, traffic calming, advanced stop bars)	Safety/Comfort	-	New – to assign weight, subject to data availability	Support safer, more comfortable child cycling (NACTO, 2013; NACTO, 2017; Paulusová, 2023)

4.2 Participatory Workshops

To empirically validate whether the model's existing and newly proposed indicators adequately capture children's mobility needs, a series of participatory workshops were conducted with SALIS as the partner school specifically because it is an English-speaking institution, enabling the author to communicate directly with students without requiring translation support during the workshops. The workshops were organised as part of regular classroom activities in coordination with the school and were facilitated with teacher supervision; hence, separate formal ethical approval was not sought for this stage of the research. The workshops were coordinated in collaboration with schoolteachers and staff, Daniela Graf and Grace Steffens, and facilitated by the author alongside i-mobyl project partners: Martin Loidl (Mobility Lab Salzburg, Z_GIS, University of Salzburg), Lina Mosshammer (POINT&), and Ursula Witzmann-Müller (UWM.Mobilität) (i-mobyl, n.d). All activities were conducted in English. The data were gathered in the form of written texts, responses, sketches and group notes, and it was ensured that all data were anonymised, with no names or identifying information recorded or retained. The objective of the workshops was to engage them through different activities focused on their everyday experience of mobility and journey to school. The tools and activities for the workshops were adapted from the "How to Engage Kids in Street Design" guide (GDCI,

2024) and the Urban Foxes Placemaking for Inclusion Cookbook (Urban Foxes, n.d.). The table below presents an overview of the tool and activities.

Table 5. Overview of workshop activities conducted with students

Method	Activity	Focus	Adapted From
See-Think-Wonder	Images of street transformation (before and after) to explore what teens observe in the streets.	Visual cues, priorities, and street features.	GDCI Guide
Ps. And Your Street	A reflective exercise to explore the emotional experience of teens on their journey from home to school.	Perception based on memory, interpretation and lived experience.	GDCI Guide
Street Evaluation	An outdoor assessment of the school street.	Sensory experience, safety, real-time experience, barriers, likes and dislikes.	Urban Foxes Placemaking Cookbook
Design Your Dream Street	A creative activity where teens imagine and illustrate their ideal street.	Aspirations, needs, and mobility experiences.	GDCI Guide
Participants: 13–14-year-old students from SALIS, 2 classes, 25 students each, total 50 students.			
Data collected: written responses, text reflections, group notes, street sketches.			

To conduct the engagement workshops, four activities were planned across two indoor and two outdoor sessions with two different classes. The first exercise, See-Think-Wonder, was an introductory session where children were given before-and-after images of street transformation. During this activity, students were given the task to critically evaluate both before and after images and spot the change happening in those images. The objective of this activity was to understand their visual cues, priorities and aspects of streets that catch their attention at first sight. After individual reflections, students were asked to make groups and discuss with each other what they had evaluated.



Figure 11. Workshops with SALIS International School (Source: Author)

The second activity, Ps. And Your Street used a reflective letter-writing exercise for the teens to express their feelings and memory-based perceptions of mobility on their journey to school. During this activity, students exchanged letters with the other class and wrote about emotions, feelings, and experiences of their journey from home to school, including what they see, hear and feel on the way, which mode of transport they use, and also

sketched the school journey based on their memory and whatever they remember. This was an important activity because the sketches of students and memory-based reflections helped in understanding what aspects of mobility influence them the most.



Figure 12. Drawings from Workshops with Teens (Source: Author)

The third activity, the Street Evaluation activity, was intended as an outdoor session in which students were given the task to assess their school streets in small groups. This activity began from the school street; students walked to the nearby Aiglhof S-Bahn train station, completed the route and came back. They were given sheets to fill in, in which the task was to observe street quality, assessment, and develop criteria for what makes a street good or bad. The main objective of this activity was to enable students to think critically and evaluate the street as experts.



Figure 13. Outdoor Activity with Teens (Source: Author)

Finally, Design Your Dream Street was a creative co-design activity in which students were assigned to reimagine, draw, and illustrate their ideal school street in groups after finishing the outdoor assessment of their school street. Students reflected on their school street in depth by using the sheets they filled during the outdoor walk, and based on their evaluation, they envisioned their ideal street. All the students worked in groups, and based on discussions and prior evaluation of streets, they came up with unique and interesting ideas for their streets.



Figure 14. Street Envisioning Activity with Teens (Source: Author)

This final activity gave students freedom to decide what they want in their streets and be highly creative with their ideas.



Figure 15. Drawings from Street Envisioning Activity (Source: Author)

Across all the engagement activities done with teens, rich qualitative data was gathered in the form of text reflections, drawings, group notes, filled templates and sketches. Teens expressed their concerns, likes, dislikes, and feelings about streets. This rich qualitative data was then analysed to validate the identified indicators.

4.3 Workshop Findings

The qualitative data gathered from the workshops, i.e., all responses and text reflections, were manually reviewed and transcribed into structured spreadsheets, where recurring words, phrases, and themes were tallied by frequency across all participant responses. These frequency-based groupings were subsequently translated into mobility dimensions and indicators used in the NetAScore4Teens framework. Although instructions and facilitation were conducted in English, students were permitted to record their written answers in German wherever needed.

4.3.1 Interpretation Reliability

To support the reliability of this interpretation, the workshop-facilitating supervisor independently reviewed all scanned participant responses alongside the author. This included responses recorded in German, which were translated and interpreted by the supervisor, as the author does not have proficiency in German; this ensured that non-English responses were accurately incorporated into the thematic analysis. While a formal inter-rater reliability statistic was not calculated, this collaborative review process provided a check on the consistency and accuracy of the thematic interpretation.

Group	What values would you like to promote in your street?	Define a Vision for your Street	What do you want in your street?							
			I can move around in a different ways	Walk and take a bus when I get tired	I cna cycle with safety and confidence	There is a lot of nature	I can buy food, drinks, and other things	There are places to rest and hangout	I can spend time with friends and family	Spaces to Play
1	Road Safety Rest and contemplation Movement and transport	More trees, fast bususes, free food at SPAR, corssing, places to sit, flowers, decoration		Bus stop Benches Tuktuk	Street lights Way finding and signage Trash Bins	Trees	Seatings Benches Foodshops	People	Street Decoration Music Painting Games	Kids Play areas
2	Health and well-being Movement and transport Road Safety	Safe, pedestrians should have more space to walk, big bike lanes, speed limit in schoool zone, trash cans , designated smoing cans to stop pollution,lots of buses	Cycles Carts Scooters Bicycle Bike parking Escooters	Bus stop	Street lights Way finding and signage Bike parking Traffic Signals	Trees	Foodshops	Play areas	Street Decoration Music Painting	Kids Play areas
3	Road Safety Nature and Sustainability Health and well-being	clean, parks, safe, benches, musicians, tuktuks, boosted train times, trash cans, sittings	tuktuk	Bus stop Tuktuk	Bike parking Traffic Signals Trash Bins	Trees	Seatings Foodshops	People Kids	Street Decoration Music	People Kids Play areas
4	Road Safety Accessibility and inclusion Nature and Sustainability	Saparate bike lanes, more nature, trashcan, cleaner, colorful, saparate route to go to spar	Cycles	Bus stop	Trash Bins	Trees	Fountain	Kids People	Games	Play areas
5	Road Safety Family Interaction Arts and culture	Family activities, nature, green, pink street, cukturral street, parents and kids, musical festivals	Escooters	Bus stop	Bike parking Way finding and signage Street lights Trash Bins Traffic Signals	Trees	Benches Seatings	People Kids	Games Music	Play areas
6	Road Safety Nature and Sustainability Health and well-being	Spaces for bikers, spped bumps to slow down cars, and pink street	Carts Cycles Scooters Escooters Bicycle tuktuk	Bus stop	Street lights Way finding and signage	Trees	Benches Seatings	People Kids Friends	Games Music	Friends Play areas Kids
7	Family Interaction Movement and transport Nature and Sustainability	bike lanes for little kids, music, clean, nature, benches, few traffic, colorful, safe, street lights, no smoking, decorations, waterfalls, streetlights, parking spaces	Cycles Scooters Escooters Bicycle	Bus stop	Seatings Bike parking Trash Bins Street lights Way finding and signage Traffic Signals	Trees	Foodshops Seatings Benches	Friends People Kids	Games Painting Music Street Decoration	Friends Kids Play areas
8	Road Safety Family Interaction Physical Activity	Asphat, clean, watefalls, places to hang around, kids friendly	Carts Scooters Escooters Bicycle	Bus stop Benches Tuktuk	Way finding and signage Seatings Trash Bins Street lights Traffic Signals	Trees	Foodshops Seatings Benches	Friends People Kids	Games Painting Music Street Decoration	Friends Kids Play areas
9	Road Safety Nature and Sustainability Socializing	Clean, Easy to bike and walk, colorful, seasonal decorations, shades (for rain), safe, comfortable, have benches	Scooters Escooters Bicycle Bike parking	Benches Bus stop	Street lights Trash Bins Way finding and signage Traffic Signals	Trees	Seatings Benches Foodshops	Friends People Kids	Games Painting Music Street Decoration	Friends Kids Play areas

Figure 16. Qualitative Data Grouping

Groups	How does the street feel at first sight	I see	I hear	On my street, I feel	We love that	We hate that	Criteria	
							The street is	Becuase
1	Boring Noisy Easy to walk/bike	Benches Trash Bins Traffic Signals Way finding and signage Bus stop Crossing Foodshops People Bike parking Street lights Nature	People talking Traffic Noise Bus arriving/departing Honking	I feel okay with the noise levels I feel okay with the noise levels I feel okay with the noise levels	There is Spar There is Bus There is Sbahn	Homeless people Here is noise	Noisy Boring Good	There are alot of cars There is nothing interesting There is SPAR
2	Comfortable Boring Easy to walk/bike Noisy	Benches Trash Bins Traffic Signals Way finding and signage Bus stop Foodshops People Bike parking Street lights Nature Seatings Car parking Crossing Kids Play areas Train Motorcycle Cars	People talking Traffic Noise Bus arriving/departing Honking Music Footsteps	I feel okay with the noise levels I feel okay with the noise levels I feel stressed and uncomforta I feel okay with the noise levels	Cars Tramstations Train	Noisy Dirty	Cool Supercool boring bad	There are cool cars of motorcycles It is not that beautiful It is dirty
3	Boring Noisy Easy to walk/bike Interesting	Benches Trash Bins Traffic Signals Way finding and signage Bus stop Crossing Foodshops People Bike parking Street lights Nature Seatings Car parking Street Decoration Kids Animals Birds	People talking Birds Chips Traffic Noise Footsteps Bus arriving/departing Honking Music	I feel relax and comfortable wit... I feel okay with the noise levels I feel okay with the noise levels	Spar nearby Bus stops Wide sidewalks Trainstation	Dirty	Dirty Noisy Unsafe Unsafe	of people of cars less crosswalks Irresponsible drivers
4	Boring Noisy Difficult to walk/bike	Benches Trash Bins Traffic Signals Bus stop People Street lights Nature Car parking Crossing Kids	Honking People talking Bus arriving/departing Footsteps Traffic Noise	I feel stressed and uncomforta I feel stressed and uncomforta I feel stressed and uncomforta	peaceful transitstop Cigarettes		Good Dirty Hostile Dangerous	Big traffic is on the street Many people are litterring It is only grey Fast bike on the pavement
5	Boring Noisy Uncomfortable Easy to walk/bike	Benches Trash Bins Traffic Signals Way finding and signage Bus stop Crossing Foodshops People Bike parking Street lights Nature Leaves	Bus arriving/departing Traffic Noise	I feel okay with the noise levels I feel okay with the noise levels	greenery of grass not too many people walking by	It is loud	Noisy Dirty Ugly Cold	Many cars drive by Leaves on the floor Everything is grey It is 5 degrees
6	Noisy Easy to walk/bike Wow Comfortable	Benches Trash Bins Way finding and signage Foodshops Nature Bus stop People Crossing Traffic Signals Trees Street lights Street Decoration Car parking Kids Birds Animals	Bus arriving/departing Traffic Noise Footsteps People talking Train	I feel okay with the noise levels I feel okay with the noise levels I feel okay with the noise levels	Nothing	Noisy Many cars	Loud safe Unsafe Ugly	Cars Crossing alot of cars it is boring
7	Uncomfortable Boring Difficult to walk/bike	Benches Trash Bins Traffic Signals Way finding and signage Bus stop Crossing Foodshops People Bike parking Street lights Nature Train Tractor	Bus arriving/departing Footsteps People talking Traffic Noise Train Tractor	I feel stressed and uncomforta I feel stressed and uncomforta	Crosswalks Sbahn SPAR Squirrels Trees	cigarretes loud homeless people dirty pigeons	Safe Noisy and loud cool super boring	there are Traffic lights there are many vehicles of spar there are many bus stop there are no shops and little people

Figure 17. Qualitative Data Grouping

The analysis and interpretation of textual data from the first activity revealed that teens easily spotted the usual street elements, crossings, cars, people, trees, benches, lighting, and bike lanes. They clearly noticed when streets felt safer or less car-dominated. However, colourful, greener and vibrant streets particularly grabbed their attention. Additionally, car-dominant streets in the before images transformed into child-friendly streets were well perceived by the teens.



Figure 18. Word Cloud from workshop data

Based on the street aspects repeatedly mentioned by the students when performing the activity, analysis revealed that colours, playful elements, crosswalks, greenery and people on the streets were the top 5 features that were noticed by students.

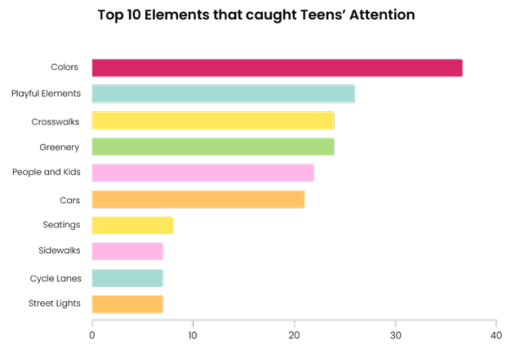


Figure 19. Elements that Caught Teens' Attention

Regarding travel mode, 38% of students travelled to school by bus and 20% by train. When asked about their feelings toward this journey, 47.7% of students described their street environment as uninteresting. While some students highlighted safety, happiness, or excitement, most described their daily journey as uneventful and repetitive, highlighting a key insight that the route to school rarely feels engaging or stimulating for them.

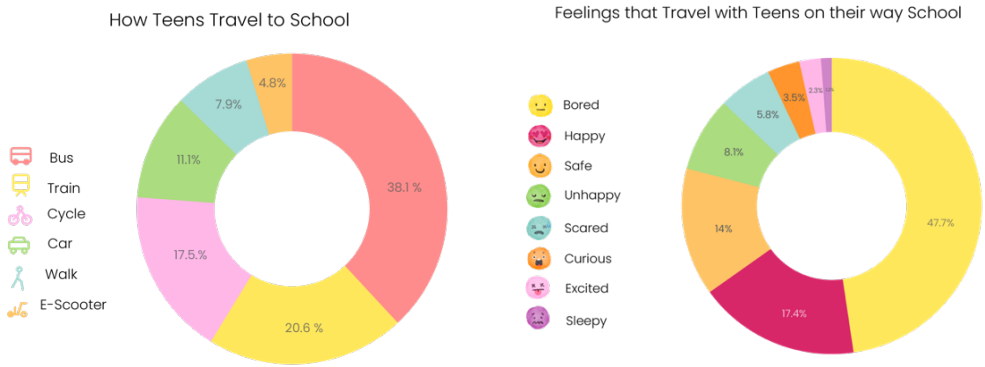


Figure 20. Feelings associated with school journey and travel mode

Another useful insight gathered from workshops was that traffic noise is the dominant soundscape. Many students highlighted honking, engines, and general road noise shaping most of their journeys. A few mentioned hearing people, nature and water. When asked about their feelings about traffic noise, almost 62% expressed neutral feelings, 33.3% expressed feeling uneasy and stressed because of the noise, while 4.3% mentioned feeling relaxed in the street.

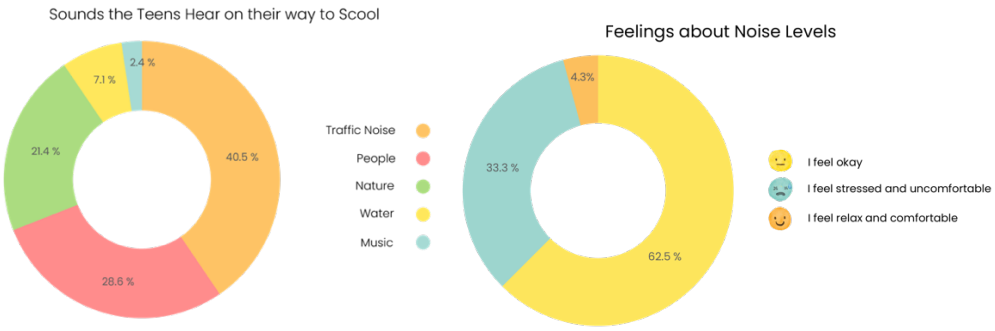


Figure 21. Soundscape during school journey and feelings about noise

The results from the street evaluation activity revealed that students do appreciate the aspects of the street that make their walk convenient, comfortable and safe, such as sidewalks, crossings, small moments of calm or greenery along the way, and the presence of a train station nearby. On the other hand, the unpleasant factors mentioned by them were mostly traffic noise, trash, or not having enough time at crossings. Again, some of them also expressed the street as being boring and monotonous. Another surprising finding from the workshops was frequent mention of SPAR by the students. SPAR is a grocery store present near the school, and it was surprising to see how it emerged as the only point of interest for students, offering them a meaningful destination for social activity, familiarity or pause space. This also aligns with Kyttä's framework of child-friendly cities (Kyttä, 2004) discussed earlier, suggesting that walkability for children is not only influenced by infrastructure but also by affordances – i.e., motivation to walk and access meaningful destinations, of which this workshop finding is great evidence.

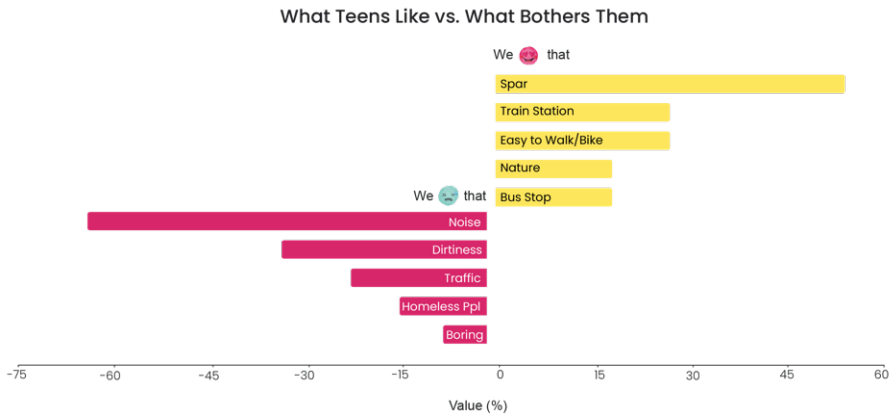


Figure 22. Likes vs Dislikes in School Street

Finally, the findings from the Design Your Dream Street activity revealed the recurring themes and preferences of students for their ideal school-street environments, where the students emphasised colourful, safer, and cleaner streets with elements such as seating, greenery, and opportunities for play. The figure below summarises this activity:

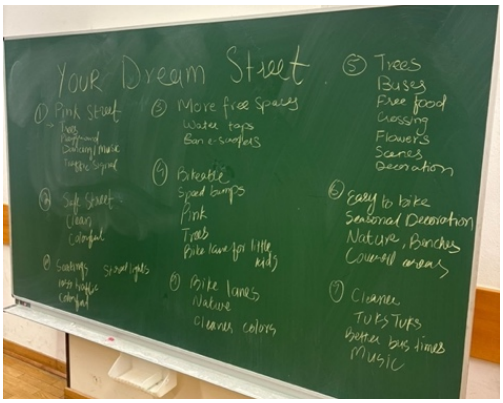


Figure 23. Engagement Workshops with Students (Source: Author)

4.3.1 Teen-informed NetAScore4Teens Model

These workshop findings were extremely useful to inform the model, integrate them so that all the aspects that teens mentioned are well represented, and the model output should represent their actual needs. Students identified colours, greenery, play

opportunities, and social activity as important features, alongside safety. To integrate these insights, the idea is to introduce indicators into the model that can represent their needs and adjust the existing weights. The table below shows how workshop findings were interpreted, leading to the NetAScore4Teens model adaptation.

Table 6. Workshop Findings, Interpretation and Model Adaptation

Workshop Finding	**Workshop Finding**	**Model Adaptation**
Frequent mention of streets to be boring and monotonous. 47.7% of students described their journey to school as boring, often stating there was "nothing happening" or "nothing to see."	Mobility is not only influenced by infrastructure, but also vibrancy and liveability.	Added **play_and_outdoor** indicator.
Students consistently noticed colours, playful elements, greenery, people, and seating before traditional transport infrastructure. Benches, seating, and places to pause appeared in evaluations and Dream Street drawings.	Greenery, nature, comfort features, street furniture can significantly influence mobility experience for children.	Increased weighting of **greenness**; introduced **attractiveness** indicator. (walk and bike)
Students associated positive experiences with nature, friends, music, and visually interesting environments! Dream Street drawings repeatedly included benches, greenery, trees, flowers, places to sit, and spaces to spend time.	Comfort and opportunities to rest are important aspects of child-friendly streets.	Added **Comfort Facilities** indicator.
Places like supermarket (Spar) emerged repeatedly as one of the most liked features of the school street and acted as a meaningful destination and mobility anchor.	Opportunities for play and pause, meaningful destinations, motivation to walk and bike, contribute to positive mobility experiences and offer streets to be inspirational. Meaningful destinations act as social and mobility anchors along daily routes.	Added **Eating Facilities** (walk and bike)
Infrastructure and pedestrian crossings were well perceived as important features linked to street safety by students.	Safe pedestrian infrastructure remains fundamental for children's mobility.	Increased weighting of road category (walk); refined pedestrian infrastructure sub-mappings (sidewalk increased, mixed way and stairs decreased); crossings weight considered for increase, retained at original value following discussion.
Teens noticed common street elements, such as people, tress, cars, crossings, trees, benches, lighting, and bike lanes, during the See-Think-Wonder activity.	Visibility and lighting conditions contribute to teens' perceived safety and awareness of the street environment.	Added lighting indicator (walk and bike).

4.4 NetAScore4Teens Development

The development of NetAScore4Teens followed the original NetAScore workflow, consisting of YAML profiles, import, network, attributes, index, and export steps. While retaining the overall workflow structure, several modifications were introduced to adapt the model for teens. The major modifications were implemented in YAML profiles, where detailed indicator mapping was done, introducing new child-specific indicators and adjusting weights of existing indicators informed by literature findings and participatory workshops. Additional modifications were made in the import, attribute, and index stages to integrate new indicators in the model workflow. The table below provides an overview of the workflow and the modified components during the development of NetAScore4Teens.

Table 7. Model Adaptation

Step	**File**	**Explanation**
YAML Profiles	profile_bike_kids.yml, profile_walk_kids.yml	Introduced new indicators lighting, play_and_outdoor, comfort_facilities, eating_facilities, attractiveness
Import Step	import_step.py	OSM datasets imported into the model, including new datasets for the five child-specific indicators
Attribute Step	attributes_step.py, osm_attribute.sql	Derives attribute tables for all indicators, including new tables for lighting, play_and_outdoor, attractiveness, comfort_facilities, and eating_facilities
Index Step	calculate_index.sql, index_step.py	Computes the weighted-average index using updated weights from the YAML profiles; applies rule-based overrides for child-specific indicators on residential, service, and calmed roads
Export Step	export_step.py	Generates the final GeoPackage output containing edge and node layers with computed walkability and bikeability indices

The detailed modifications introduced in each step are explained in the sections below.

4.4.1 OSM Data Audit

Before integrating the final set of indicators into the model, a thorough review of OpenStreetMap (OSM) data was done thoroughly to check available attributes required to incorporate children's mobility. The review focused on identifying the quality of OSM keys, tags, and types of features that could represent the indicators derived earlier for literature and workshops. The availability of point, line and polygon features was evaluated, which ensured the chosen indicators could be appropriately represented in the model and operationalised using the OpenStreetMap data that was readily available. There were limitations in terms of data availability and completeness for some indicators, while others were consistently mapped and were selected to be used in the model.

4.4.2 Weighting Methodology

The original NetAScore model uses evaluation studies for establishing the weights of bikeability and walkability indicators (Werner et al., 2024a, 2024b), while some of the weights are treated as already validated baseline; the weighting decisions for NetAScore4Teens relied on the following inputs:

1. Scientific literature (Section 4.1.1., Tables 4a and 4b) was used to identify which indicators to retain, introduce, or modify for a child-specific context.
2. The findings from workshops with young adolescents (Section 4.3.1., Table 7) informed the indicators through children's own expressed experiences.

3. An internal NetAScore4Teens workshop with the model's original developers, experts in segment-based mobility modelling at the Mobility Lab Salzburg (Z_GIS, University of Salzburg) (Werner et al., 2024a), to reconcile and finalise each weight based on findings from 1) and 2),

As the adaptive architecture of the model allows a further refinement and adaption of the weights, the weighting decisions were directly informed by children themselves through the participatory workshops, positioning young adolescents as the primary experts on their own mobility experience rather than relying solely on adult professional judgement. This aligns with Kyttä's (2004) affordance-based framework, which emphasises that children's own perception of meaningful, usable environments is central to assessing child-friendly mobility, and directly addresses a gap identified in the literature review: existing walkability and bikeability models are typically informed by adult expert consultation, overlooking children's own expressed priorities (Carrión et al., 2024). These inputs informed which indicators to include and how they should be prioritised. Following initial weight assignment, outputs were iteratively reviewed and refined through rule-based overrides, as described in Section 4.4.5. The final mode profiles, including assigned weights and the reasoning behind each, are summarised in Table 8a and 8b.

Table 8a. Walkability Profile: Weights

Indicator	**Original**	**Adapted**	**Rationale**
Pedestrian infrastructure	0.4	0.4	Weight unchanged; sub-mappings adjusted sidewalk 0.5→0.85, mixed_way 0.85→0.5, stairs 0.7→0.3, to reflect literature on pedestrian-cyclist conflict as a safety concern for young pedestrians (WHO, 2023) and the reduced suitability of stairs for caregivers with young children.
Road category	0.3	0.4	Increased to reflect literature identifying traffic exposure as a primary safety determinant for children's independent mobility (WHO, 2023; GDCI, 2020).
Max speed (greatest)	0.3	0.3	Retained unchanged from the validated original model.
Gradient	0.3	0.3	Retained unchanged from the validated original model.
Greenness	0.3	0.3	Retained; consistent with literature linking green infrastructure to children's activity and wellbeing (Larsen et al., 2009; Lovasi et al., 2011).
Water	0.4	0.4	Retained unchanged from the validated original model.
Noise	0.3	0.3	Retained unchanged; however, underlying data was unavailable across the entire network.
Crossings	0.2	0.2	Retained; safety-critical for children (GDCI, 2020).
Number of lanes	0.1	0.1	Retained unchanged from the validated original model.
Buildings	0.1	0.1	Retained unchanged from the validated original model.
Facilities (generic)	0.3	(disaggregated)	Replaced by four child-specific indicators below, directly informed by workshop findings (Section 4.3).
Lighting	-	0.3	New; directly derived from workshop findings that streets felt unsafe or uninteresting after dark

			(Section 4.3); consistent with NACTO (2013) street lighting guidance for child safety.
Play and outdoor	-	0.2	New; directly derived from workshop finding that the school street felt "boring" (Section 4.3, 6.2); consistent with Krysiak (2023) and Brown et al. (2019) on the role of play spaces in child-friendly streets.
Comfort facilities	-	0.1	New; derived from workshop mentions of benches and rest points (Section 4.3); consistent with GDCI (2020) street furniture guidance.
Attractiveness	-	0.1	New; derived from workshop emphasis on colour and visual interest (Section 4.3); consistent with Carrión et al. (2024) on children's prioritisation of enjoyment alongside functional efficiency.
Eating facilities	-	0.1	New; derived directly from the mobility-anchor finding (Section 4.3, 6.2), where a nearby grocery store was identified by students as the single most meaningful destination on their route.
Sights	NULL	NULL	Not weighted in either walkability model (Tourism version)
Width	NULL	NULL	Existing attribute; unweighted in both models.
Bicycle infrastructure	NULL	NULL	Not applicable to walkability.
Designated route	NULL	NULL	Not applicable to walkability.
Parking	NULL	NULL	Not weighted in either model.
Pavement	NULL	NULL	Not weighted in either model.

Table 8b: Bikeability Profiles: Weights

Indicator	**Original**	**Adapted**	**Rationale**
Road category	0.3	0.3	Retained unchanged; core determinant of cycling safety (Werner et al., 2024a).
Bicycle infrastructure	0.2	0.2	Retained unchanged; forms core of the cycling network (Werner et al., 2024a).
Sights	-	-	Not weighted in either walkability model (Tourism version)
Lighting	-	0.3	New; directly derived from workshop findings on visibility and safety after dark (Section 4.3); consistent with NACTO (2013).
Play and outdoor	-	0.2	New; derived from workshop finding that routes felt "boring" (Section 4.3, 6.2).
Designated route	0.1	0.1	Retained unchanged from the validated original model.
Max speed	0.1	0.1	Retained; key risk factor for cyclists (Werner et al., 2024a).
Pavement	0.1	0.1	Retained; affects cycling comfort and safety, particularly for younger or less experienced cyclists.
Parking	0.1	0.1	Retained unchanged from the validated original model.
Gradient	0.1	0.1	Retained unchanged from the validated original model.

Attractiveness	-	0.1	New; derived from workshop emphasis on colour and visual interest (Section 4.3); consistent with Carrión et al. (2024).
Comfort facilities	-	0.1	New; derived from workshop mentions of benches and rest points (Section 4.3).
Eating facilities	-	0.1	New; derived directly from the mobility-anchor finding (Section 4.3, 6.2).
Pedestrian infrastructure	NULL	NULL	Not applicable to bikeability.
Max speed (greatest)	NULL	NULL	Not applicable to bikeability (walk-specific variant).
Width	NULL	NULL	Existing attribute; unweighted in both models.
Number of lanes	NULL	NULL	Not weighted in either model.
Facilities	NULL	NULL	Not weighted in either model.
Crossings	NULL	NULL	Not weighted in either model.
Buildings	NULL	NULL	Not weighted in either model.
Greenness	NULL	NULL	Unweighted in bikeability for both original model and this adaptation, recommended for future work.
Water	NULL	NULL	Unweighted in bikeability for both original model and this adaptation; recommended for future work.
Noise	NULL	NULL	Not weighted in either model.

4.4.3 Import Step

After mapping the indicators in the YAML profiles, the import step was crucial to include datasets needed for NetAScore4Teens. For this purpose, relevant OSM keys and tags were mapped and extracted for each indicator and new datasets for Play and Outdoor, lighting, Attractiveness, Comfort Facilities, and Eating Facilities were developed. The OpenStreetMap keys and tags used for each indicator are shown in Table 10.

Table 9. OSM Dataset Import

Play_and_ Outdoor	leisure IN ('playground', 'park', 'sports_centre', 'pitch', 'garden', 'track', 'fitness_station'
Attractiveness	'arts_centre', 'artwork', 'cinema', 'theatre', 'music_venue', 'community_centre', 'toy_library', 'public_bath', 'fountain') OR tourism IN ('museum', 'attraction', 'gallery', 'viewpoint','castle','theme_park' , 'zoo')
Comfort_facilities	'drinking_water', 'toilets', 'shelter', 'bench', 'waste_basket', 'water_point', 'watering_place'
Eating Facilities	'cafe', 'restaurant', 'fast_food', 'ice_cream', 'food_court','marketplace', 'vending_machine') OR shop IN ('bakery', 'confectionery', 'pastry', 'beverages', 'supermarket'
Lighting	Yes, no, intermittent

4.4.4 Attribute, Index and Export Steps

Following the import of new datasets, the attribute step was updated to create additional indicator tables for Play and Outdoor, Attractiveness, Comfort Facilities, Eating Facilities, and lighting, following the existing NetAScore attribute derivation procedure. Afterwards, in the index step, newly introduced indicators and updated weights defined in the YAML

profiles were incorporated into the scoring framework while retaining the original weighted-average calculation. Finally, after performing these modifications, the model was run, and output was generated, resulting in a GeoPackage.

4.4.5 Rule-based Overrides

The execution of the model resulted in walkability and bikeability indices, which were then iteratively reviewed and refined, following a similar approach to Stutz et al. (2025). Computed scores were cross-checked against Street View imagery across multiple locations to assess whether they depict the actual conditions of street segments. This iterative check revealed that certain streets receive unfavourably low scores despite exhibiting characteristics generally supporting child-friendly mobility. The reason is that the weighted average may not always adequately capture walkability/bikeability for certain indicator combinations (Stutz et al., 2025). For instance, residential, service, and calmed streets, often suitable for walking and biking, received low scores due to the absence of certain POIs and were highly penalised. To address this situation, rule-based overrides, which are available within the NetAScore framework, were implemented for the following combinations:

Table 10. Overrides Condition

Override Indicator	**Condition**	**Action**	**Rationale**
play_and_outdoor, comfort_facilities, eating_facilities, attractiveness	Residential, Service, and Traffic-Calmed Roads	Weight = 0	Prevent these indicators from disproportionately influencing the score where road category already reflects favourable street conditions.

4.4.6 Plausibility Check

As discussed in section 3.5, NetAScore4Teens builds on the original NetAScore, validated through a large-scale survey study by Stutz et al. (2025 for walkability, while the bikeability component was checked for suitability through expert workshops and surveys (Werner et al., 2024a). Given the time constraint of this study, conducting an equally extensive validation study was not feasible; however, a small sample of road segments was checked for plausibility through Google Street View and satellite imagery. After implementing a stratified sampling approach directly in the model's PostgreSQL database for both walkability and bikeability, 10 road segments (one for each class range: excellent, good, average, moderate, poor) were chosen. Centroid coordinates for each road segment were extracted and used to generate a direct Google Street View link, allowing each segment to be visually cross-checked against its assigned score. A targeted check for 2 additional street segments around SALIS International School located on Zaunergasse was done. It is the area where the outdoor street evaluation activity was done as part of the workshops. The location was directly observed and evaluated by teen participants of the workshop; this comparison offered a valuable opportunity to assess the model's computed scores against children's own first-hand assessment of the same streets.

5 DASHBOARD DESIGN

The results of the NetAScore4Teen are visualised through an interactive dashboard; this section of the report includes the step-by-step process of dashboard design for visualisation and communication of the model's results.

5.1 User Experience (UX) Design Process

The layout of the dashboard was first sketched by hand, and all the UX, including screen layout, panels, interactions, and components, were visualised on paper and in Adobe Illustrator before the code was written. See figure below:

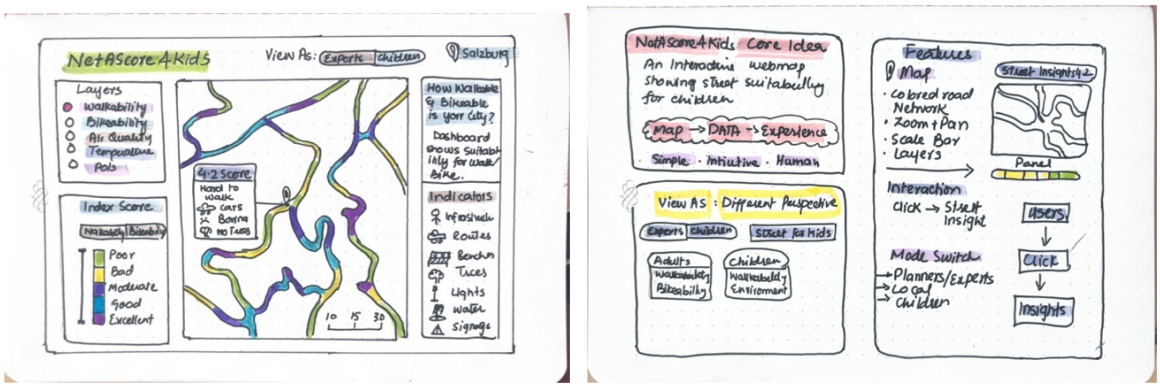


Figure 24. Hand Sketches of Dashboard

After the basic layout was sketched, key questions regarding the users and objectives of the dashboard were defined, as shown in the figure below.

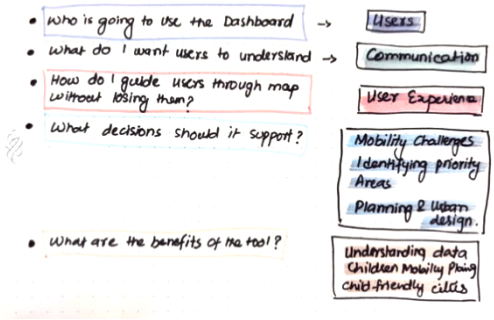


Figure 25. Target Users

Based on these questions, key UX decisions were made for the dashboard, as summarized in Table X below.

Table 11. UX Decisions

UX Decisions	**Reason**
There should be a landing page with Child-Friendly City Scene and Welcoming Text	Developing context before showing data.
The scores should not only be in numbers, but colors, emojis, filters, and charts.	Intuitive interpretation, rather than numbers.
There should be dynamic hoovering over the road segments, statistics should change simultaneously.	Support Exploratory Analysis

There should be two modes/tabs for data interpretation, one more technical and other less technical.	Offering multiple perspective of same data.
List of Indicators along with their definitions.	Giving context of how NetAScore defines indicators. should be there to make user understand how model perceive indicator.
POIs should overlay over Mobility Scores.	Compare scores, relate mobility scores with destinations most relevant to children.
Dark and light Mode	Accessibility
Export feature	For decision makers
Increased thickness of road upon click/pin.	To highlight the selected road segment.
Checklist and Improvement Ideas	Support users (planners, decisionmakers)
Mobility Trend Insights resulting from the data.	Give interactive insights to the results and trends emerging from netAScore
Global Statistics on Children Mobility.	Providing global context to the challenge.

5.2 User Interface (UI) Design

The dashboard interface was structured into 3 components. First is the controls panel (left) that allows for layer selections. It begins with an introduction text, and then there are layer selection tabs, score filter chips, a slider, POI toggles, and a light/dark mode button. The centre of the dashboard is the map display, and includes zoom in-out, maximise, insights tab, score legend, and scale bar. On the extreme right is the indicator panel where the score ring, bar chart, indicator flip cards, experience tab including child-insights, checklist, and improvement section have been added. A footer has been added for accreditation text, organisational logos, and a part of the footer is dedicated to the display of global statistics on children's mobility. The details with images of each one of the components are discussed in the results section. The interface was prototyped in Adobe Illustrator to visualise the overall layout, colour scheme, structure, and typography, before going into technical implementation.



Figure 26. UI Prototype designed in Illustrator

Table 12. Design Decisions

Decisions	Reason
Nunito Font	Friendly and highly readable interface.
Pastel background Scheme with Vibrant Colours	Light basemap with vibrant colours, Supports intuitive interpretation of scores.
Icons	Dashboard has a lot of text, to avoid bland, use of icons.
Road Symbology	It's a simple lines map, colours with diff hues
Layout Structure	Simple, minimal, and easy to use

All these design decisions were intended to mathe ke NetAScore4Teens model into an accessible, intuitive and user-friendly interface for researchers, urban planners, and decision-makers.

5.3 Dashboard Architecture

The dashboard consists of a web app visualising NetAScore4Teens outputs from the model, which is a GeoPackage file containing road geometries, walkability, and bikeability indices. The GeoPackage file was first converted into GeoJSON, then into vector tiles using Tippecanoe, further packaged into PMTiles format hosted directly on GitHub Pages. The dashboard uses these vector tiles, rendered through MapLibre GL JS, which reads the PMTiles files directly from GitHub Pages without requiring a backend server or API key. The front end is developed in HTML, CSS, and JavaScript.

5.3.1 Technical Implementation

This section includes the core technology used in the development of the dashboard, including libraries, platform, and external APIs. The entire dashboard consists of three files:

Table 13. Frontend Developments

index.html	All dashboard structures. Includes HTML elements: panel, buttons, SVG (Intro scene).
styles.css	All dashboard styling. Colours, sizes, layout, animations, dark/like mode, fonts.
script.js	All dashboard behaviours. Charts rendering, indicators definition, map initialization, scores, POIs, export.

5.3.2 MapLibre GL JS

To render the map, an open-source JavaScript Library, MapLibre GL JS has been used. It allows streaming hundreds of thousands of road segment features from a CDN without any backend, rendering the vector tile in the browser using WebGL. For the dashboard, it performs the following specific functions:

- Renders vector tiles (NetAScore Output) containing road segments and walkability and bikeability index.
- Renders Copernicus Urban Atlas Land Use (2021) and Street Tree Layer
- Rendering the basemap (Light/Dark OpenFreeMap styles)
- Colouring of road segments according to walkability and bikeability score.
- Map navigation (zoom in/out, scale, full screen) via map.addControl().

- Handling hover functions, clicks, and loading details with respect to the road segment.
- Score filter uses map.setFilter() to apply a filter on road segments above certain threshold.
- Upon click, highlighting of the road segment is handled by Maplibre.
- Street Trees rendering with a tree icon pattern

5.3.3 Charts.Js

Charts.Js has been used to render the bar chart inside the dashboard that displays indicators contributing to the walkability/bikeability index. It is part of the right panel in the metrics tab. It has been integrated directly via the CDN script tag.

5.3.4 Tabler Icons

To give the dashboard a lively look, Tabler icons have been used, providing the dashboard a modern icon language mixed with plain text. These icons are used in the indicator cards, mode buttons, POI toggles, score filter chips, city insights button inside the map.

5.3.5 POIs Fetch

The dashboard includes Point-of-interest (POI) data for four categories: bus, schools, parks and playgrounds. The data was pre-fetched from the Overpass API for both Salzburg and Olomouc using a standalone script and exported as static GeoJSON files.

5.3.6 PMTiles (JS library)

PMTiles open-source JS library is used to read self-hosted PMTiles files directly from GitHub without requiring a dedicated server. This allows the dashboard to serve vector tilesets of the road network, Land Use, and Street Tree layers) efficiently.

Finally, the table below summarises the technology used for each one of the dashboard components used for visualisation and interpretation of the data.

Table 14. UX Decisions

Component	**Purpose**	**Technology used**
Interactive Map	To visualise the walkability and bikeability scores.	Implemented using MapLibre GL JS with vector tiles self-hosted as PMTiles files on GitHub Pages and rendered in the browser through WebGL.
Score Filters & Slider	Explore segments index by score range	MapLibre GL JS filter expressions dynamically update visible road segments according to user-defined thresholds.
POI Toggles	Relate mobility scores to destinations relevant to children	POI data is loaded by defaulted; pre-fetched from the Overpass API and stored as static files.
Bar Chart (Metrics Tab)	Display indicator contributions to final index	Implemented using Chart.js to generate interactive horizontal bar charts updated upon road selection.
Dynamic Score Ring	Display Walk and bike scores upon hoovering.	SVG/CSS-based ring visualization, updated via JavaScript based on the hovered road segment's score

Dark-Light Mode	Improve accessibility	CSS theme switching combined with dynamic basemap style changes
Indicator Cards	Provide indicator values and explanations	Dynamic HTML, CSS, and JavaScript components displaying normalized indicator scores and definitions.
Experience Tab	Translate technical scores into accessible insights	JavaScript-based logic generating child-friendly interpretations, checklist assessments, and improvement suggestions.
Export Feature	Support reporting and decision-making	Browser-based export functionality generating cartographic map outputs including legends and metadata.
Environmental Layers	Contextual Information alongside mobility indices.	Copernicus Urban Atlas, Land Use and STL data, packaged as PMTiles rendered through MapLibre GL JS

5.3.7 Colour Scheme

The colour scale of the layers was chosen to be spectral, making each classification range distinguishable.

Table 15. Colour Scheme

Range	Hex	Label	Indicator Pannel
0-0.2	#E24B4A	Poor	This street is not teen friendly
0.2-0.4	#EF9F27	Average	This street needs improvement
0.4-0.6	#F5C518	Moderate	This street is fair for teens
0.6-0.8	#97C459	Good	This street is teen friendly
0.8-1	#378ADD	Excellent	A great street for teens

5.3.8 GitHub Hosting

The dashboard is hosted via GitHub Pages without any backend server. PMTiles comprising road network, POIs and environmental layers are also hosted on GitHub, and all files, including HTML, CSS, and JavaScript, are stored in a single GitHub repository.

5.4 User Testing Experiment

This section represents the results from user-testing of the dashboard's usability and functionality done with 10 participants as discussed in section 3.8. The recruitment of participants was done from the author's professional and academic network, comprising colleagues and researchers, two of whom had a background in urban planning and the remainder in GIS research. Participants explored the dashboard on desktop devices, using their own web browsers, and were guided through a series of questions covering the dashboard's key components. Responses were recorded through handwritten notes taken during each session. Of the 10 participants, 7 explored the Salzburg dashboard view, while 3 additionally explored the Olomouc case study view. A qualitative feedback was obtained that formed primary basis for refinement of the dashabord. The think-aloud protocol was followed by the participants during which they verbalize their thoughts, gave

suggestions, and identified navigation challenges while they took part in in individual session.

Throughout each session, observations and participant comments were systematically documented and feedback was structured around ten specific dashboard components against list of UI features in Table 15; the Interactive Map, Score Filters & Slider, POI Toggles, Bar Chart (Metrics Tab), Dynamic Score Ring, Dark/Light Mode, Indicator Cards, Experience Tab, Export Feature, and Environmental Layers. Participants were asked targeted questions relating to each component to capture specific, actionable feedback rather than general impressions alone. Following sample questions were organised:

- Interactive Map: "Was it clear what the colours/scores on the map represent?
- Score Filters & Slider: "How clear are the filter segments by score range? Did the slider moved smoothly?"
- POI Toggles: "Did you identify POI icons? Was it clear what each POI toggle would show or hide? Did you understand what the icons represented?"
- Bar Chart (Metrics Tab): "Was the bar chart easy to interpret? Did it help you understand the overall distribution of scores?"
- Dynamic Score Ring: "Was it clear what the score ring was showing, and how it updated as you interacted with the map?"
- Dark/Light Mode: "Did you notice the mode toggle? Did switching modes affect your ability to read the dashboard?"
- Indicator Cards: "Was the information in the indicator cards clear and useful? Was anything confusing or missing?"
- Experience Tab: "Did this tab give you a clear sense of how the model incorporates children's perspectives?"
- Export Feature: "Was it clear how to export data? Did the exported output match what you expected?"
- Environmental Layers: "Were the environmental layers (e.g., greenery, water) easy to toggle and interpret alongside the main score?"

6 RESULTS

This section discusses the results in two parts. The first part includes the results from the NetAScore4Teens Model for Salzburg, including score distributions, a brief comparison with the original NetAScore, indicator-level contributions, plausibility check, findings, and transferability of the model to Olomouc. The second part discusses the results of the interactive dashboard, including user testing outcomes.

6.1 Model Output

The NetAScore4Teens model was implemented for the broader Salzburg area via the Overpass API, with results clipped to the administrative boundary of the City of Salzburg for analysis that generated a total of 45,853 street segments. The original (adult) version in for the city of Salzburg generated 40,100 segments. The model was executed for the case study of Olomouc, Czechia as well, generating a total of 57,881 road segments as shown in the table below.

Table 16. Segment counts by model and study area

Dataset	Total Segments	Scored (Walk)	Scored (Bike)
NetAScore4Teens (Salzburg)	45,853	41,045	27,151
NetAScore4Teens (Olomouc)	57,881	51,024	25,716
NetAScore Adult (Salzburg)	40,100	34,401	23,984

6.1.1 NetAScore4Teens: Salzburg

The execution of NetAScore4Teens for Salzburg generated a total of 45,853 street segments with a total length of 1,551.4 km, comprising of 22,569 (49.2%) street segments having pedestrian infrastructure and 5380 (11.7) with bicycle infrastructure.

Table 17. Segments counts by model and study area

Metric	Value
Total segments	45,853
Total network length	1,551.4 km
Segments with pedestrian infrastructure	22,569 (49.2%)
Segments with bicycle infrastructure	5380 (11.7)

Within the Salzburg network, car-free (no_mit) 40.5% of the segment count and 517.01 of segment length, forming the largest share of the network. Service and residential streets account for nearly half of the segments together. Primary (high-traffic) and secondary roads show a small proportion of the network (2.3% and 1.2% of segments, respectively).

Table 18. Street Network Composition by Road Category

Road Category	Segments	Length (km)	% of Segments
no_mit (car-free)	18,545	517.01	40.5%
Service	11,518	363.68	25.1%
Residential	10,831	398.65	23.6%
Track	3,169	180.26	6.9%
Primary	1,040	56.45	2.3%

Secondary	538	27.05	1.2%
Calmed	203	7.60	0.4%

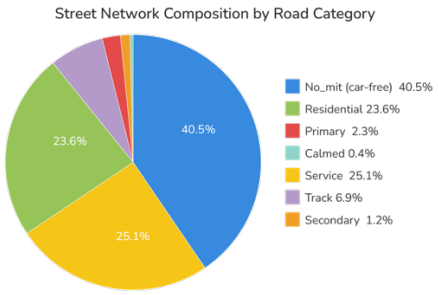


Figure 27. Street Network Composition by Road Category

6.1.2 Score Distributions

The model results from NetAScore4Teens revealed that most of the road segments for walkability concentrated in the moderate range (70.0%), with Good (18.6%), Average (9.0%), Poor (1.3%), and Excellent (1.1%), giving a mean score of 0.516. Bikeability scores split between Average (47.2%) and Moderate (43.1%), on the other hand, with Good (8.2%), Poor (0.9%), and Excellent (0.6%), giving a notably lower mean of 0.434. The table below summarises the distribution of road segments for walkability indices across 5 classes.

Table 19. Street Network Composition by Road Category

Category	**Walk**		**Bike**	
	Segments	**Percentage**	**Segments**	**Percentage**
Poor (0.0–0.2)	525	1.3%	231	0.9%
Average (0.2–0.4)	3,676	9.0%	12,821	47.2%
Moderate (0.4–0.6)	28,718	70.0%	11,709	43.1%
Good (0.6–0.8)	7,654	18.6%	2,218	8.2%
Excellent (0.8–1.0)	472	1.1%	172	0.6%
Mean		**0.516**		**0.434**

The bar charts below show score distribution walkability and bikeability:

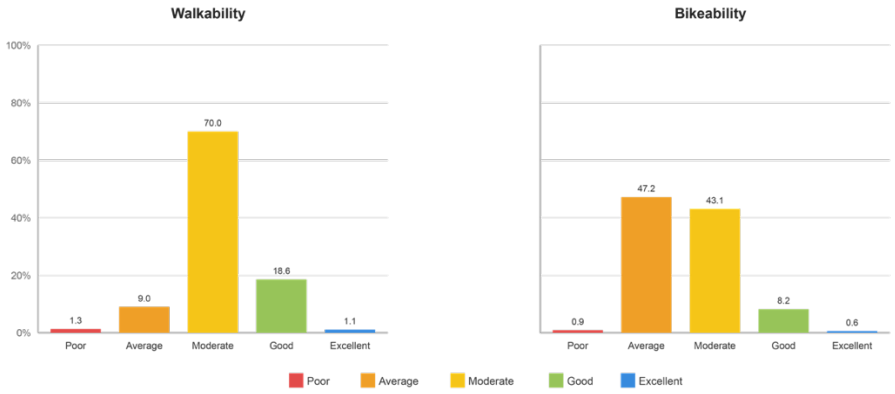


Figure 28. Score Distribution

6.1.3 Indictors Contribution

The indicator contributions to the final score were examined to see the influence of each indicator across the full dataset. Road category and lighting indicators appear most consistent indicators influencing the final score for both modes. Indicators such as comfort facilities, play and outdoor, attractiveness, and eating facilities on average contributed least for both modes, accurately representing the low weights combined with rule-based overrides that set their weight to zero on residential, service, and calmed roads (Table 9), which together account for nearly half of all segments. The most heavily weighted indicators, i.e., pedestrian infrastructure and bicycle infrastructure, contributed relatively little to the average score, where 49.2% of segments recorded any pedestrian infrastructure and roughly 11.7% recorded dedicated bicycle infrastructure.

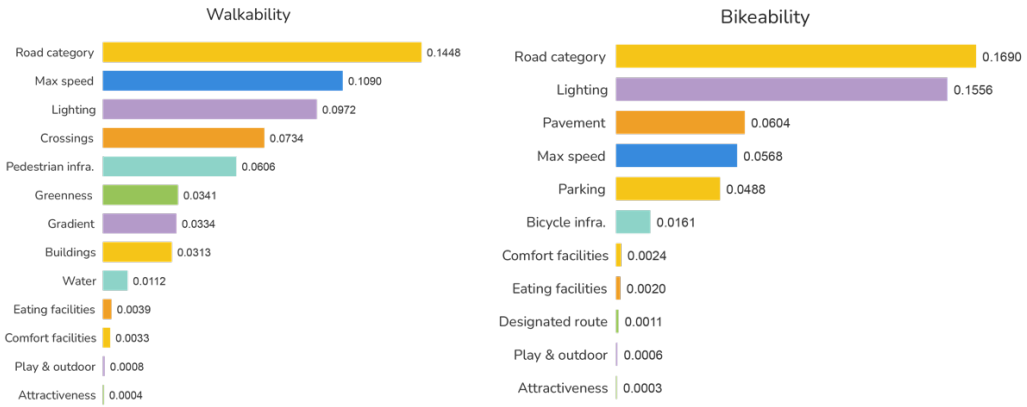


Figure 29. Score Distribution

Presence Child-Specific Indicators

To understand the scoring impact of newly added indicators for the children-context, the individual impact of lighting, play_and_outdoor, attractiveness, eating_facilities, and comfort_facilities was specifically examined. The indicators were found on a small share of segments across the network: lighting on 16,821 segments (36.7%). Play and outdoor on 663 segments (1.4%), eating facilities on 7,773 segments (17.0%), comfort facilities on 5,907 segments (12.9%), and attractiveness on 1,438 (3.1%).

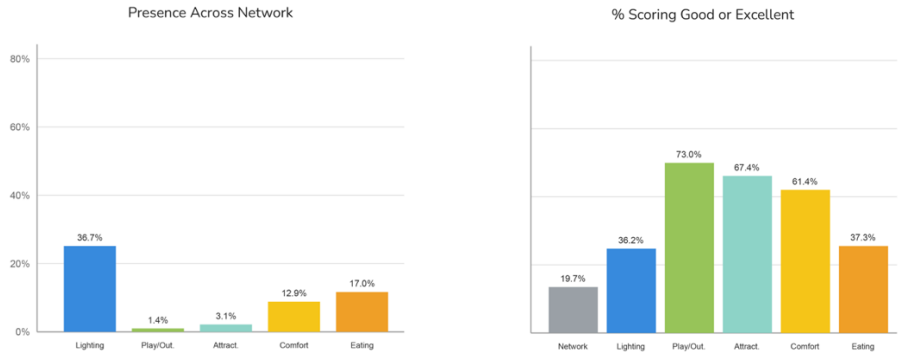


Figure 30. Presence of Child-Specific Indicators

The segments where these features are present scored higher on average than segments without them. See Table .21. Segments with play and outdoor scored Good (0.6-0.8) or Excellent (0.8-1): 73.0%, attractiveness, 67.4%, comfort facilities, 61.4%, for eating facilities, 37.3%, and lighting, 36.2%), all far above the network average of 19.7%.

Table 20. Child-Specific Indicators Distribution across Road Categories

Category	Network Overall	Lighting	Play and Outdoor	Attractiveness	Comfort Facilities	Eating Facilities
Poor (0-0.2)	1.3%	2.3%	0.5%	0.8%	0.8%	1.9%
Average (0.2-0.4)	9.0%	4.1%	2.7%	1.9%	2.3%	5.3%
Moderate (0.4-0.6)	70.0%	57.3%	23.8%	29.9%	35.5%	55.5%
Good (0.6-0.8)	18.6%	29.1%	49.5%	42.4%	42.0%	28.4%
Excellent (0.8-1)	1.1%	7.1%	23.5%	25.0%	19.4%	8.9%
% Good + Excellent (0.6-1)	19.7%	36.2%	73.0%	67.4%	61.4%	37.3%

6.1.4 Spatial Distribution

The spatial distribution of the NetAScore4Teens for walkability reveals a uniform spread of low-scoring 0-0.2 (red) segments on primary roads. The Salzach river corridor and car-free (no_mit) segments reflect favourable walkability conditions and score consistently well, 0.6-1 (blue/green). The inner-city centre is generally walkable overall, though the frequent absence of greenery and water features prevents these central segments from reaching the highest score category, despite otherwise favourable pedestrian infrastructure and low traffic exposure. Residential neighbourhoods show a mixed trend, falling into an average (0.2-0.4) to moderate (0.4-0.6) pattern. Spatial distribution of Bikeability scores reveals good scoring segments (0.6-1) to be present alongside the Salzach River corridor, some arterial roads and highway-adjacent corridors, while some of them spread across residential neighbourhoods, where a majority of them show a mix of average (0.2-0.4) to moderate (0.6-0.8)



Figure 31. Salzburg Walkability and Bikeability

6.1.5 Plausibility Check

A total of 12 street segments were examined across walkability and bikeability for plausibility check (5 walkability, 5 bikeability, 2 workshop study area), cross-checked against Google Street View imagery and their indicator-level explanations, with each segment classified as showing full agreement (all visible features matching their corresponding indicator values), partial agreement (a plausible score with one or more values diverging from expectations for that road category), or discrepancy (a visibly present feature absent from its corresponding indicator value). Across these segments,

computed scores were generally consistent with observed street conditions: low-scoring segments corresponded to road category, speed, and infrastructure quality, while high-scoring segments showed strong alignment with visible greenery, water, and dedicated infrastructure. Of the 12 segments, 7 (58.3%) showed full agreement, 2 (16.7%) showed partial agreement, and 3 (25%) revealed discrepancies related to pedestrian_infrastructure recording zero contribution despite a visibly present sidewalk (two segments), and one segment showing a visibly present mixed-use pedestrian/cycling path entirely untagged for both modes. Overall, this plausibility check does not indicate any flaw in the computation or scoring logic itself; rather, it suggests that NetAScore4Teens, despite the addition of new indicators, behaves consistently with the original NetAScore model (Werner et al., 2024a; Stutz et al., 2025), which has itself been independently validated. This constitutes an exploratory credibility check rather than a comprehensive validation, given the small sample size relative to the full network; the results support the plausibility of this study's computed scores while highlighting OSM data completeness as a recurring limitation. For future reproducibility, a more detailed validation on a larger sample is recommended, which was beyond the scope of this thesis. See the results in Tables 21a and 21b.

Table 21a. Walkability Segments for Plausibility Check

Category	Location & ID	Road Category	Key Contributing Indicators	Google Street View Observation	Street View	Level of Agreement
Poor (0.20)	17 Linzer Bundesstraße 611147990001)	primary	lighting 0.10, buildings 0.02, max_speed 0.06; road_category, greenness, pedestrian_infra = 0	The street functions as a busy highway with poor-quality pedestrian provision, consistent with its low score; no dedicated sidewalk infrastructure is captured by the model at this location, however, i tis visilbe in google street viw.	 Open Street View	Discrepancy.
Average (0.34)	Salzburger Str. 677403790001	primary	greenness 0.08, lighting 0.10, max_speed 0.06; pedestrian_infra, road_category = 0	A primary road with no visible dedicated pedestrian infrastructure; the segment's modest greenery contribution is consistent with vegetation visible in the street view image.	 Open Street View	Matches expectations
Moderate (0.54)	Lessingstraße 14228528610001	no_mit	pedestrian_infra 0.15, max_speed 0.12, road_category 0.15; greenness = 0	A visible sidewalk is present, matching the model's pedestrian infrastructure contribution. Although classified as no_mit, a category that typically yields higher scores ,the complete absence of greenery here moderates the overall score, reflecting exactly how the model is designed to compute such combinations.	 Open Street View	Partial Agreement.

Category	Location & ID	Road Category	Key Contributing Indicators	Google Street View Observation	Street View	Level of Agreement
Good(0.71)	Alois-Stockinger-Straße 270862790001	residential	road_category 0.13, lighting 0.13, max_speed 0.11, pedestrian_infra 0.14, greenness 0.09	A residential street where road category, street lighting, and roadside greenery are all clearly visible in the image, consistent with their positive contributions to the score.	 Open Street View	Matches expectations
Excellent (0.84)	Derra-de-Moroda-Straße 1189286720002	no_mit	pedestrian_infra 0.15, road_category 0.15, water 0.15, max_speed 0.12, greenness 0.08, play_and_outdoor 0.08	Greenery is clearly visible in the image, and the segment's close proximity to Preuschenpark, a green space with a playground, multi-use field, walking paths, benches, basketball court, picnic tables, public toilets, slides, and swings (confirmed via Google reviews) , directly validates the model's play_and_outdoor contribution.	 Open Street View	Matches expectations

Table 21b. Balkability Segments for Plausibility Check

Category	Location & ID	Road Category	Key Contributing Indicators	Google Street View Observation	Street View	Level of Agreement
Poor (0.16)	43 Fanny-von-Lehnert-Straße 1578398790002	secondary	road_category 0.03, pavement 0.06, max_speed 0.05; bicycle_infrastructure = 0	The street view image confirms the complete absence of dedicated cycling infrastructure, consistent with the model's zero contribution for bicycle_infrastructure.	 Open Street View	Matches expectations

Category	Location & ID	Road Category	Key Contributing Indicators	Google Street View Observation	Street View	Level of Agreement
Average (0.37)	9 Ferdinand-Sauter-Straße 311706340004	residential	road_category 0.18, pavement 0.08, max_speed 0.06; bicycle_infrastructure = 0	The residential character of this street makes it inherently calm and safe for cycling, well captured by its road_category contribution; however, the lack of any dedicated cycling provision limits the overall score.	Open Street View 	Matches expectations
Moderate (0.48)	3 Moosstraße 966375500003	residential	road_category 0.15, max_speed 0.06, lighting 0.19, pavement 0.06; bicycle_infrastructure = 0	The street view image reveals a mixed-use pedestrian/cycling path (indicated by a visible bicycle sign on the sidewalk), yet neither pedestrian_infrastructure nor bicycle_infrastructure records this feature in OSM for this segment both tagged as "no."	Open Street View 	Discrepancy – Data Limitation
Good (0.67)	Salzach River 1306276620003	residential	road_category 0.15, lighting 0.19, bicycle_infrastructure 0.13	Street view does not confirm dedicated bike infrastructure however, this stretch alongisde Salzach generally has bike infrastructure.	Open Street View 	Partial agreement, bicycle infrastructure contribution plausible but not directly confirmed via Street View
Excellent (0.80)	27 Giselakai 557053560003	no_mit (car-free)	road_category 0.14, lighting 0.14, bicycle_infrastructure 0.10, comfort_facilities 0.05	Dedicated cycling infrastructure is clearly visible in the image; the segment's location along the scenic Salzach corridor further supports its strong contribution.	Open Street View 	Matches expectations

Plausibility Check of Road Segments: Workshops Study Area

The two segments at the workshop study area Zaunergasse (0.38 and 0.54 index) were examined to check alignment with students' own qualitative evaluation of this street during the outdoor Street Evaluation activity. Students consistently described the school street as "boring" or "nothing interesting" yet not empty: functional elements such as crossings and buildings were present, but the street lacked anything visually engaging or "fun." This somewhat reflects this in its indicator breakdown showing contributions from road_category, crossings, and buildings, which confirms the presence of basic functional infrastructure; however, play_and_outdoor and attractiveness registered zero contribution at both locations, mirroring students' repeated observation that the street, despite having "the right components," felt visually and experientially uninspiring. A discrepancy was also observed, as the model shows recorded zero contribution from pedestrian_infrastructure for one road segment (1722591350002), however, a visibly separate sidewalk can be spotted sidewalk confirmed via Street View. This is most likely an OSM tagging gap rather than the model's ability to capture genuine walkability, since the segment's favourable road_category classification (residential) already compensates for this in the weighted average.

Table 22. Plausibility Check of Road Segments outside Workshops Study Area

Edge ID	Score	Road Cat.	Key Contributing Indicators	Google Street View Observation	View	Level of Agreement
Zaunergasse 1722591350002	0.381 (Walk) 0.346 (Bike)	residential	pWalk: road_category 0.152, crossings 0.095, max_speed 0.086, buildings 0.048; pedestrian_infrastructure = 0. Bike: road_category 0.185, pavement 0.077, max_speed 0.046, parking 0.038; bicycle_infrastructure = 0	A physically separated sidewalk is visible in the street view image; however, pedestrian_infrastructure records zero contribution, indicating a discrepancy between the visible infrastructure and model result.	 Street View	Discripency
Zaunergasse 14252248160002	0.546 (Walk) 0 (Bike)	no_mit	pedestrian_infrastructure 0.131, road_category 0.154, max_speed 0.115, crossings 0.077, eating_facilities 0.038, buildings 0.031	Pedestrian infrastructure and eating facilities are both confirmed in the image, consistent with the model's	 Street View	Matches expectations

Edge ID	Score	Road Cat.	Key Contributing Indicators	Google Street View Observation	View	Level of Agreement
				respective positive contributions.		

A convergence worth noticing is that students repeatedly and unprompted identified this small supermarket as the single most memorable, "exciting" feature of their daily route a rare point of destination, social visibility, and pause along an otherwise monotonous street. The model independently captured this same feature: the segment nearest SPAR (14252248160002) shows a measurable contribution from eating_facilities (0.038), the only segment in this immediate area to register any value for this indicator. This convergence between an entirely qualitative, student-generated finding and an independently computed, quantitative model output demonstrates that the model, without any knowledge of the students' own testimony, identified the same specific location that students themselves singled out as meaningful.

Table. 23. Indicators Matching: Model vs Teens' Observations

Teens' Finding	Model Indicator	Model Value	Match
"Boring," lacks colour/visual interest	Attractiveness = 0 (both segments)	0 (both segments)	✓
SPAR grocery as meaningful destination	eating_facilities	0.038 (14252248160002 only)	✓
Crossings present	crossings,	0.095 (1722591350002) / 0.077 (14252248160002)	✓
Sidewalks	pedestrian_infrastructure	0.131 (14252248160002) / 0 (1722591350002)	Discrepency

6.1.6 Comparison: Original NetAScore (Adult) vs NetAScore4Teens (Salzburg)

This section presents results from a comparison between NetAScore4Teens and the original NetAScore (Adult) version. Figure 32 compares score distributions of the computed NetAScore4Teens with NetAScore (Adult) for both modes.

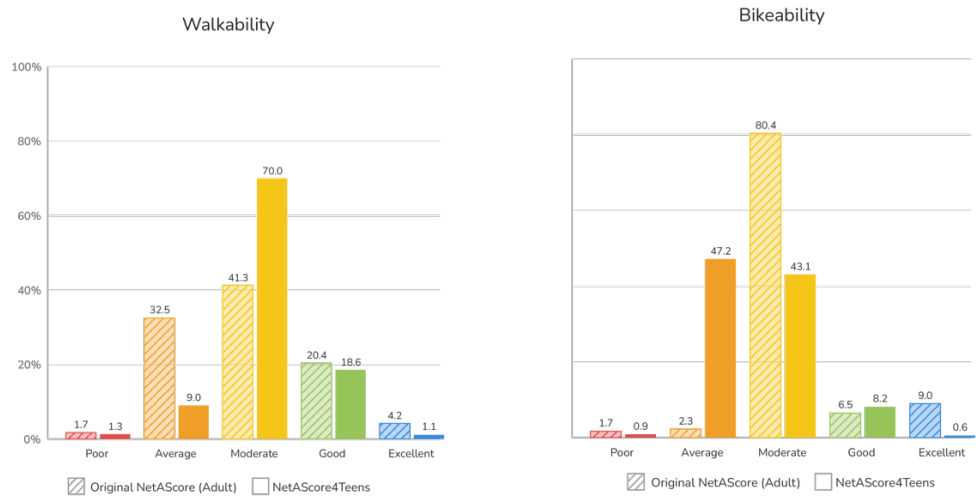


Figure 32. Comparion: NetAScore (Adult) vs NetAScore4Teens

Overall, there is a slight increase in mean score (0.497 to 0.516), and the distribution of the scores shifted. Many segments that scored in the average range in the NetAScore (Adult) shifted upward into the moderate range under NetAScore4Teens; overall, the average shifted from 32.5% to 9.0%, and moderate from 41.3% to 70.0%. The comparison between bikeability scores shows a substantial decrease from 0.545 to 0.434 in the mean, where moderate (0.4–0.6) scoring segments fell from 80.4% to 43.1% while excellent-scoring segments fell from 9.0% to 0.6%. This asymmetry reflects the different ways the model's adaptation affected each mode; a detailed investigation into the precise mechanism and individual indicator contributions, supported by a larger validation sample, is recommended as a direction for future work.

Table 24. Comparison NetAScore (Adult) vs NetAScore4Teens Salzburg

	Walk		**Bike**	
Category	**NetAScore (Adult)**	**NetAScore4Teens**	**NetAScore (Adult)**	**NetAScore4Teens**
Poor (0.0–0.2)	1.7%	1.3%	1.7%	0.9%
Average (0.2–0.4)	32.5%	9.0%	2.3%	47.2%
Moderate (0.4–0.6)	41.3%	70.0%	80.4%	43.1%
Good (0.6–0.8)	20.4%	18.6%	6.5%	8.2%
Excellent (0.8–1.0)	4.2%	1.1%	9.0%	0.6%
Mean	**0.497**	**0.516**	**0.545**	**0.434**

The spatial distribution change across Salzburg for walkability and bikeability can be observed in the figures below:

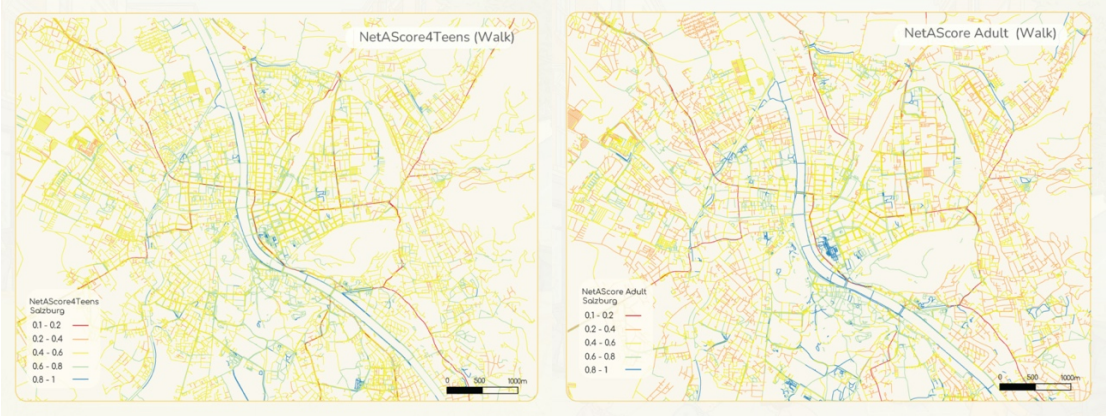


Figure 33. Walkability Comparison



Figure 34. Bikeability Comparison

6.1.7 NetASCore4Teens Olomouc, Czechia

The NetAScore4Teens model was implemented for Olomouc as a second study area to check the transferability of model. For Olomouc, the model generated 57,881 street segments across 1,793.6 km, with pedestrian infrastructure present on 29,279 segments (50.6%), and bicycle infrastructure on 2,552 segments (4.4%).

Table 25. General Metrics

Metric	**Value**
Total segments	57,881
Total network length	1,793.6 km
Mean segment length	31.0 m
Segments with pedestrian infrastructure	29,279 (50.6%)
Segments with bicycle infrastructure	2,552 (4.4%)

The road category with total length (km) is shown in the table below having Car-free (no_mit) roads forming the largest share of the network (50.3%), with service (21.7%) and residential (16.1%) roads.

Table 26. Olomouc Road Category Composition

Road Category	Segments	Length (km)	% of Segments
no_mit (car-free)	29,094	620.54	50.3%
Service	12,583	317.55	21.7%
Residential	9,342	299.62	16.1%
Track	4,678	390.10	8.1%
Secondary	900	57.83	1.6%
Primary	880	94.97	1.5%
Calmed	391	11.52	0.7%

The overall walkability scores were seen mostly in the moderate (0.4-0.6) range. 32.4%% of segments achieved a good (0.6-0.8) score, and 0.4% fell in the range of excellent (0.8-1). Bikeability scores were heavily concentrated in the average category (56.6%), with 5.1% of segments reaching good or excellent combined.

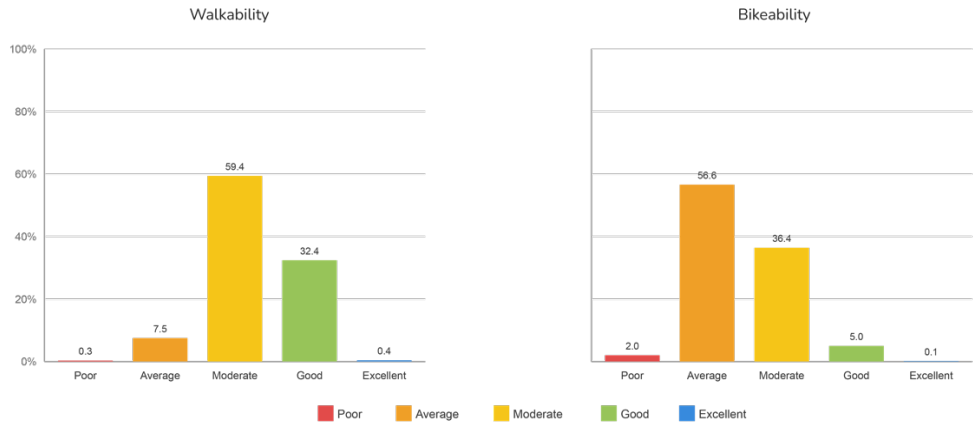


Figure 35. Olomouc Score Distribution

Table 27. Olomouc Score Distribution

Category	Walk Segments	Walk %	Bike Segments	Bike %
Poor (0.0–0.2)	175	0.3%	505	2.0%
Average (0.2–0.4)	3,812	7.5%	14,559	56.6%
Moderate (0.4–0.6)	30,324	59.4%	9,356	36.4%
Good (0.6–0.8)	16,514	32.4%	1,282	5.0%
Excellent (0.8–1.0)	199	0.4%	14	0.1%

The spatial distribution of both walkability and bikeability scores can be seen in the figure below.

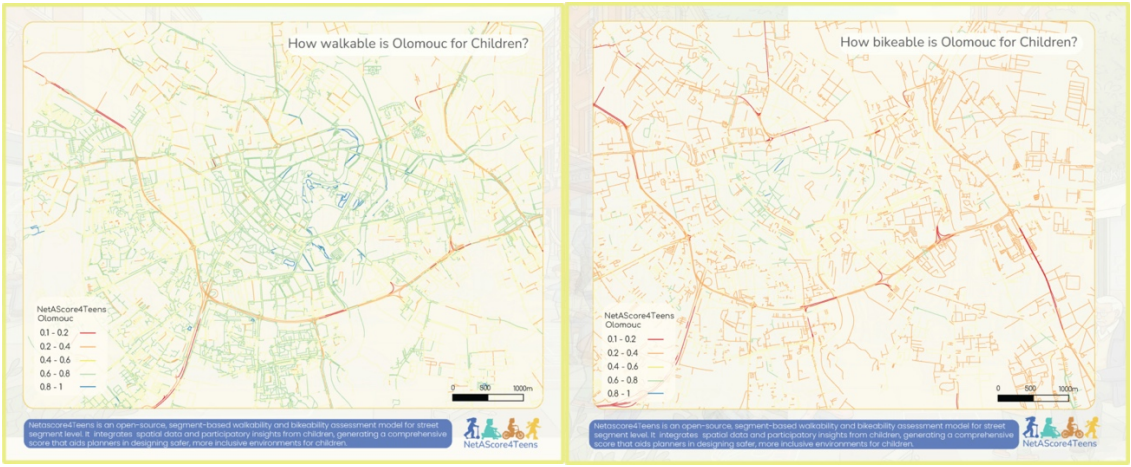


Figure 36. Olomouc: Spatial Distribution of Walkability and Bikeability

6.1.8 Comparison: NetASCore4Teens Salzburg vs Olomouc

Applying NetAScore4Teens to Olomouc demonstrates that the model transfers successfully to a new urban context using the same open-data pipeline. Olomouc's pedestrian infrastructure coverage is broadly similar to Salzburg (50.6% vs. 49.2%) but shows markedly less dedicated bicycle infrastructure (4.4% vs. 11.7%), directly consistent with Olomouc's substantially lower and more narrowly concentrated bikeability scores. Olomouc has a higher proportion of car-free roads than Salzburg (50.3% vs. 40.5%), however walkability scores are lower on average and more concentrated in the moderate range, suggesting that the impact of pedestrian infrastructure quality, greenery, and comfort-related features continues to shape final scores.

Table 28. Comparison: Salzburg vs Olomouc Score Distribution

Category	**Walk**		**Bike**	
	Salzburg	**Olomouc**	**Salzburg**	**Olomouc**
Poor (0.0–0.2)	1.3%	0.3%	0.9%	2.0%
Average (0.2–0.4)	9.0%	7.5%	47.2%	56.6%
Moderate (0.4–0.6)	70.0%	59.4%	43.1%	36.4%
Good (0.6–0.8)	18.6%	32.4%	8.2%	5.0%
Excellent (0.8–1.0)	1.1%	0.4%	0.6%	0.1%

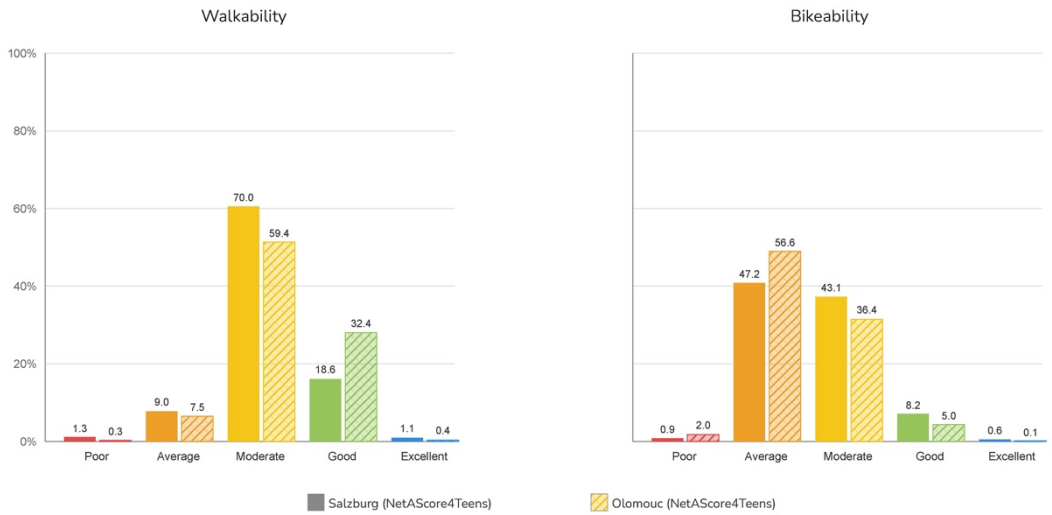


Figure 37. Comparison: Salzburg vs. Olomouc score distribution

6.2 Dashboard Design

A central objective of this study was to explore how effective communication of the NetAScore4Teens' walkability and bikeability indices and underlying indicators could be to a wider audience. This required translating complex, multi-indicator model output into an accessible, interactive format that supports exploration, interpretation, and decision-making by planners, researchers, and other stakeholders. To this end, an interactive geo-visualisation dashboard was developed, allowing users to explore walkability and bikeability scores at the street-segment level alongside supplementary environmental and points-of-interest data. The resulting dataset visualised earlier in QGIS was incorporated into the dashboard for interactive exploration and interpretation. This section discusses results from code implementation.

6.2.1 Landing

The dashboard begins with a landing page, welcoming the users with an introductory text displayed over a child-friendly city animation scene in the background. The purpose is to establish a context before any data is displayed. This scene has been created as a single SVG element in index.html with CSS keyframe animations. Typewritten text with "Small Steps Matter", "Streets for Teens", and "Safer Routes, Happier Teens" has been added. Finally, the "Let's Explore" button enables to access the dashboard interface.

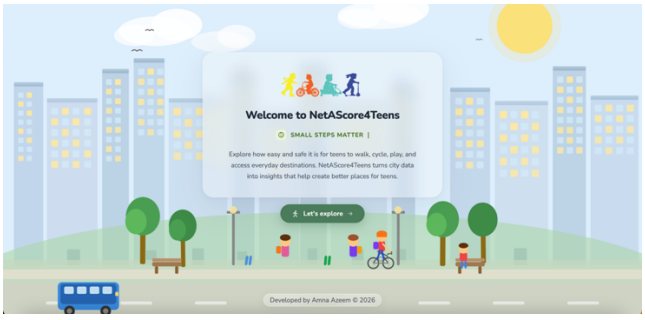


Figure 38. Dashboard Landing Page

6.2.2 Main Interface

Users are landed on the main interface divided into three components: a map display in the centre, a controls panel on the left, and an indicators panel on the right. There is a header which includes a logo and title alongside a subtitle, while the footer has accreditation text, organisational logos and some global children mobility statistics. It offers a dark mode as well as a small icon next to the heading of the introduction text. It allows for better accessibility.

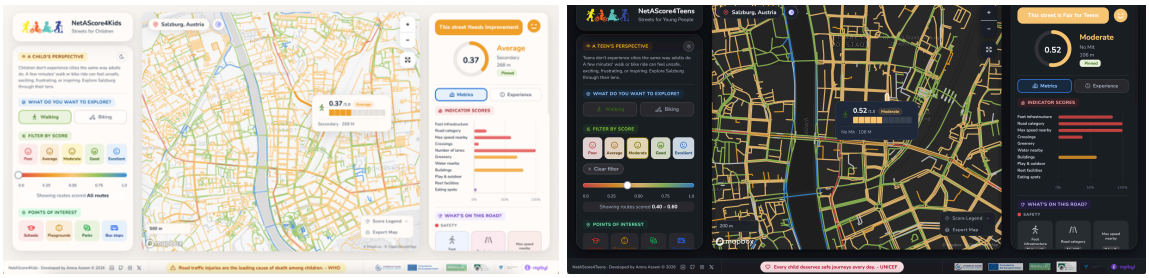


Figure 39. Dashboard Interface

6.2.3 Controls Panel

The control panel on the left begins with an introduction to the dashboard, so that users can understand what they are going to explore before any clicks and hovers. Underneath the text are layer-switching tabs offering users the ability to switch between the data layers. Clicking on the modes, the active MapLibre layer changes, making the walkability layer visible and hiding the bikeability layer, or vice versa, and the same goes with the city layers. The dashboard offers multiple ways to explore the scores in the control panel. First is filtering by face chips with “poor”, “average”, etc. labels on them. When users click on “poor”, only poor road segments are activated, and so on. Below the face chips is a slider that enables the exploration of walkability or bikeability index manually by sliding the pointer to a specific threshold. This activates the relevant routes while also updating the index values displayed under the slider gradient.

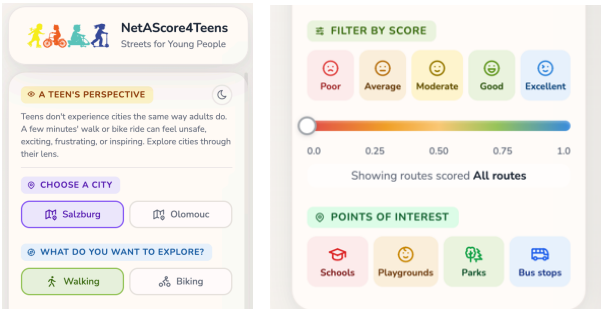


Figure 40. Controls panel (Left)

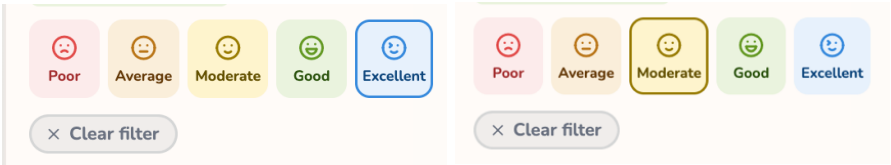


Figure 41. Filter by Face Chips

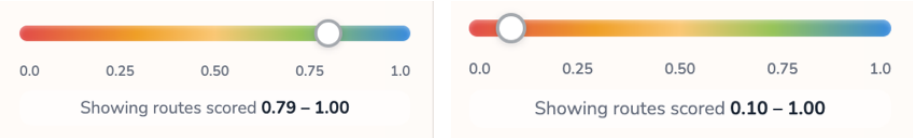


Figure 42. Filter by Slider

The controls also include POI toggles, where multiple POIs can be turned on simultaneously. These POIs are fetched from the Overpass API (OpenStreetMap) and are overlaid on the map. Upon clicking the POI, a pop-up appears with the POI label. The final part of the controls is Copernicus data layers, which provide contextual knowledge to the dashboard through land-use and tree layer data.

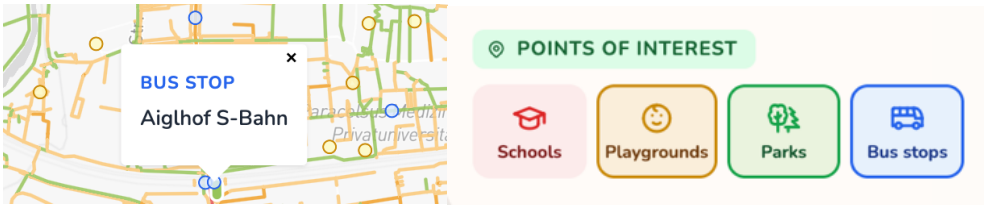


Figure 43. POIs Toggle and Pop Up

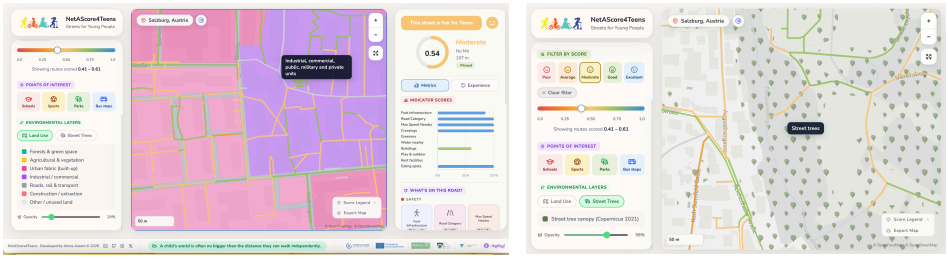


Figure 44. Copernicus Data layers

6.2.4 Map Display

The centre of the map is dedicated to the display of walkability and bikeability scores using the OpenFreeMap basemap. Map display consists of zoom in/out toggles and a maximise toggle (Full Screen) on the top right. Top left is a location tag, whereas on the bottom left, the map scale is available. Upon hover, a popup appears on each road segment, displaying the index score. The map is initialised with MapLibre, and upon activation, layers appear on the basemap.

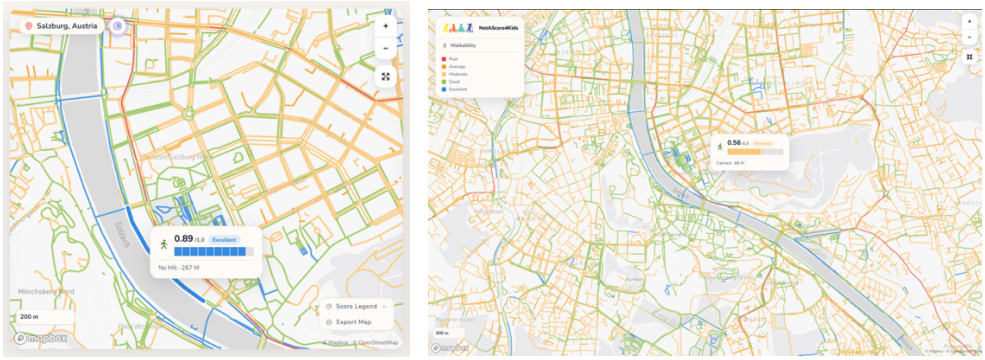


Figure 45. Map Display Box

Upon clicking a particular road segment, it is highlighted with increased thickness to make it prominent, and simultaneously the statistics of that road segment are pinned in the right indicators panel, populating the right panel with indicators and attributions of that road. The mood chips and slider in the left panel are also simultaneously updated when clicking a road segment.

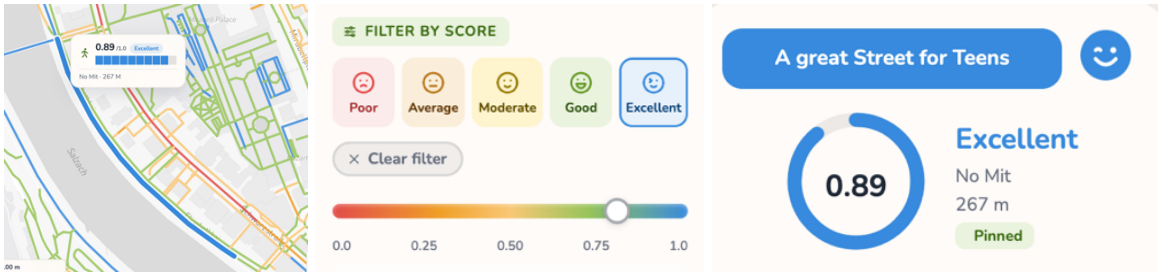


Figure 46. Score Ring, Line Segment Selection and Pop-Up

An interactive map legend has also been added separately inside the map area to fulfil all basic map elements. It is made interactive; users can decide to toggle and expand it. There is an export feature available in the bottom right corner that lets the user export the PNG or PDF of the map to the extent of which the map is displayed. Another useful detail has been added inside the map display panel, next to the location tag. A pulsing icon represented with a curious face emoji has been added representing city insights. The purpose of adding a pulsing effect was to prompt users to click on it and explore. Upon clicking, a fact card appears showing mobility trends resulting from the model's results. These insights can be navigated with an arrow button.

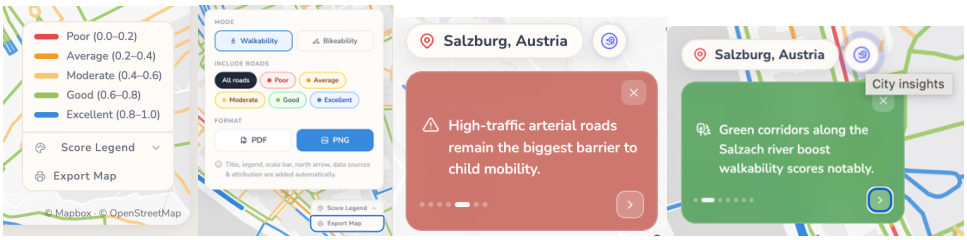


Figure 47. Score Ring and filter update, score trends

6.2.5 Indicators Panel

The indicator system is what makes this dashboard novel and unique, making the data interpretation visible. It connects the raw tile properties to everything displayed in the right panel. It displays a score ring which dynamically changes with the road segment, and the indicators score chart displays all the indicators contributing to the final index displayed in the score ring. Below the bar chart are indicator cards, showing individual indicator values, and upon click, the cards are flipped, and users can read the definition of indicators. This provides context to the users on how NetAScore4Teens interprets each indicator. The indicator panel includes an experience tab that offers a different perspective to interpret the same data, which is displayed in the metrics tab. This section communicates the road's quality in simple language, giving a child perspective, and a mood pill communicating how a child would feel experiencing mobility on that road segment. This section also includes group scorecards, done based on thematic categorisation of indicators. Below this section is a checklist for child-friendly mobility and then finally improvement ideas.

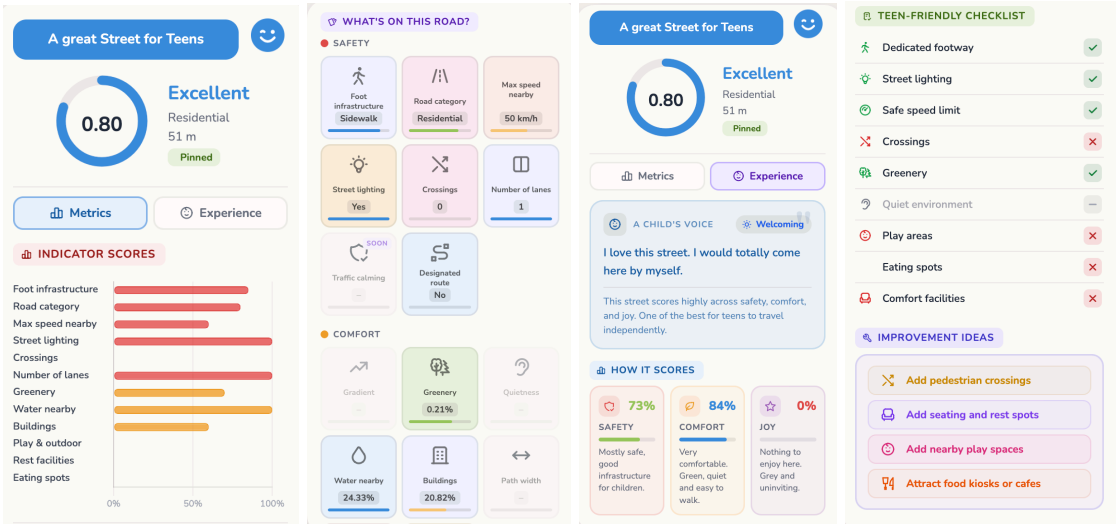


Figure 48. Indicators Panel (Metrics Tab)

6.2.6 Footer

The footer section of the dashboard consists of accreditation text on the left, institutional logos on the right and a fact pill showing global stats on children's mobility, mentioning sources like UNICEF, GDCI, WHO, and UN-Habitat.



Figure 49. Footer Design

6.3 User Testing Evaluation

Based on the feedback collected during the user-testing sessions as explained in section, several improvements were incorporated into the final version of the geo-visualization tool.

Table 29. User Testing Evaluation

Dashboard features	**Feedback**	**Implementation of user feedback**
Interactive Map	Straightforward, intuitive and easy to navigate. A few participants reported issue with hoovering to be slow.	Hoovering function was optimized.
Score Filters & Slider	Mood filtering was liked by the users.	No changes.
POI Toggles	Suggestion to improve POI icons, and adding a quick option to "clear all" feature.	(POI) icons were redesigned to improve visual clarity and recognition. A "Clear POIs" button was added.
Bar Chart (Metrics Tab)	Suggestion was made to improve visual hierarchy and colours pf the bars.	Colours of the bars were improved.
Dynamic Score Ring	It was perceived engaging and intuitive, however one user found	To be improved in the future.

	"no-mit" (road category from the model data) confusing and required clarity.	
Dark-Light Mode	Suggestion was made to enlarge the dark-light mode button and make it visually prominent.	To be improved in the future.
Indicator Cards	Most of the participants found this feature engaging and very intuitive.	No changes.
Experience Tab	This component received the most positive feedback. Almost all participants appreciated the narrative presentation of data and found it very helpful for interpretation of the data.	No changes.
Export Feature	Feedback indicated that layer selection within the export dialog duplicated controls already available in the main interface	A simplified export feature. Redundant layer-selection options were removed.
Environmental Layers	A suggestion to make separate opacity slide bar for both environmental layers which was initially combined.	Suggestions were implemented.

6.3.1 General Feedback on Navigation and Control

In addition to the feedback received on individual features, several suggestions were provided by participants on interactions and navigation:

- Loading messages, including "Loading road network" and "Loading POIs", were introduced based on user feedback during data retrieval, which can sometimes take time. This feature improved perceived system responsiveness.
- Tooltips were introduced for selected interface elements to provide additional guidance and improve discoverability of available functions.
- A manual location search function was proposed.
- A suggestion to make selection of road segment more prominent. One participant even suggested having a pointer instead of hover for better selection of roads.
- Recommendations on smoother transitions between walkability and bikeability layer switching were given.
- An overall summary of road statistics is missing and was suggested to be included.
- A mobile phone-optimised layout was also suggested.

Overall, most of the suggestions focused on usability rather than changing the underlying functionality. Based on these observations, several improvements were made that informed the final version of the dashboard. However, due to time constraints, some enhancements remain for future development.

6.3.2 Assessment of Research Objectives

A systematic assessment of research objectives outlined in the introduction, evaluating the main objective and each of its three sub-objectives against the work completed throughout this thesis is presented below.

Table 29. Assessment of Research Objectives

Objectives & Sub Objectives	**Achieved**	**Remarks**
Main Objective: Design and implement an interactive visualization tool for assessing and communicating child-friendly urban mobility	Yes.	NetAScore4Teens dashboard developed, deployed, and user-tested (Sections 6.4, 6.5)
Sub-objective 1a: Review and analyse literature on child-friendly mobility	Yes.	Systematic literature review conducted (Section 2)
Sub-objective 1b: Identify existing geospatial methods and tools for assessing children's mobility	Yes.	Geo-communication approaches identified and categorized from literature, revealing a gap this thesis addresses. (Section 2.8)
Sub-objective 1c: Identify indicators contributing to children's mobility	Yes.	Identified from literature (Section 2.4)
Sub-objective 2a: Adapting the NetAScore4Teens model, implementing the design and user interface of geo-visualisation tools	Yes, (Model adaptation (with noted limitation)	Model adapted via weight adjustments and new indicators (Section 4.4); dashboard interface designed and developed (Section 5). Weighting decisions were informed by literature and workshops but not statistically validated through external expert consultation; model results checked for plausibility on a small sample as an exploratory credibility check (Section 6.1.5, 7)
Sub-objective 2b: Building a dashboard using the input and output data from NetAScore4Teens	Achieved.	Dashboard integrates computed walkability/bikeability outputs with environmental and POI data (Section 6.4)
Sub-objective 3a: Conduct user testing of the dashboard to test the tool's functionality, effectiveness, and usability	Achieved	10 participants tested via moderated think-aloud sessions across 10 dashboard components (Section 3.8, 6.5)
Sub-objective 3b: Evaluate performance, benefits, and limitations of the tool based on user feedback	Achieved with limitations.	Feedback informed refinements; testing scope limited to small, non-representative sample (Section 7)

7 DISCUSSION

7.1 NetAScore Framework

This thesis's core objective was to implement, visualise, and communicate NetAScore4Teens's results. A basic comparison with the original NetAScore model and between the two case study cities was conducted; however, a detailed investigation into the underlying mechanisms behind specific score changes, alongside large-scale statistical validation, was beyond the scope of this work. The existing results, validated through a small sample of segments as an exploratory credibility check, were found to be plausible, and were subsequently visualised through the interactive dashboard. The following discussion evaluates the model's methodological approach, its treatment of children-specific indicators, and its transferability beyond the primary case study, identifying strengths and constraints that inform recommendations for future validation and calibration.

A major strength of NetAScore is its reliance on OpenStreetMap, a globally available and openly accessible database, providing a rich collection of attributes related to street networks, pedestrian infrastructure, POIs, etc., which made the adaptation from adult-version NetAScore to the teens' version possible. This allows for the model to be transferable and adaptable across different cities and regions, supporting mobility assessments for children beyond the study area of Salzburg. However, the literature on children's mobility identifies various social, environmental, and physical determinants for a comprehensive representation of children's mobility experiences including sidewalks, crossings, safety infrastructure, and lighting (WHO, 2023; GDCI, 2020; NACTO, 2013), green infrastructure (Larsen et al., 2009; Lovasi et al., 2011), and play spaces or meaningful destinations (Krysiak, 2023; Brown et al., 2019). These determinants were further unveiled through participatory workshops. For example, workshop activities conducted with children that highlighted the importance of colourful streets, playful environments, and other qualitative characteristics that influence how children experience urban spaces. While OpenStreetMap offered datasets covering many physical aspects of the built environment, it was a challenge to capture experiential and perceptual dimensions of children's mobility within the existing geospatial datasets, such characteristics are rarely represented. Although measurable, these aspects are difficult to map within the OSM data and require additional processing efforts. Representation of children's priorities was ensured both through weight and mapping adjustments to existing indicators and additions, however many aspects are still missing.

While richer representation of children's mobility needs may call for additional indicators, it comes with another challenge that the current model presents: adding new indicators without careful scrutiny of their conceptual distinctiveness can risk redundancy and introduce conceptual overlap instead of genuine explanatory value. For instance, in NetAScore4Teens, segments with play_and_outdoor present frequently also register a positive greenness value, since a single park can trigger both indicators simultaneously, meaningfully inflating these segments' total score. This risk is inherited directly from the original model: NetAScore's facilities indicator explicitly includes park among its qualifying amenity types, computed using the same 30-metre buffer as greenness. This concern is echoed by Werner et al. (2024a), who recommend that new indicators be tested individually for their explanatory contribution before inclusion. While the current adaptation has considered the unique contribution of each indicator, future work should carefully assess such overlaps to ensure that added indicators enhance, rather than duplicate, the model's explanatory power.

Additionally, the weighted-average approach does simplify the calculation by aggregating the indicators into a single score but also can also cause compensatory effect. Strong performance in some indicators can offset weaker performance in others. For example, a street segment could receive a moderate to good score due to the presence of greenery or lighting despite lacking sidewalks or good crossings. Such situations are currently addressed in the model using overrides, preventing certain indicator combinations from relying solely on weighted average. Nevertheless, overrides still may not fully capture complex interactions between indicators as they are limited to predefined conditions. This requires exploration of a rule-based, or hierarchical scoring framework, where the relative importance of certain groups of indicators should be reflected. This hierarchy was conceptually structured during the indicator development stage, where safety conditions act as prerequisites for higher levels of children's mobility dimensions, such as comfort and inspiration. The final aggregation in NetAScore currently lacks this hierarchical relationship, and future research could therefore explore these alternative scoring techniques in which Safety, Comfort, and other dimensions are evaluated independently before being aggregated into a weighted average.

Further, the transferability of NetAScore is highly influenced by how well and completely OpenStreetMap data is mapped within the study area. While the datasets are available globally, the quality of data varies between cities and contexts. Salzburg is relatively a well-mapped area; however, applying the model to any other study area will rely highly on how comprehensively local environments are mapped. Hence, it is important to evaluate data quality, completeness and availability before implementing the model in any other city, area or region. The model's transferability was assessed by applying it to a second case study, Olomouc, Czechia, demonstrating at the level of successful model execution rather than confirmed accuracy against ground-truth conditions. The results show plausible output, reason Olomouc being a broadly comparable Central European city in terms of urban context and scale. However, these results may vary when applying the same parameters to any city in the global South, Asia or any other region with different context. The reason is that importance and impact of the indicators may vary according to local conditions of urban environments. Hence, careful calibration and understanding of the local context of a given region is recommended before model implementation

7.2 Geo-visualisation of NetAScore4Teens

The main contribution of this research, besides the model adaptation is designing a Geovisualization tool for the interpretation and communication of the model’s input and output data. The model generates walkability and bikeability indices resulting from the sum of multiple indicators, computation formulas, and extensive coding. The geovisualization tool translates these highly technical assessment results into interactive and accessible formats, combining user-friendly layouts, charts, filters, texts, and icons within a single interface. Previous NetAScore outputs visualised the results in the form of static maps. While these traditional maps are the most common and effective way to present results, many underlying factors that contribute to the final score stay hidden and uncommunicated. Limited in their ability to enable users to dynamically explore results, static maps are also not so effective at communicating complex multi-indicator assessments such as NetAScore. This interactive Geo-visualization dashboard makes those underlying factors visible, enabling users to investigate specific road segments and explore the different dimensions of children's mobility captured by the assessment. While the NetAScore4Teens dashboard effectively demonstrates the potential of translating complex and technical knowledge into user-friendly geo-communication formats, some technical aspects should be discussed in this section for future research. The current

technical implementation of the dashboard uses plain HTML, CSS, and JavaScript, allowing for direct control over all interaction and interface. For a research prototype, this architecture was sufficient; however, the maintenance of such a JavaScript codebase can be challenging if the dashboard complexity increases in the future. To address this challenge, frameworks such as React can be considered for enhanced scalability and better state management. Moreover, presently the assessment model and interactive geovisualization follow separate workflows, extensive manual processing and a certain level of technical expertise. A suggestion to streamline this is integrating direct GeoJSON export functionality within the NetAScore pipeline itself, removing the need for a separate manual conversion step from GeoPackage to GeoJSON before dashboard preparation.

Future research could also explore the development of a child-oriented interface for the NetAScore4Teens dashboard. While the current visualization platform is primarily designed for subject experts, researchers, urban planners, urban designers and decision-makers, the underlying focus of the model's assessment is children. This research applied participatory methods with teens during the model's development stage; however, these engagement methods were not extended to the dashboard's interface design itself. This gap is consistent with a broader limitation identified in the literature (Section 2.5): while participatory tools such as PGIS and PPGIS effectively capture children's spatial perceptions and engagement, they typically lack quantifiable, street-level indicators (Mansournia, 2024, 2025; Torun et al., 2024; Preto et al., 2016). A child-oriented interface for NetAScore4Teens could uniquely bridge this gap, combining the model's quantified, segment-level scoring with a communication format directly accessible to children themselves, rather than only to the adult planners and experts the current dashboard was designed for. Hence, research opportunity exists where focus can be made on communicating the model outputs to children and young population by developing child-friendly UI and UX, more simplified interfaces and age-appropriate visualizations. This offers a promising direction for the future to support community engagement and participatory planning, consistent with calls in the literature for participatory approaches that meaningfully involve children as co-designers of the tools intended to represent them (Freeman et al., 2017; GDCI, 2024).

7.3 Limitations

Several limitations of this study should be acknowledged:

- The adapted NetAScore4Teens model produced plausible results; the overall comparison indicates a modest increase in the walkability mean score and a more substantial decrease in the bikeability mean score. Further research is required to determine how individual indicators, weighting decisions, and rule-based adjustments contribute to these changes.
- A systematic sensitivity analysis, additional calibration, and using a larger independent sample were beyond the scope of the present thesis and should therefore form part of future development of the NetAScore4Teens model.
- Weights for NetAScore4Teens were finalised through workshop findings and discissions, rather than through consultation with external experts in the field. Future work should involve such experts to further validate and refine the model's weighting.
- The plausibility check was exploratory, based on a selective sample of segments cross-checked against street view imagery, rather than a large-scale, statistically representative survey validation. A more detailed, statistically robust validation is recommended for future work.

- The Olomouc results were not independently checked through manual street view cross-checking, meaning transferability was demonstrated at the level of successful model execution, rather than confirmed accuracy against ground-truth conditions. Plausibility check and validation of the model's results for Olomouc is recommended.
- Given the limited timeframe available for this thesis, extensive usability evaluation using standardised questionnaires and larger participant groups was not feasible. The evaluation also focused on general users rather than, public authorities or transport practitioners specifically; future work should involve these stakeholder groups and larger, more diverse participant samples to strengthen the assessment of usability and user acceptance.

8 CONCLUSION

The main contribution of this thesis is to address the gap in child-friendly urban mobility assessment by integrating children's perspectives through direct engagement with them and systematically incorporating their perspectives into a data-driven mobility assessment model (NetAScore) to evaluate mobility infrastructure from a child-specific perspective, while simultaneously communicating the assessment through an interactive geo-visualisation dashboard. Despite growing attention to child-friendly cities and active mobility, urban environments continue to be evaluated using mobility assessment models largely developed from the perspective of the general population and that seldom incorporate the priorities, experiences, and everyday mobility needs of children and young adolescents. Although sophisticated spatial assessment models are increasingly available, their outputs often remain difficult to interpret. This research addressed this gap by developing an interactive geo-visualisation dashboard that transforms complex model outputs and technical indicators into intuitive, interpretable, and actionable information, while combining literature review, participatory methods, spatial assessment, and web-based geo-visualisation.

The indicators for the child-specific mobility context were identified from scientific literature and international design guidelines, informed through participatory workshops with young adolescents, and translated into measurable indicators within the NetAScore framework. The findings demonstrate that young adolescents perceive urban mobility through a broader lens than conventional transport performance measures alone. While safety remains the fundamental requirement, the workshops revealed additional factors that shape young adolescents' independent mobility, including opportunities for play, social interaction, engaging street environments, greenery, and attractive public spaces.

The scientific contribution of this thesis in extending the NetAScore framework to represent child-oriented mobility through the integration of participatory knowledge and insights gathered directly from young adolescents, rather than relying exclusively on expert-defined parameters demonstrate that children's priorities can be operationalised into measurable, inclusive, child-centred indicators and incorporated into spatial modelling workflow. This contributes to the growing body of research advocating for greater inclusion of children's perspectives within urban planning and urban design. From a methodological perspective, the model's workflow is transferable relying primarily on openly available datasets and open-source software, making it reproducible and adaptable for application in other cities and for different population groups, as demonstrated in this research.

Additionally, the practical contribution of this research lies in the development of an interactive geovisualisation dashboard that transforms complex model outputs into an intuitive and interactive interface, facilitating the interpretation of technical indicators and enabling planners, researchers, and decision-makers to evaluate mobility infrastructure, identify areas requiring intervention, and support evidence-based planning decisions. Additionally, the priorities highlighted by teens not only shaped the NetAScore4Teens indicators, but also the dashboard design. The features included in the dashabord such as an experience tab showing "A Teen's Voice" and indicator cards specifically communicate the presence of features highlighted by adolescents in the workshops related to play spaces, comfort facilities, and attractive features are intended to translate their expressed needs into a form immediately visible to dashboard users.

Such a tool has the potential to support planning interventions, communicate spatial evidence more effectively, and encourage the consideration of children's needs within mobility planning processes. This practical importance and transferability align directly with i-mobyl, the European-funded project within which this research was conducted, which works with young adolescents across three Living Labs (Salzburg, Paris, and Guildford). NetAScore4Teens offers a ready-to-apply tool directly usable within i-mobyl's Salzburg Living Lab, with the potential to extend to its other participating cities.

Despite these contributions, several limitations should be acknowledged. The model remains dependent on the quality and completeness of OpenStreetMap and other open datasets, limiting the inclusion of certain child-relevant indicators for which consistent spatial data are currently unavailable. Furthermore, the weighting of indicators within the adapted NetAScore framework was informed by literature and participatory workshops rather than being established through a broader expert consensus or formal multi-criteria weighting approach. Future research could therefore incorporate expert elicitation or structured decision-making methods to further refine and validate the weighting scheme. The plausibility check conducted within this research was qualitative and exploratory, and future studies should undertake statistically robust validation using larger samples, field observations, and user-based evaluations. Further research should also investigate the applicability of the framework across different cultural contexts, expand participatory engagement to additional age groups, and explore the integration of emerging data sources such as street-view imagery, computer vision, traffic data, and real-time environmental information.

Overall, this thesis demonstrates the potential of combining participatory approaches, open geospatial data, spatial modelling, and interactive geovisualisation to support the assessment of child-friendly urban mobility. Beyond extending the NetAScore framework, the research illustrates how digital tools can make complex spatial assessments more transparent, accessible, and actionable for planning practice. In doing so, it contributes to the broader discourse on child-friendly cities, sustainable and active mobility, digital transformation in urban planning, and evidence-informed decision-making. The proposed methodology and geovisualisation tool provide a transferable foundation for future research while supporting planners and decision-makers in creating urban environments that better reflect the everyday needs, experiences, and independent mobility of children and young adolescents.

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ATTACHMENTS

Free Attachments

Attachment 1	Thesis Poster
Attachment 2	Thesis Website
Attachment 3	NetAScore4Teens Dashaboard

NetAScore4Teens Dashboard can be found here:
https://urbanistamna.github.io/Dashboard-NetAScore4Teens/
The poster can be found on the website:
https://www.geoinformatics.upol.cz/dprace/magisterske/azeem26/index.html