THEMENKONGRESS MOBILITÄT 2026

Mobility Congress 2026

Proceedings

Contributions, Perspectives and Impulses for the Future of Mobility

HAW Hamburg • 4 June 2026 • Campus Berliner Tor, Hamburg

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Themenkongress Mobilität 2026

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Proceedings

Contributions, Perspectives and Impulses
for the Future of Mobility

Herausgegeben von / Edited by

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4 June 2026 · Campus Berliner Tor · Hamburg

Foreword

Hamburg is a city where mobility is never abstract. It is part of everyday life: in the movement of people and goods, in the reliability of infrastructure, and in questions of participation and quality of life. This is one of the reasons why the Mobility Congress has found such a fitting home at Hamburg University of Applied Sciences (HAW Hamburg). The publication of the first proceedings volume of the Mobility Congress marks an important milestone for HAW Hamburg. More than a record of an annual conference, this volume reflects a development that has been shaping our university for some years. It demonstrates how research, teaching and knowledge transfer reinforce one another to address questions of high societal relevance while creating lasting scientific value.

This publication also reflects how HAW Hamburg has developed in recent years. We have strengthened our research profile, expanded international cooperation, established subject-specific doctoral programmes and introduced new academic structures, including the Faculty of Sustainable Engineering. The launch of the English-language Bachelor's programme in Mechanical Engineering in 2025 further underlined this direction by welcoming students from around the world to our university. Together, these developments reflect a common ambition: to strengthen HAW Hamburg as an internationally connected University of Applied Sciences that combines scientific quality with societal relevance. These proceedings are among the first visible academic outcomes of this development.

Few fields illustrate this mission more clearly than mobility. Mobility is no longer simply about moving people and goods. It shapes cities, public space, infrastructure, energy systems and digital services. Responding to this complexity requires more than technological innovation. It requires engineers, planners, computer scientists, economists, companies, public authorities and citizens to work together across disciplinary and institutional boundaries. Progress depends not only on new ideas but also on the ability to connect knowledge, experience and responsibility.

This understanding has shaped the Mobility Congress from the very beginning. It brings together researchers, students, companies, public authorities and practitioners who share a common interest in shaping the future of mobility. Scientific contributions meet practical experience. Research questions emerge from real-world challenges, while research findings return to practice. In doing so, the Mobility Congress reflects one of the defining characteristics of HAW

Hamburg: application-oriented research that develops solutions together with partners from industry, the public sector and society.

Conferences create dialogue, while proceedings preserve, review and disseminate knowledge. For a congress built on scientific exchange, the publication of reviewed proceedings is therefore a natural next step. It extends the impact of the event beyond the conference itself, makes its contributions accessible to an international audience and strengthens the visibility of application-oriented research. At the same time, it creates a lasting foundation for future collaboration.

In this respect, the Mobility Congress makes HAW Hamburg's mission particularly tangible. International speakers and authors broaden the discussion beyond national borders, while contributors from academia, industry and public institutions ensure that scientific exchange remains closely connected to practical implementation. As a result, the Mobility Congress has become more than an annual event. It is a platform where disciplines meet, partnerships develop and ideas continue to evolve long after the conference has ended.

Hamburg provides an exceptional setting for this dialogue. As host of the ITS World Congress in 2021 and the UITP Summit in 2025, with its return scheduled for 2027, the city has established itself as an internationally recognised centre for mobility innovation. Major infrastructure projects such as the metro line U5, together with advances in digital and autonomous mobility, make Hamburg a living laboratory for applied research. HAW Hamburg contributes actively to this ecosystem through research, teaching and knowledge transfer, while the Mobility Congress connects local experience with national and international perspectives.

Another distinctive feature of the Mobility Congress is the close integration of research and teaching. Students do not simply attend the event; they help shape it. As part of the Master's course in Project Management, interdisciplinary teams take responsibility for real projects under real-world conditions. The preparation of this proceedings volume was one of these projects. Students contributed to editorial processes, publication management and conference organisation while experiencing first-hand how scientific knowledge is created, reviewed and communicated. In doing so, they learned project management not only in the classroom but also through meaningful responsibility within an international academic environment. This close integration of teaching, research and knowledge transfer is one of the defining strengths of HAW Hamburg.

The success of the Mobility Congress has always depended on strong and lasting partnerships. Deutsche Bahn deserves particular recognition for its continued commitment as both a sponsor and an active contributor. At a time when Germany is undertaking the most comprehensive modernisation of its railway infrastructure in decades, the exchange between academic research and operational practice is more valuable than ever. The many contributions from companies, public institutions and research organisations in this volume demonstrate that the mobility transition can only succeed through sustained collaboration.

My sincere thanks go to all authors, reviewers, speakers, session chairs, exhibitors, sponsors, students and institutional partners whose commitment has made both the Mobility Congress and this proceedings volume possible. I would like to express my special appreciation to Prof. Dr.-Ing. Tankred Müller, Prof. Dr.-Ing. Henner Gärtner and Vanessa Claus. Their vision, dedication and perseverance have shaped the Mobility Congress over many years and laid the foundation for this first proceedings volume.

I hope that the ideas presented in this volume will help set further developments in motion by inspiring new research, new partnerships and new perspectives. The challenges ahead will not be addressed by individual disciplines or institutions alone. They require people who are willing to connect scientific knowledge with practical experience, innovation with responsibility, and local initiatives with international cooperation. It is my hope that these proceedings will carry this spirit forward.

Prof. Dr. Ute Lohrentz
President of HAW Hamburg

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PARTICLE – Participatory Lighting Design in Urban Environments Using AR/VR Technologies

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Abstract **The PARTICLE tool is a hardware and software system that facilitates collaborative and immersive co-design processes for environmentally-sound outdoor lighting in urban spaces. Using an interactive touch table, VR headsets and AR tablets, participants can adjust lighting scenarios in real time and experience their effects on light pollution or visual comfort. This paper investigates how such immersive, multi-modal visualization changes the way non-expert stakeholders assess lighting scenarios compared to conventional, abstraction-based presentation formats. The system allows several people to work on the same scenarios simultaneously across different locations. As part of the EU Interreg North Sea Programme DARKER SKY, PARTICLE was developed from a predecessor project, PaKoMM, and successfully used for two pilot projects in the Borough of Altona in Hamburg. This paper presents the co-design concept, the system architecture and the findings from the workshop processes involving a broad network of stakeholders.**

Keywords— participatory lighting design, co-design, urban planning, augmented reality, virtual reality, digital twin, light pollution, DARKER SKY

I. Introduction

Artificial light at night (ALAN) is increasingly recognized as a challenge for both biodiversity and human well-being. Recent reviews highlight ecological impacts on species' behavior, ecosystem functioning and urban nightscapes, while emphasizing the need for evidence-based lighting strategies [1].

Lighting in public spaces is far more than just an infrastructural necessity: it shapes the sense of visual comfort and wayfinding for pedestrians and cyclists, influences ecosystems and biodiversity, and accounts for significant energy consumption [2]. At the same time, lighting design is a highly technical field – involving standards, complex regulations, and specialized simulation tools with technical vocabulary that presents barriers to non-specialists [3].

The result is that participatory processes in urban lighting planning often fail not because of a lack of will or knowledge on the part of experts, but due to structural barriers. The public is largely unfamiliar with the subject; stakeholders do not immediately recognize the added value of good lighting; decision-making processes within local authorities are complex; and the staffing capacity in local councils for comprehensive participatory procedures is constrained.

The hardware and software tool PARTICLE (Participation, AR, Reality, Transparency, Interaction, Co-Design, Lighting, Enlightenment) addresses these challenges with an innovative approach: an immersive, multi-modal co-design system that conceals technical complexity, enables intuitive interaction and supports cross-location collaboration in the context of outdoor lighting. PARTICLE was developed as part of the EU Interreg North Sea Programme DARKER SKY and tested in Hamburg.

This paper examines how immersive, multi-modal visualization changes the way non-expert stakeholders assess lighting scenarios compared to conventional (illuminance-map-based) presentation formats.

II. Project Background: DARKER SKY

DARKER SKY is a transnational project under the EU Interreg North Sea Programme, involving 13 partners from four countries, with a total budget of €4.2 million and ERDF co-financing of €2.5 million (April 2023 – October 2026). The aim is to reduce light pollution and develop environmentally-sound lighting infrastructure at eight demonstration sites in municipalities close to the North Sea [4].

The project structure follows a three-phase approach: (1) Framing – analysis and conceptual framework; (2) preparation, installation, testing and evaluation of pilot lighting systems; (3) roll-out and scaling of lighting solutions. Measurement methodologies for light pollution, sociological surveys and scientific monitoring accompany all phases.

The HAW Hamburg team is responsible, at a transnational level, for the lighting measurement methodology and the application of innovative AR/VR systems in participatory processes; locally, it provides scientific and technical support for two demonstration sites in the area of the Borough of Altona: the walking and cycling path 'Strandweg' and the area around the small road 'Bullnwisch'. As support for the Borough of Altona team, HAW Hamburg is undertaking the evaluation of the lighting installations and developing the PARTICLE framework to assist the co-design processes [5].

III. Pilot Projects in Hamburg-Altona

A. Strandweg

The Strandweg is a section of a popular European cycling and walking route along the River Elbe, which is heavily used and situated in an ecologically sensitive location on the riverbank. The focus here is on striking a balance between road safety and minimising environmental impact.

A particularly detailed digital twin has been created for the Strandweg, which also considers and allows for the assessment of the dense tree cover and the water surface of the River Elbe, as well as the light pollution from industry on the opposite bank. In the VR experience, users can virtually explore and evaluate various scenarios – ranging from reduced, minimal lighting to lighting adapted to high usage levels – under different weather conditions and at different times of day.

B. Bullnwisch

The small road Bullnwisch on the outskirts of Sülldorf in Hamburg-Altona is a typical example of a lighting system in need of improvement. As part of the DARKER SKY project, the old lighting infrastructure was replaced with adaptive warm white LED luminaires capable of adjusting colour temperatures from 3000 K to 2200 K. At the same time, by increasing the number of light points on existing poles whilst maintaining the total luminous flux, a significantly higher degree of lighting uniformity was achieved. The aim was to enhance biodiversity compatibility while maintaining visual comfort, which is supported by a uniform, non-glary lighting, that allows wayfinding and see surroundings effectively.

The before-and-after documentation of the lighting installation at 'Bullnwisch' (Fig. I) clearly shows the change in light quality: the warmer colour temperature is the result of a reduced proportion of short-wavelength light in the blue spectrum, which is generally considered beneficial for insects and nocturnal mammals.

Fig. I Pilot project 'Bullnwisch'; Left: Old installation before modification, warm white at 3000 K light but low uniformity at street level; Right: New installation after modification with warmer coloured light at 2200 K and high uniformity at street level (Photos: C. Liedtke)

Light measurements taken before and after the retrofit in 2024 documented the illuminance and correlated colour temperature values of both installations and validated the design objectives. In detail, the lighting has changed from a static illumination (not dimmable, fixed correlated colour temperature 3000 K) to an automated switched and dimmed illumination depending on the time of day and year. The luminous flux of the installation did not change during the modification, but instead of 3 poles used for the lighting, 5 poles with a shorter distance from each other were equipped, each with a lower lumen output. This supported to raise the uniformity of the lighting on street level significantly – which is a requirement in street lighting standards - while the average illuminance slightly increased from 3 lx to 4 – 5.5 lx). During the vegetation period from March to November, the lighting is dimmed down (from 5.5 lx to 4 lx average illuminance) in the night hours (appr. after 10 and before 5 o' clock, depending on the time of year) at 2250 K CCT. In the winter period CCT 3000 K is used in general, while keeping the dimming down in night hours (same levels as in summer).

IV. Challenges in Responsible Urban Lighting Design

Practical experience reveals recurring structural barriers to genuine participation in lighting planning when applying a comprehensive approach to achieving responsible urban lighting design. Obstacles identified during the DARKER SKY project can be grouped into four categories:

A. Lack of public awareness

For most people, lighting only becomes an issue when it causes a complaint. Its negative environmental impacts are not widely understood, nor can they be properly assessed in relation to other forms of pollution [2]. The positive aspects – environmentally friendly lighting (e.g. sensibly directed, shielded, warm white, adaptive) – and its benefits for people and the environment are scarcely known.

B. Complexity for stakeholders

Even experts – administrative representatives, transport planners, nature conservation officers – find it difficult to assess the consequences of different lighting concepts without visualization [3].

C. Administrative complexity

Coordination processes between authorities follow formal procedural channels that have so far made little provision for genuine co-creation. Policy screenings carried out as part of the DARKER SKY project confirm these structural challenges [6].

D. Limited municipal resources

Staff available for extensive public engagement processes or the evaluation of alternative options are limited. Tools that enable efficient and high-quality civic engagement are therefore essential for holistic urban lighting planning, rather than mere conveniences.

V. Co-Design Stages for Lighting Design

PARTICLE employs a phased co-design strategy that combines analogue and digital participation formats into a hybrid approach [7]. The four stages follow a progression from physical presence to full digital immersion.

A. Analogue – On-site workshop:

The process begins with traditional on-site participatory formats: site visits, scenario discussions and analogue mapping workshops. This phase serves to understand the planning area and identify stakeholders' needs at an early stage.

B. 2.5D – Interactive touch table:

The touch table displays a 2.5D top-down view of the planning area – whilst simultaneously representing the perspective of a human observer – on a very large wall-mounted monitor, and allows users to manipulate light sources, colours and intensities via multi-touch [8].

C. 3D AR – Augmented Reality:

AR tablets superimpose the planned lighting onto the real-world camera view of the planning site – particularly suitable for on-site workshops where spatial orientation within the real-world context is crucial.

D. 3D VR – Virtual Reality:

VR headsets enable immersion in the digital twin of the planning area. Participants can virtually walk along a street or cycle path and experience different lighting scenarios with a sense of spatial depth. Multi-user VR allows several people to be present in the same virtual space at the same time [9].

One or more formats can be used for a single planning task, either with the same users or as part of a multi-stage process.

VI. The PARTICLE Tool

A. System architecture

The technical foundation is a shared, physics-based digital twin of the planning environment, created from survey data, 3D photogrammetry and GIS information. The lighting visualization adheres to real-world lighting specifications, e.g. colour temperature in Kelvin, luminous intensity distribution curves (LDC).

In the urban and built-environment context, a distinction is commonly made between a digital model (no automated data connection between the physical and virtual counterpart), a digital shadow (automated, one-way data flow from the physical object to the digital model), and a digital twin in the narrower sense, which establishes a bidirectional feedback loop between the virtual and the physical environment [10]. The representations used in PARTICLE are created once from survey and photogrammetry data and subsequently updated manually when the physical lighting infrastructure changes; they therefore correspond most closely to a digital shadow, while the term "digital twin" is retained here in its broader, commonly used sense as a high-fidelity spatial replica used for simulation and co-design.

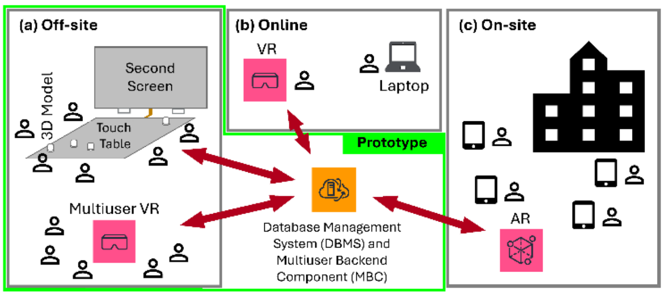

Fig. II PARTICLE's system architecture: (a) off-site setup with a touch-screen table and multi-user VR, (b) online access via VR and laptop, (c) on-site use with AR tablets. All components are connected via DBMS and MBC. (Image: [3], Fig. I, font size changed by authors)

All end devices – touch tables, VR headsets and AR tablets – are connected via a central database management system (DBMS) and a multi-user backend component (MBC), as shown in Figure II. Changes are transmitted in real time, enabling simultaneous co-creation across different locations [5].

B. Digital twins of the DARKER SKY pilot sites

High-resolution digital twins were created for both pilot sites in Hamburg. The ‘Strandweg’ at the river Elbe (see Figure III) and the small street Bullnwisch (see Figure IV) in Sülldorf – both located in Hamburg-Altona were captured using photogrammetry and integrated into VR and touch-table environments.

FIG. III VR-SCREENSHOT OF THE HIGH-RESOLUTION DIGITAL TWIN OF THE ‘STRANDWEG’ PILOT PROJECT (IMAGE: B. ASSIG, SHAPESHIFT)

FIG. IV VR-SCREENSHOT OF THE HIGH-RESOLUTION DIGITAL TWIN OF THE ‘BULLNWISCH’ PILOT PROJECT (IMAGE: B. ASSIG, SHAPESHIFT)

VII. STAKEHOLDER NETWORK AND CO-DESIGN PROCESS FOR THE DARKER SKY HAMBURG PILOT PROJECTS

A. Stakeholder mapping

A key first step was the systematic identification of all relevant stakeholder groups [11]. The network comprises local authorities, transport and environmental associations, user groups (cyclists, pedestrians, residents, tourists) and the operator of the lighting infrastructure, which in Hamburg is the public utility company 'Hamburg Verkehrsanlagen' (HHVA).

In a second step, the stakeholders were grouped into clusters to enable specific issues to be addressed in a more targeted manner, using the most appropriate format in each case (depending on time constraints, local availability, etc.).

Both the overall overview and the breakdown into clusters are important resources within the overall process and serve, following each participation format, to reflect on intermediate results and plan further activities.

As the participation activities progress, the PARTICLE tool itself is evaluated by the participants at each stage and subsequently further developed directly by the researchers, with implementation carried out by third parties.

B. Evaluation Method

To assess how the immersive, multi-modal visualization approach affects stakeholder engagement with lighting scenarios, the co-design workshops were accompanied by a structured evaluation. Participants were drawn from the stakeholder clusters identified in Section VII.A, comprising representatives from local authorities, transport and environmental associations, and members of user groups (cyclists, pedestrians), for a total of 21 participants across both workshops.

Feedback was collected through semi-structured group discussions and moderated plenary feedback rounds], focusing on three dimensions: (1) usability of the PARTICLE tool itself, (2) perceived comprehensibility of the lighting scenarios compared to conventional illuminance-map presentations, and (3) acceptance of the proposed lighting solutions with respect to safety, visual comfort, and environmental impact. Where relevant, feedback was analysed separately by stakeholder group to identify differences in assessment between, for example, technical experts and lay participants.

The AR/VR model itself has not yet been validated, against physical installation. An on-site comparison of luminance and illuminance values, as well as participant cross-checks, are planned in future steps.

C. Workshop Process

At the heart of the development and application of the PARTICLE tool are facilitated co-design workshops that combine in-person participation with digital immersion. In spring 2024, the first major workshop, ‘Sustainable Lighting Strategies for Altona’, took place [12], followed in autumn 2024 by the second workshop, ‘Cyclists’ and Pedestrians’ Perspectives on Environmentally-Sound Lighting Planning’, organised in cooperation between the Altona Borough Office and HAW Hamburg [13].

Fig. V Left: Co-design workshop with a touch table (2.5D). Workshop at HAW Hamburg, May 2024 (Photo: R. Greule / DARKER SKY), Right: Participants join simultaneously the PARTICLE Online mode via VR glasses, September 2024 (Photo: A.C. Mosler)

The workshops followed a phased programme: an introduction to the planning area and the objectives (analogue), joint scenario development at the touch table (2.5D), an immersive site visit using a VR headset (3D) and a concluding evaluation discussion in a plenary session. Feedback collected during the workshops suggests that this phased approach was well received: participants confirmed that the physical introduction helped them familiarize themselves with the planning area before digital tools were introduced.

A key factor in the process was the user-friendly nature of all the tools. Even participants with no prior technical knowledge were able to operate the touch table, with its intuitive multi-touch controls, independently after a brief introduction.

VIII. Discussion

A. The benefits of the co-design approach

PARTICLE demonstrates that immersive technologies can substantially break down communication barriers in participatory urban planning. Three mechanisms of impact are particularly worth highlighting:

- Experiential engagement rather than abstraction: Whilst conventional presentations using illuminance maps require abstract specialist knowledge, the immersive walkthrough of the digital twin enables a direct sensory experience. Participants can directly evaluate how a change in lighting affects the perception of safety or the atmosphere along a route.
- Shared reference object: The digital twin creates a shared artefact to which all stakeholders – planners, representatives of public authorities and members of the public – can refer simultaneously [3]. This significantly accelerates iterative decision-making processes.
- Location-independent collaboration: PARTICLE's network architecture enables stakeholders in different locations to participate simultaneously – particularly relevant for external specialist planners or regulatory authorities.

B. Limitations and outlook

Challenges lie in the scalability of digital twins: their creation requires specialised GIS and 3D expertise, as well as a considerable investment of time. Future steps aim to achieve automated or semi-automated twin generation from open data sources (OpenStreetMap, official geodata) [14].

The assessment module is to be expanded to include acoustic parameters, glare estimates and more detailed biodiversity indicators.

The perceived safety of the new lighting solutions was outside the scope of the present pilot projects and has therefore not yet been systematically evaluated; this is planned as a subject for future assessment.

PARTICLE highlights the close interconnection between lighting design and urban mobility: visual comfort at night, orientation in the street environment and the appeal of active mobility depend significantly on the quality of the lighting.

IX. Conclusion

The PARTICLE system demonstrates how digital twins and immersive AR/VR technologies can be integrated into a comprehensive co-design process to substantially improve participatory urban planning. The multi-stage strategy – ranging from analogue on-site workshops through to interactive touch-table scenarios and VR and AR immersion – caters for different user profiles and levels of abstraction within a unified system.

While shared visualization has already been shown to support collaborative participation settings [3], and the underlying system architecture builds on prior work [5], PARTICLE extends these contributions by combining touch-table, AR, and multi-user VR modalities within a single, real-time-synchronized system that allows stakeholders at different physical locations to co-create using the same lighting scenario simultaneously.

The pilot projects in Hamburg-Altona, carried out as part of the DARKER SKY initiative, demonstrate the practical viability of this approach. PARTICLE is not an isolated tool, but an integrated process-based approach that combines technical innovation with social science expertise in participatory planning, thereby contributing to the democratisation of complex planning processes.

ACKNOWLEDGEMENT

This project is funded by the EU Interreg North Sea Programme as part of the DARKER SKY project (ERDF co-financing: €2.5 million). The authors would like to thank all workshop participants, the Borough of Altona DARKER SKY team, the project partners in the DARKER SKY consortium, as well as Shapeshift (development of the high-resolution digital twins) and Matthias Kuhr (development of touch table applications and PARTICLE system architecture).

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Integration von Gesundheit in die Stadt- und Verkehrsplanung

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Im humanökologischen Modell gelten Umwelt- und Lebensbedingungen im Siedlungsraum als zentrale Determinanten von Gesundheit [1]. Dabei lassen sich strukturelle Faktoren wie Lärm, Luftqualität und Grünflächen von individuellen Faktoren, etwa gesundheitsrelevantem Verhalten oder Lebensstil, unterscheiden. Mobilität nimmt eine besondere Rolle ein, da sie durch Umweltbedingungen geprägt ist und zugleich individuelles Verhalten ausdrückt, wodurch sie beide Ebenen miteinander verknüpft. Zudem stellt sie eine zentrale Voraussetzung für gesellschaftliche Teilhabe und gesundheitsbezogene Lebensqualität (Health-related Quality of Life, HrQoL) dar.

Im urbanen Raum ermöglicht Mobilität den Zugang zu Arbeit, Bildung, Versorgung und sozialen Netzwerken und trägt damit wesentlich zur HrQoL bei. Insbesondere aktive Mobilität – wie Zufußgehen, Radfahren – entfaltet gesundheitsförderliche Effekte. Systematische Reviews zeigen Zusammenhänge mit erhöhter körperlicher Aktivität, geringerer kardiovaskulärer Mortalität sowie reduzierten Risiken für chronische Erkrankungen [2; 3]. Mobilität ist somit nicht nur funktionale Voraussetzung moderner Stadtregionen, sondern auch eine zentrale Gesundheitsressource.

Gleichzeitig kann Mobilität mit gesundheitlichen Belastungen einhergehen. Im stadtregionalen Kontext zeigt sich dies u. a. in der Pendelmobilität: Wohnen am Stadtrand und im Umland geht häufig mit langen Pendelwegen einher, die mit geringerem Wohlbefinden und niedrigerer Lebenszufriedenheit verbunden sind [4]. Zudem führt die zunehmende Verkehrsbelastung zu Umweltproblemen. Verkehrslärm zählt zu den wichtigsten umweltbedingten Risiken und wird mit Schlafstörungen sowie kardiovaskulären und psychischen Erkrankungen in Zusammenhang gebracht [5–8]. Auch Luftverschmutzung stellt eine zentrale Belastung dar und wirkt sich negativ auf das respiratorische, kardiovaskuläre und neurologische System aus, besonders bei vulnerablen Gruppen [9]. Frühzeitige Exposition gegenüber Luft- und Lärmbelastungen erhöht zudem das Risiko für psychische Erkrankungen [10]. In dicht besiedelten Regionen wie der Metropolregion Hamburg kumulieren diese Belastungen entlang stark frequentierter Verkehrsachsen und sind sozial ungleich verteilt, wodurch gesundheitliche Ungleichheiten verstärkt werden [11; 12]. Darüber hinaus stimmen objektiv gemessene Umweltbelastungen nicht zwingend mit subjektiven Wahrnehmungen überein, wobei beide Dimensionen die Gesundheit und die HrQoL beeinflussen können. Diese Diskrepanz wird von sozialen und kontextuellen Faktoren geprägt und kanngesundheitliche Unterschiede zwischen Bewohner:innen unterschiedlich belasteter Wohnlagen verstärken [13–15].

Mobilität ist somit als ambivalente Gesundheitsdeterminante zu verstehen, deren gesundheitsförderliche und -belastende Effekte räumlich und sozial ungleich verteilt sein können. Diese Ambivalenz spiegelt sich in Zielkonflikten zwischen Verkehrsentwicklung, Umwelt- und Gesundheitsschutz wider. Das Forschungsprojekt „GeSGo – Integration von Gesundheit in die Stadt- und Verkehrsplanung – Neue Governancestrukturen in stadtregionalen Verkehrskorridoren“ untersucht diese Zusammenhänge sowie

Governancestrukturen im Sinne einer integrierten Planung. Im Mittelpunkt steht die Frage, wie gesundheitliche Auswirkungen verkehrsinfrastruktureller Entwicklungen in stadtregionalen Verkehrskorridoren systematisch erfasst und im Sinne des Ansatzes „Health in All Policies" in Planungs- und Entscheidungsprozesse integriert werden können. Dabei wird analysiert, wie Mobilitätsverhalten, verkehrsbedingte Belastungen und gesundheitsförderliche Ressourcen mit der Gesundheit der Bevölkerung zusammenhängen und welche Governancestrukturen die Berücksichtigung gesundheitlicher Belange in der Stadt- und Verkehrsplanung fördern oder hemmen. Ziel ist es, gesundheitliche Auswirkungen systematisch in politischen Entscheidungsprozessen zu berücksichtigen und Instrumente wie Gesundheitsfolgenabschätzungen in Stadtentwicklung und Verkehrsplanung zu verankern. Dadurch kann eine nachhaltige und sozial gerechte Gestaltung urbaner Räume gefördert werden, die gesundheitliche Belastungen reduziert und gesundheitsförderliche Potenziale stärkt.

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Erklärbare Entscheidungen in twin-nativer autonomer Mobilität: Entscheidungsspuren im S-PACT-Zyklus

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Kurzfassung **Eine Fahrentscheidung ist nachträglich nur dann überprüfbar, wenn die Größen, auf denen sie beruht, zum Entscheidungszeitpunkt festgehalten werden. Für die twin-native Architektur S-PACT wird festgelegt, welche Größen das sind: Die Entscheidungsspur ist ein pro Entscheidungszeitpunkt protokolliertes Tupel aus semantischem Zustand des Digitalen Zwillings, den im Prädiktiven Zwilling simulierten Handlungskandidaten mit ihren prädizierten Verläufen, der ausgeführten Handlung und den Gründen für die Verwerfung der übrigen Kandidaten. Gefordert werden Vollständigkeit, Lokalität und Nachprüfbarkeit der Spur. Die Trennung von faktischem und prädiktivem Zwilling schafft dafür die strukturellen Voraussetzungen, erzeugt die Spur jedoch nicht; vorgeschlagen wird deshalb eine explizite Repräsentation von Kandidaten, prädizierten Verläufen und Verwerfungsgründen. Dargestellt wird der Vorschlag an einem Minimalaufbau der Miniature Autonomy und gegen den implementierten Funktionsumfang abgegrenzt. Als Prüfkriterien werden Vollständigkeitsrate, Rekonstruierbarkeit und Prognosefehler benannt; ihre Erhebung steht aus.**

Schlüsselwörter*— *erklärbare Autonomie, Digitaler Zwilling, Prädiktiver Zwilling, neuro-symbolische Architektur, Entscheidungsspur, Miniature Autonomy

I. Motivation und Forschungsfrage

Autonome Fahrfunktionen werden zunehmend datengetrieben realisiert. Damit wächst der Abstand zwischen der ausgeführten Handlung und einer Begründung, die ein Mensch nachvollziehen und ein Dritter überprüfen kann. Für Zulassung, Unfallanalyse und Akzeptanz ist nicht allein entscheidend, ob ein System sich korrekt verhält, sondern ob im Nachhinein angegeben werden kann, worauf eine einzelne Entscheidung beruhte.

Ob eine solche Angabe möglich ist, entscheidet der Architekturentwurf: Tragen kann eine Begründung nur diejenigen Größen, die während der Entscheidung entstehen und festgehalten werden. Daraus ergibt sich die Frage: Welche Struktur muss eine twin-native Architektur aufweisen, damit zu einer einzelnen Fahrentscheidung eine vollständige und nachprüfbare Begründung angegeben werden kann?

Beantwortet wird die Frage konzeptionell. Vorgeschlagen wird mit der Entscheidungsspur ein operationaler Erklärungsbegriff; gezeigt wird, welche Bestandteile der Architektur S-PACT zu dessen Bestandteilen beitragen, und benannt werden Kriterien, an denen sich der Vorschlag künftig messen lassen muss. Architektur und Verarbeitungszyklus sind in [1] eingeführt und werden hier nicht als eigener Beitrag beansprucht; neu sind der Erklärungsbegriff, die daraus abgeleitete Repräsentationsschicht und die Prüfkriterien. Neue empirische Ergebnisse werden nicht berichtet.

II. Forschungsstand

Erklärungen für Fahrentscheidungen werden bislang überwiegend nachträglich erzeugt. Überblicksarbeiten unterscheiden Adressaten, Zeitpunkte und Formate solcher Erklärungen [4] und ordnen die Verfahren nach ihrem Ansatzpunkt im Verarbeitungsstapel [5]; für bildbasierte Fahrsysteme liegt eine systematische Übersicht ihrer Grenzen vor [6]. Ein großer Teil dieser Verfahren rekonstruiert aus einem bereits trainierten Modell nachträglich eine Begründung, etwa über Saliency-Karten oder sprachliche Beschreibungen; daneben werden auch von vornherein interpretierbare Entwürfe untersucht [6]. Für die rekonstruierenden Verfahren gilt, dass ihre Übereinstimmung mit dem tatsächlichen Zustandekommen der Entscheidung selbst wieder eine offene Prüffrage ist. Daraus ergibt sich eine Trennlinie: Eine Begründung kann nachträglich rekonstruiert oder während der Entscheidung mitgeschrieben werden.

Mitschreiben setzt voraus, dass die für eine Begründung nötigen Größen im System als benannte Objekte existieren. Diese Forderung ist außerhalb der Mobilität bereits formuliert worden: Unter dem

Begriff der decision provenance wird vorgeschlagen, Entscheidungsketten samt Eingangsgrößen und Folgewirkungen systematisch aufzuzeichnen, um automatisierte Systeme rechenschaftsfähig zu machen [7]. Offen bleibt dort, welche Größen ein geschlossener Regelkreis in jedem einzelnen Zyklus bereitstellen muss, damit eine solche Aufzeichnung vollständig ist. Die Digital-Twin-Forschung stellt geeignete Größen bereit, verfolgt sie jedoch unter anderen Fragestellungen: Der Sim-to-Real-Transfer und seine Fehlerquellen sind umfassend beschrieben [8], kontinuierlich synchronisierte Zwillinge dienen der Bewertung realer Regelstrategien am mitlaufenden Modell [9]. Die Zwischenrepräsentationen, an die eine Begründung anknüpfen könnte, liefern neuro-symbolische Ansätze zur Kopplung von subsymbolischer Wahrnehmung und symbolischer Handlungsplanung [10] sowie die hierarchische Verstärkungslernliteratur mit ihrer Zerlegung von Verhalten in wiederverwendbare Teilfertigkeiten [11]; der zugrunde liegende modulare Zyklus geht auf die klassische deliberative Zerlegung in Wahrnehmung, Planung und Handlung zurück [12].

Offen bleibt in beiden Strängen dieselbe Frage: Welche dieser Größen machen zusammengenommen eine Begründung aus, und wann ist sie vollständig? Solange das nicht festgelegt ist, bleibt der Digitale Zwilling ein Mittel zur Verbesserung von Übertragbarkeit und Sicherheit, aber kein Träger einer Begründungsstruktur. Genau diese Festlegung wird im Folgenden vorgenommen.

III. Hintergrund: S-PACT und der SUPPA-Zyklus

S-PACT (Synchronized Predictive Adaptive Collaborative Twin) ist eine neuro-symbolische Architektur, die neuronale Wahrnehmung, symbolische Repräsentation und zwei getrennte Zwillinge verbindet [1]. Der Digitale Zwilling (DT) hält den beobachtbaren Zustand des realen Systems in strukturierter, semantisch annotierter Form. Er simuliert nicht und prognostiziert nicht, sondern dient als faktische Verankerung mit nachvollziehbarer Datenherkunft. Der Prädiktive Zwilling (PT) ergänzt den DT um zeitliche und kausale Modelle. In ihm werden Zustandsübergänge ausgeführt, Handlungsalternativen durchgerechnet und Regelstrategien erlernt, bevor sie auf dem realen System zum Einsatz kommen. Beide Zwillinge werden fortlaufend abgeglichen.

Der Ablauf der Verarbeitung wird in [1] als SUPPA-Zyklus beschrieben, eine Erweiterung der klassischen deliberativen Zerlegung in Wahrnehmung, Planung und Handlung [12] um zwei Stufen. Die Stufen sind als funktionale Zuordnung zu verstehen und nicht als starre Verarbeitungsreihenfolge; die Kritik an einer solchen Festschreibung ist seit den verhaltensbasierten Architekturen bekannt [13]. Sense überführt Rohdaten in strukturierte Beobachtungen. Understand bildet diese auf die semantische Repräsentation des DT ab, also auf Objekte, Relationen und Rollen. Predict rechnet im PT die Folgen möglicher Handlungen über einen endlichen Horizont durch. Plan wählt anhand dieser Prognosen eine Handlung aus. Act führt sie aus und speist die Abweichung zwischen Prognose und Messung in den nächsten Zyklus zurück.

IV. Entscheidungsspuren als Erklärungsbegriff

Als Erklärung einer Fahrentscheidung zum Zeitpunkt t wird im Folgenden nicht eine nachträgliche Zuschreibung verstanden, sondern ein während der Entscheidung entstehendes Protokoll. Die Entscheidungsspur E(t) ist definiert als das Tupel

$$E(t) = (\, z(t), A(t), P(t), a^*(t), R(t) \,)$$

mit dem semantischen Zustand z(t) im DT, der Menge A(t) der zum Zeitpunkt t zulässigen Handlungskandidaten, den im PT für diese Kandidaten prädizierten Verläufen P(t), der ausgeführten Handlung $a^*(t)$ und den Verwerfungsgründen R(t), also der Angabe, welches Kriterium die nicht gewählten Kandidaten verletzt haben.

An diesen Begriff werden drei Anforderungen gestellt. Vollständigkeit verlangt, dass alle fünf Bestandteile für jede protokollierte Entscheidung vorliegen. Lokalität verlangt, dass sich die Spur auf einen einzelnen Entscheidungszeitpunkt bezieht und nicht auf ein aggregiertes Verhalten über eine Fahrt. Nachprüfbarkeit verlangt, dass jeder Bestandteil unabhängig gegen aufgezeichnete Daten geprüft werden kann: z(t) gegen die Messung, P(t) gegen den tatsächlich eingetretenen Verlauf und $a^*(t)$ gegen die im Fahrzeug ausgeführten Stellgrößen.

Die zentrale These lautet: Die in S-PACT vorgenommene Trennung von faktischem DT und kausal-zeitlichem PT ist eine besonders geeignete, aber weder eine notwendige noch eine hinreichende Struktur für E(t). Nicht notwendig ist sie, weil andere Architekturen dieselben Bestandteile explizit repräsentieren können, etwa modellprädiktive Regelung oder modellbasiertes Verstärkungslernen mit expliziten Rollouts; notwendig ist allein, dass die fünf Bestandteile überhaupt als benannte Objekte vorliegen. Geeignet ist sie, weil z(t) und P(t) in ihr verschiedene Herkunft und verschiedene Prüfinstanzen besitzen: Der DT ist gegen die Messung prüfbar, der PT gegen den tatsächlich eingetretenen Verlauf. Damit zerfällt die Nachprüfbarkeit der Spur in zwei unabhängige Prüfungen statt in eine gemeinsame. Nicht hinreichend ist die Trennung, weil der PT in [1] als Simulations- und Lernumgebung eingeführt ist: Er stellt die Mittel bereit, Handlungsalternativen durchzurechnen, erzeugt jedoch im laufenden Betrieb nicht von selbst zu jeder ausgeführten Handlung eine protokollierte Kandidatenmenge samt Verwerfungsgründen.

Abzugrenzen ist der Vorschlag gegen rein end-to-end gelernte Regler ohne explizite Kandidaten- und Bewertungsrepräsentation. Sie liefern a*(t) und implizit z(t), aber weder A(t) noch P(t) noch R(t), sodass Begründungen dort nachträglich approximiert werden müssen. Wertbasierte Verfahren über einer diskreten Aktionsmenge stellen dagegen A(t) und eine Rangfolge bereit; was ihnen fehlt, ist R(t) im hier verwendeten Sinn, also die Angabe des verletzten Kriteriums statt eines bloßen Wertunterschieds.

Vorgeschlagen wird deshalb eine zusätzliche Schicht über der bestehenden Architektur: die explizite Repräsentation von A(t), P(t) und R(t) im Entscheidungszyklus sowie deren Protokollierung.

Der kritische Bestandteil ist damit R(t). Verwerfungsgründe lassen sich nur angeben, wenn die Plan-Stufe eine Auswahl über einer benannten Kandidatenmenge trifft und ihr Auswahlkriterium explizit vorliegt. Die vorgeschlagene Schicht ist damit nicht kostenlos, sondern schränkt die Gestaltung der Plan-Stufe ein: Sie verlangt entweder eine Kandidatengenerierung mit anschließender Bewertung im PT oder eine gelernte Strategie, deren Ausgabe über einer endlichen Kandidatenmenge normiert und deren Bewertungsfunktion mitgeführt wird. Ob sich diese Einschränkung ohne Einbußen an Regelgüte einlösen lässt, ist offen und stellt die zentrale technische Frage des Vorschlags dar.

V. MINIMALAUFBAU: MINIATURE AUTONOMY

Als Untersuchungsgegenstand dient ein bewusst reduzierter Aufbau. In einer Modellwelt im Maßstab 1:87 fährt ein Fahrzeug mit Bordkamera und Mikrocontroller; zwei Deckenkameras erfassen fortlaufend seine Pose und aktualisieren damit den DT [2]. Die Fahrbahn ist im DT als zweidimensionales Belegungsgitter mit Mittellinien und Rändern abgebildet, das Fahrzeug durch ein kinematisches Einspurmodell mit dem Lenkwinkel als einziger Stellgröße. Synthetische Kamerabilder werden mit den Parametern der realen Kamera gerendert, sodass beide Domänen denselben semantischen Beobachtungsraum besitzen. Die Querabweichung von der Mittellinie wird in beiden Domänen identisch berechnet und dient als Abgleichsignal; bei größerer Divergenz hält der PT die Vorwärtssimulation an und reinitialisiert seinen Zustand aus dem DT [1].

δ bezeichnet im Folgenden einen Lenkwinkelkandidaten, H den endlichen Prädiktionshorizont und CTE (cross-track error) die Querabweichung des Fahrzeugs von der Fahrspurmitte. Abb. 1 zeigt den Zusammenhang an einem einzelnen Entscheidungszeitpunkt t0.

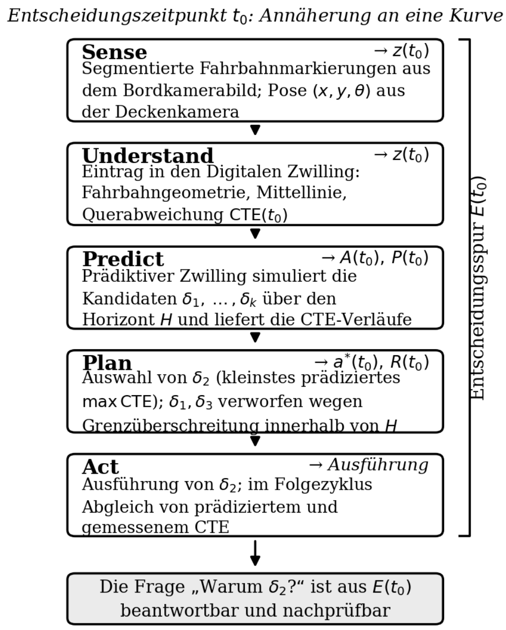

ABB. 1 Zerlegung einer einzelnen Fahrentscheidung in die Bestandteile der Entscheidungsspur, dargestellt am Fahrszenario der Miniature Autonomy (Abschnitt 5). Von oben nach unten sind die fünf Stufen des SUPPA-Zyklus aufgetragen; die kursive Angabe am rechten Rand jedes Kastens nennt den Bestandteil von E(t0), den die jeweilige Stufe erzeugt. Der Darstellung ist zu entnehmen, dass die Spur kein zusätzliches Erhebungsverfahren erfordert: Sense und Understand liefern gemeinsam z(t0), Predict die Kandidatenmenge A(t0) samt prädizierten Verläufen P(t0), Plan die ausgeführte Handlung a*(t0) und die Verwerfungsgründe R(t0). Alle fünf Bestandteile entstehen an genau einer Stelle des ohnehin durchlaufenen Zyklus, sodass die Frage nach der Begründung einer Stellgröße ohne nachträgliche Rekonstruktion beantwortbar ist. Eigene Darstellung.

Dieser Aufbau folgt dem Prinzip der minimalen Modellierung: Es wird nicht versucht, die Realität möglichst vollständig abzubilden, sondern nur diejenigen Eigenschaften, die für die untersuchte Frage entscheidend sind. Für den Erklärungsbegriff ist das ein Vorteil, denn der Zustand z(t) besteht aus wenigen, einzeln prüfbaren Größen: Pose, Fahrbahngeometrie und Querabweichung. Damit ist die Nachprüfbarkeit des Zustandsanteils z(t) nicht nur formulierbar, sondern praktisch einlösbar; für P(t) und R(t) gilt das noch nicht.

Der in Abb. 1 dargestellte Ablauf ist entsprechend zu lesen: Er beschreibt, wie sich eine Entscheidungsspur mit den vorhandenen Komponenten protokollieren ließe, nicht ein bereits durchgeführtes Experiment. Tabelle 1 grenzt ab, welche Bestandteile heute implementiert sind und welche den vorgeschlagenen Ausbau darstellen.

Bestandteil	Stand
Synchronisierter DT: Pose und Fahrbahngeometrie [2]	implementiert
Identische Berechnung der Querabweichung in beiden Domänen [1]	implementiert
Reinitialisierung des PT aus dem DT bei Divergenz [1]	implementiert
Erlernen und Rückspielen von Regelstrategien, Real2Sim2Real [1]	implementiert
Prädiktive Aufgabenvalidierung am Manipulator [3]	implementiert, anderer Demonstrator
Explizite Kandidatenmenge A(t) und Bewertung P(t) je Zyklus	vorgeschlagen
Protokollierung vollständiger Entscheidungsspuren E(t)	vorgeschlagen
Sprachliche Aufbereitung der Spur für Adressaten [4]	vorgeschlagen

TABELLE 1 Abgrenzung des implementierten Standes von der vorgeschlagenen Erweiterung. Die linke Spalte nennt den Bestandteil, die rechte seinen Realisierungsstand; Quellenangaben verweisen auf die Arbeit, in der der jeweilige Bestandteil beschrieben ist. Der Tabelle ist zu entnehmen, dass die Zwillingssynchronisation und der Lernkreislauf bereits realisiert sind, während genau die drei Bestandteile fehlen, die die Entscheidungsspur ausmachen: die explizite Kandidatenmenge, deren Bewertung und die Protokollierung. Die vorgeschlagene Erweiterung betrifft ausschließlich die untere Gruppe.

VI. Limitationen und geplante Evaluation

Nicht belegt wird, dass Entscheidungsspuren Menschen tatsächlich beim Verstehen helfen; dies wäre in einer Nutzerstudie zu prüfen und ist eine von der Struktur unabhängige Frage. Ebenso wenig wird gezeigt, dass die vorgeschlagene Struktur post-hoc erzeugten Erklärungen überlegen ist, da ein Vergleich mit entsprechenden Verfahren aussteht. Eine protokollierte Spur begründet eine Entscheidung, sie rechtfertigt sie nicht: Ist das Prognosemodell im PT falsch, so ist auch die Begründung nachvollziehbar falsch. Der betrachtete Aufbau ist zudem einspurig, einzelfahrzeugbezogen und frei von anderen Verkehrsteilnehmern, und die in Abschnitt 4 benannte Einschränkung der Plan-Stufe ist ein Eingriff in den Regelentwurf, dessen Auswirkung auf die Regelgüte hier nicht bestimmt wird.

Für die Erweiterung sind drei Größen vorgesehen, die sich ohne Nutzerbeteiligung erheben lassen. Die Vollständigkeitsrate gibt den Anteil der Zyklen an, für die alle fünf Bestandteile von E(t) vorliegen. Die Rekonstruierbarkeit prüft, ob eine erneute Simulation aus der aufgezeichneten Spur dieselbe Handlung innerhalb einer Toleranz reproduziert. Der Prognosefehler misst die Abweichung zwischen prädizierter und gemessener Querabweichung über den Horizont und bewertet damit, wie belastbar der Bestandteil P(t) ist. Erst diese drei Größen erlauben es, die eingangs gestellte Frage empirisch zu beantworten.

VII. Fazit

Vorgeschlagen wurde, Erklärbarkeit in twin-nativer autonomer Mobilität nicht als Eigenschaft eines Modells, sondern als Protokolleigenschaft eines Entscheidungszyklus zu fassen. Die Entscheidungsspur benennt fünf Bestandteile, die eine Architektur erzeugen muss. Die Trennung zwischen faktischem und prädiktivem Zwilling in S-PACT schafft dafür die Voraussetzungen, ersetzt aber nicht die vorgeschlagene explizite Repräsentation von Handlungskandidaten, prädizierten Verläufen und Verwerfungsgründen. Sein Wert entscheidet sich an der Frage, ob sich vollständige, rekonstruierbare Spuren im laufenden Betrieb des beschriebenen Aufbaus erheben lassen. Die dafür nötigen Kriterien sind benannt, ihre Erhebung ist der nächste Schritt.

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Precise Localization of Mobile Robots in GNSS-Challenged Urban Mobility Scenarios: Experimental Insights on the Influence of Anchor Vertical Placement Using Ultra-Wideband

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Abstract **Autonomous navigation of mobile robots and micromobility vehicles in dense urban corridors requires decimeter-level localization accuracy that GNSS (Global Navigation Satellite System) alone cannot reliably provide. Ultra-wideband (UWB) offers a promising complementary solution via precise time-of-flight measurements. However, UWB outdoor localization remains underexplored, particularly how anchor geometry affects positioning performance. This paper presents experimental insights into the influence of anchor vertical placement on two-dimensional (2D) UWB positioning accuracy outdoors. Three anchor-height configurations were evaluated over a 7 m x 10 m field using a custom Qorvo DWM3000-based UWB beacon system built at HAW Hamburg: one homogeneous baseline configuration (all anchors at 2.7 m) and two configurations with incremental height variations up to 0.6 m. Static measurements were conducted with the tag mounted at 0.80 m to simulate a mobile robot. Positioning performance was assessed via mean position offsets, standard deviations, 2D positional scatter, and Dilution of Precision (DOP) analysis.**

Keywords— Ultra-wideband, UWB outdoor localization, UWB outdoor positioning, Qorvo DWM3000, anchor vertical placement, anchor geometry, dilution of precision, mobile robots, micromobility vehicles, GNSS-challenged environments

I. Introduction

The increasing deployment of autonomous mobile robots and micromobility vehicles in urban environments demands robust, decimeter-level positioning capabilities. Classical satellite-based navigation using the Global Navigation Satellite System (GNSS) is widely available but fails to meet precision and reliability requirements in dense urban corridors, under bridges, in tunnels, and wherever signal multipath or blockage degrades accuracy or causes complete outages [10], [14], [32]. Unlike in road traffic, these limitations are particularly acute on narrow sidewalks, where lane markings are absent, and the boundary between pedestrian and vehicle zones is ambiguous, making sub-decimeter accuracy a hard requirement for safe autonomous operation.

Ultra-wideband (UWB) technology has emerged as a promising complementary or alternative positioning solution, offering decimeter ranging accuracy for outdoor localization. UWB is based on ultra-short radio pulses transmitted across an exceptionally wide bandwidth of at least 500 MHz, enabling high temporal resolution and precise ranging. It achieves time-of-flight (ToF) measurements with theoretical ranging accuracy in the centimeter range under line-of-sight (LOS) conditions [1], [3], [7]. These properties result in UWB being inherently robust against multipath interference and narrowband noise, predominant error sources in conventional RF (Radio Frequency) positioning systems. The growing integration of UWB transceivers into commercial infrastructure further supports the vision of city-scale UWB-aided localization as a cost-effective complement to GNSS for future autonomous mobility systems [24].

This combination of ultra-wide bandwidth, centimeter-level ranging capability, and multipath robustness is directly relevant to the "Shared Guide Dog 4.0" developed at HAW Hamburg, a self-driving navigation device for blind and visually impaired individuals which requires sub-decimeter to centimeter outdoor positioning for use cases in urban scenarios [31]. The UWB system operates as a UWB localization setup consisting of fixed anchors and a mobile tag: anchors are deployed at known positions within the environment, typically mounted on existing urban infrastructure, while the tag is attached to the moving platform, which in this work corresponds to the *Shared Guide Dog 4.0*. The HAW Hamburg UWB beacon system for indoor [27], [28] and preliminary outdoor settings [31] has emerged from a series of student research works, confirming the suitability of the test environment and establishing the performance baseline from which this publication draws its experimental findings [32].

While UWB performance in indoor environments is well-established [9], [10], outdoor deployments introduce additional challenges stemming from environmental geometry and deployment constraints. First, the operating surface is often non-planar (i.e., sloped terrain), which introduces spatial variability in both user position and signal propagation conditions. Second, practical installation constraints prevent strict control over anchor geometry, including the inability to mount all anchors at the same physical height. In real urban deployments, anchors are typically attached to lampposts, building walls, or other fixed urban infrastructure, resulting in significant variations in elevation above ground level. Consequently, the anchor network forms a non-planar 3D geometry rather than an idealized planar configuration, raising a fundamental practical question: How does vertical heterogeneity in anchor placement affect 2D localization accuracy?

This question of vertical heterogeneity is addressed through a controlled outdoor experimental study using a custom UWB beacon system built at HAW Hamburg, based on a Qorvo DWM3000 module. We are investigating three anchor-height configurations within a defined 7 m × 10 m measurement field, evaluating both static tag positioning accuracy and dynamic trajectory performance under conditions representative of micromobility use cases [32].

The main contributions of this paper are:

(1) A systematic outdoor experimental study of UWB anchor vertical placement effects on 2D localization accuracy using production-grade UWB beacon DWM3000 hardware.

(2) Quantitative position statistics (σ_x, σ_y, $\Delta\bar{x}$, $\Delta\bar{y}$, σ_{2D}) and Horizontal Dilution of Precision (HDOP) analysis for three anchor-height configurations.

(3) Practical infrastructure design guidelines for UWB-based outdoor localization in GNSS-challenged urban environments.

II. Related Work

A. UWB Fundamentals and Standards

UWB localization rests on foundational signal theory established by Win and Scholtz [1], [2], who demonstrated that sub-nanosecond impulse-radio signals achieve exceptional temporal resolution for ranging. Dardari et al. [3] catalogued the primary error sources in multipath environments, while Shen and Win [25] derived information-theoretic limits showing that accuracy depends jointly on ranging quality and anchor geometry. Molisch [4] characterized UWB propagation channels relevant to outdoor deployments. The regulatory baseline is the IEEE 802.15.4z-2020 amendment [6], which standardized the enhanced UWB PHYs used by the DWM3000; Coppens et al. [24] and Alarifi et al. [9] review the changes of the IEEE UWB standards and the transceiver chipset development from 2007 to 2020. Gezici et al. [7] provide the foundational tutorial on UWB positioning methods covering time-of-arrival (ToA), time-difference-of-arrival (TDoA), and hybrid approaches.

B. UWB Localization at HAW Hamburg

A series of student research works at HAW Hamburg has progressively refined and extended the UWB beacon system developed at HAW Hamburg. Harnisch [27] conducted the first systematic performance characterization of the HAW UWB system, benchmarking accuracy and signal stability at distances from 2 m to 75 m. Koch [28] subsequently developed a two-stage UWB positioning system combining Kalman and particle filters with a reinforcement-learning-based correction, achieving up to 10 cm accuracy under indoor conditions. Koch [29] extended this work to automatic anchor-position calibration, significantly reducing infrastructure setup time and removing the need for manual survey measurements. Gleitzmann [30] demonstrated on-board UWB localization for a miniature watercraft platform (MS nHAWigatora) in laboratory and field conditions, achieving a median root-mean-square-error (RMSE) of 4.9 cm in controlled LOS environments and confirming the versatility of the HAW beacon design across mobile platform types. Obaid and Al-Aloush [31] conducted a preliminary outdoor investigation of the UWB system for the Shared Guide Dog 4.0, confirming a car park test site as suitable for outdoor UWB measurements with low building-induced interference. These works collectively form the research lineage from which the present study [32] is derived.

C. Indoor UWB Localization

Most published UWB localization research focuses on indoor environments. Ridolfi et al. [11]

demonstrated that UWB scalability in high-density deployments depends critically on anchor geometry. Tiemann et al. [12] applied UWB to UAV navigation in GNSS-denied indoor environments, achieving sub-decimeter accuracy with optimized anchor configurations. Zafari et al. [10] provided a comprehensive survey positioning UWB as the most accurate short-range radio technology. Marano et al. [13] addressed non-line-of-sight (NLOS) identification in UWB ranging, highlighting that ground-surface reflections are among the most significant error sources, a finding directly relevant to outdoor anchor-height studies. Patwari et al. [8] noted that non-uniform node heights introduce 3D geometric ambiguities degrading 2D estimation.

D. Outdoor UWB and Anchor-Height

Outdoor UWB research is comparatively sparse. Kristem et al. [14] experimentally measured ranging errors in a dense urban environment at antenna heights of 10 cm and 100 cm, finding that errors increase significantly when antennas are positioned closer to the ground, with NLOS errors exceeding 10 m when a building fully blocks the direct path. Lee et al. [15] provided the most comprehensive outdoor UWB dataset to date, sweeping antenna heights from 0.5 m to 2.0 m, and explicitly concluding that "ranging errors from ground reflections and Fresnel-zone attenuations depend on the antenna height." These errors "should be prevented in anchor deployment." The Wi-PoS outdoor platform [16] derived a ground-reflection path-loss model and achieved sub-5 cm accuracy at 50 to75 m outdoors.

As with UWB localization research in general, research on anchor placement geometry has also been studied primarily indoors. Kramařić et al. [17] evaluated UAV localization under varying indoor anchor configurations; Cho et al. [18] demonstrated that DOP does not always predict empirical error in compact UWB fields; Pan et al. [19] proposed genetic-algorithm-based anchor placement optimization; and Chen et al. [20] jointly optimized anchor placement and NLOS mitigation. Studies investigating DOP in UWB systems have shown that anchor-height affects z-axis DOP. Specifically, Feng et al. [21] and Yao et al. [22] reported this effect, although both studies were conducted indoors. Polonelli et al. [23] reported 33.2 % better ranging accuracy for the DW3000 (introduced in 2021) compared with the earlier-generation DW1000 (introduced in 2013) at short distances. Consistent with this generational shift, HAW Hamburg has likewise migrated from the widely adopted DW1000- to the DW3000-based UWB hardware.

E. Research Gap

To the best of the authors' knowledge, no prior study has experimentally isolated anchor vertical placement as a single variable in an outdoor UWB deployment using a ground-level mobile platform and current-generation Qorvo DWM3000 hardware, while evaluating accuracy via both 2D position statistics and DOP. This paper fills that gap, based on the experimental data of [32].

III. UWB SYSTEM DESCRIPTION

A. Technology Fundamentals

UWB is defined by the Federal Communications Commission (FCC) as any signal occupying more than 500 MHz of bandwidth or exceeding 20 % of its center frequency. In practice, UWB operates in the frequency range between approximately 3.1 GHz and 10.6 GHz, well separated from narrowband technologies such as Bluetooth Low Energy (2.4 GHz) or Wi-Fi (2.4/5 GHz). UWB transmitters emit very short pulses (typical duration ≈ 100 ps to 2 ns) at low power spectral density (below −41.3 dBm/MHz), enabling precise ToA measurements.

UWB system uses the ToF technique to calculate the distance between two UWB nodes. The UWB tag transmits a frame at time $t1$, and the anchor receives it at $t2$. The drawback of this technique is that precise clock synchronization between all nodes is necessary.

The fundamental range (r) equation for ToF is:

$$r = c \cdot (t_2 - t_1) \tag{1}$$

$$r = c \cdot ToF \tag{2}$$

where c is the speed of light (299.8 × 10^6 m/s), t_1 is the transmission time, t_2 is the reception time, and ToF is calculated as $t_2 - t_1$.

The double-sided two-way ranging (DS-TWR) technique, used in this study [34], eliminates clock-synchronization requirements between anchor and tag [3]. DS-TWR is an extension of the two-way ranging (TWR) technique. In TWR (single-sided), a UWB node sends one message, waits for a reply, and calculates the round-trip time. The issue is that the anchor's clock and the tag's clock are never perfectly synchronized; even tiny differences in their oscillator frequencies (known as clock drift) introduce small timing errors which result in corresponding distance errors. DS-TWR mitigates this effect by performing the exchange twice, once measured from the anchor's clock and once from the tag's clock, and then combining both measurements mathematically such that the clock drift cancels out, as depicted in FIG. 1.

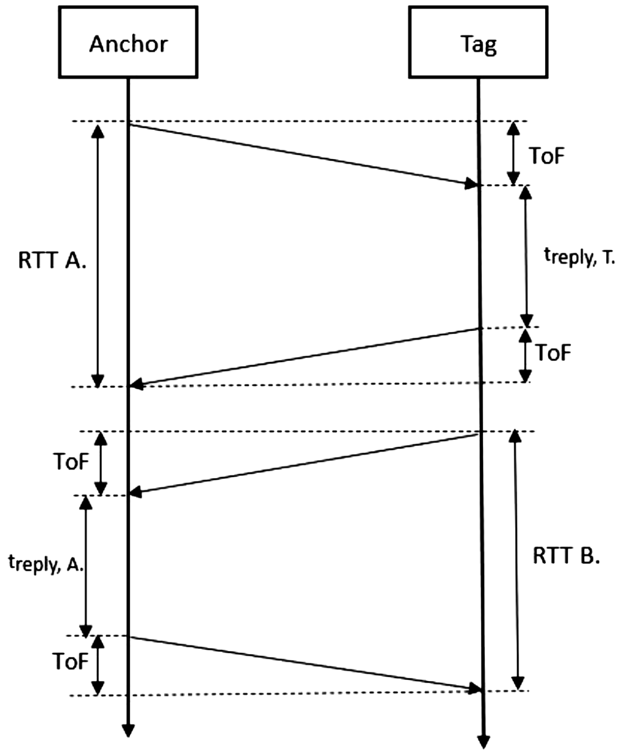

FIG. 1 DOUBLE-SIDED TWO-WAY RANGING (DS-TWR) TECHNIQUE [34]

$$RTT\ A. = 2 \cdot ToF + t_{reply,\ T.} \tag{3}$$

$$RTT\ B. = 2 \cdot ToF + t_{reply,\ A.} \tag{4}$$

$$RTT\ A. + RTT\ B. = 4 \cdot ToF + t_{reply,\ T.} + t_{reply,\ A.} \tag{5}$$

$$ToF_{DS-TWR} = \frac{RTT\ A. + RTT\ B.\ - t_{reply,\ T.} - t_{reply,\ A.}}{4} \tag{6}$$

$$r = c \cdot ToF_{DS-TWR} \tag{7}$$

Where RTT denotes the round-trip time, $RTT\ A.$ is the round-trip time A and $RTT\ B.$ is the round-trip time B, $t_{reply,\ T.}$ is the reply time of the tag, $t_{reply,\ A.}$ is reply time of the anchor.

B. Positioning via Trilateration

With at least three anchors at known positions, the tag location is estimated by trilateration: the intersection of spheres centered on each anchor with radii corresponding to the measured distances. The position is obtained by solving the nonlinear least-squares problem [35].

C. Hardware Platform — DWM3000 Beacon

The custom UWB beacon system, as depicted in FIG. 2, was designed and progressively refined at HAW Hamburg through a series of student works [27], [28], [29], [30], [31], [32], [33].

Each beacon integrates: (1) a Qorvo DWM3000 UWB transceiver (DW3110 chip, IEEE 802.15.4 [6], Channel 5, 6.4896 GHz, 499.2 MHz bandwidth) [5]; (2) an RP2040 dual-core 32-bit microcontroller (133 MHz) implementing DS-TWR and trilateration in firmware; and (3) an ESP32-C3 module for UART/Wi-Fi output. The enclosure meets IP67 weatherproofing with an integrated 2000 mAh Li-ion battery, enabling up to 40 Hz data acquisition [32]. Metallic fasteners were excluded from the antenna keep-out zone (10 mm clearance) to preserve the radiation pattern [5].

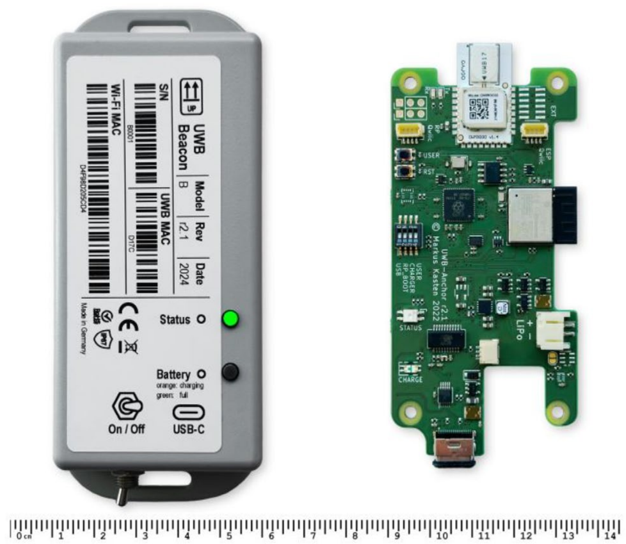

FIG. 2 UWB DWM3000 BEACON [29]

IV. EXPERIMENTAL METHODOLOGY

A. Test Site and General Setup

All experiments were conducted outdoors on the car parking lot at campus Berliner Tor, HAW Hamburg (GNSS coordinates 53.55703256° N, 10.02212560° E), a semi-open urban surface confirmed to exhibit low building-induced UWB interference in the preliminary study by Obaid and Al-Aloush [31].

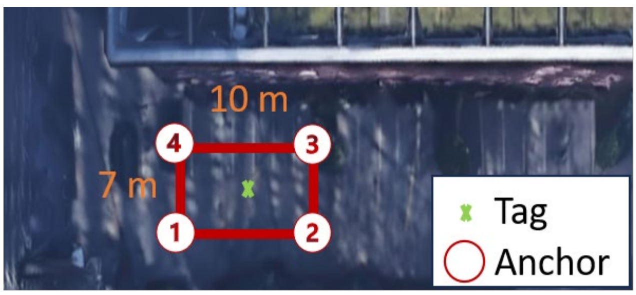

FIG. 3 TEST SITE CAR PARKING LOT BETWEEN BERLINER TOR 5 AND LÜBECKERTORDAMM 4 AT CAMPUS BERLINER TOR, HAW HAMBURG [SOURCE: GOOGLE EARTH]

The test field was a rectangle of 7 m (width) × 10 m (length), representative of a typical micromobility corridor or pedestrian pathway, as depicted in FIG. 3. Four UWB anchors and one tag were deployed. Anchors were mounted on 2 m PVC poles fixed to

0.7 m tripod stands (Hama LS-L200); all hardware in the antenna vicinity was plastic or taped to prevent metallic signal disruption [5]. A spirit level ensured beacon alignment at each position [32], as depicted in FIG. 4.

FIG. 4 SPIRIT LEVEL ALIGNMENT TO PREVENT UWB BEACON POSITIONED AT AN ANGLE [32]

B. Anchor-Height Configurations

The horizontal anchor footprint (7 m × 10 m rectangle) was held identical across all configurations, isolating the vertical placement effect from any horizontal geometric change [32]. The minimum anchor-height of 2.7 m was chosen to remain well above the first Fresnel-zone clearance, minimizing ground-reflection-induced ranging bias recommended by Kristem et al. [14] and Lee et al. [15]. Three sequential height Configurations were tested as described in TABLE I and depicted in FIG. 5.

Configuration	Height (m)	Description
A	2.7/2.7/2.7/2.7	All anchors have a uniform baseline
B	2.7/2.9/2.7/3.1	Two anchors raised (+20, +40 cm)
C	2.7/2.9/3.1/3.3	All anchors staggered (steps of +20 cm)

TABLE I ANCHOR-HEIGHT CONFIGURATIONS (A, B, AND C)

C. Reference Position and Measurement Procedure

The reference tag position was physically marked and measured with a tape measurement, giving two-dimensional (2D) coordinates (x_{ref}, y_{ref}) = (3.50 m, 5.00 m) relative to anchor-1 in FIG. 5. Ground-truth uncertainty is estimated at ±10 cm (tape alignment).

- Static Measurements: For each configuration (A to C), the tag was placed at the reference position, and approximately 4000+ samples were recorded over a 2-minute measurement series. The area was kept free of all people and moving objects (except the operator).

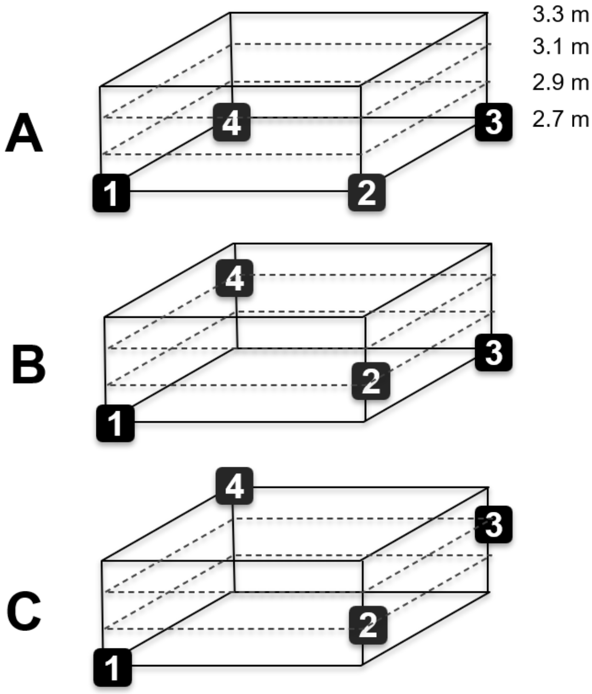

FIG. 5 ANCHOR-HEIGHT CONFIGURATIONS (A, B, AND C)

D. Evaluation Metrics

Position accuracy is evaluated using the mean position offsets, standard deviations, 2D positional scatter, and complemented by horizontal dilution of precision (HDOP) analysis [32].

$$\Delta\bar{x} = \bar{x} - x_{ref} \tag{8}$$

$$\Delta\bar{y} = \bar{y} - y_{ref} \tag{9}$$

$$\sigma_x = \sqrt{\frac{1}{N}\sum_i^N (x_i - \bar{x})^2} \tag{10}$$

$$\sigma_y = \sqrt{\frac{1}{N}\sum_i^N (y_i - \bar{y})^2} \tag{11}$$

$$\sigma_{2D} = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{12}$$

Where $\Delta\bar{x}$ and $\Delta\bar{y}$ are the mean position offsets in the x- and y-axes, respectively; $\bar{x}$ and $\bar{y}$ are the mean values of measurement series in the x and y axes, respectively; x_{ref} and y_{ref} are the reference position coordinates in x- and y-axes, respectively; σ_x and σ_y are the standard deviations in the x- and y-axes, respectively; N is the number of measurements; x_i and y_i are the measured position values of the i-th measurement in the x- and y-axes, respectively; i = 1, 2, . . . , N is the sequence index of the measurements; and σ_{2D} is the 2D positional scatter.

DOP quantifies how strongly the geometric arrangement of anchors amplifies ranging errors into position errors. DOP is derived from the diagonal elements of the covariance matrix Q, where H is the linearized design matrix (13) of unit direction vectors between tag and anchors [32].

$$H = \begin{bmatrix} \frac{x-x_1}{r_1} & \frac{y-y_1}{r_1} \\ \frac{x-x_2}{r_2} & \frac{y-y_2}{r_2} \\ \vdots & \vdots \\ \frac{x-x_n}{r_n} & \frac{y-y_n}{r_n} \end{bmatrix} \tag{13}$$

Where x_i and y_i are known coordinates of n tracking anchors in x and y axes, respectively; r_i is true geometric 2D distance from tag to each anchor; and i = 1, 2,…, n represents the number of anchors.

$$r_i = \sqrt{(x-x_i)^2 + (y-y_i)^2} \tag{14}$$

$$Q = (H^T H)^{-1} \tag{15}$$

$$Q = \begin{bmatrix} q_{xx} & q_{xy} \\ q_{yx} & q_{yy} \end{bmatrix} \tag{16}$$

Where q_{xx} represents the geometric dilution variance scaling factor for the x-axis, q_{yy} represents the geometric dilution variance scaling factor for the y-axis. The horizontal dilution of precision (HDOP) is derived as:

$$HDOP = \sqrt{q_{xx} + q_{yy}} \tag{17}$$

The lower DOP indicates a favorable geometry. Standard classification: DOP ≤1 (Ideal), 1-2 (Excellent), 2-5 (Good), >5 (Poor). All HDOP values in this study lie in the "Excellent" range (1-2).

V. Result and Discussion

A. Static Position Statistics

TABLE II presents the static position statistics for all three anchor-height configurations [32]. The reference position of the tag is (x_{ref}, y_{ref}) = (3.50 m, 5.00 m).

Configuration	$\bar{x}$ (m)	$\bar{y}$ (m)	$\Delta\bar{x}$ (cm)	$\Delta\bar{y}$ (cm)	σ_x (cm)	σ_y (cm)	σ_{2D} (cm)
A	3.317	4.636	-18.3	-36.4	1.20	0.85	1.47
B	3.313	4.616	-18.7	-38.4	1.19	0.87	1.47
C	3.295	4.646	-20.5	-35.4	1.97	1.14	2.28

TABLE II STATIC POSITION STATISTICS VS ANCHOR-HEIGHT CONFIGURATIONS (x_{ref}=3.50 METER, y_{ref}=5.00 METER)

Several key observations emerge. First, the systematic positional offsets ($\Delta\bar{x}$ ≈ -18 to -21 cm; $\Delta\bar{y}$ ≈ -35 to -39 cm) are consistent across all Configurations, indicating a systematic bias independent of anchor-height. This bias is attributed to tape-based reference position measurement uncertainty (±10 cm [32]) combined with minor environmental reflections. Critically, since this offset is common to all configurations, it does not affect the comparison between anchor-height configurations.

Second, the positional scatter (σ_x , σ_y) is consistently low across all three configurations. Configurations A and B both achieve σ_x ≈ 1.2 cm and σ_y ≈ 0.9 cm, while Configuration C shows a modestly larger scatter of σ_x ≈ 2.0 cm and σ_y ≈ 1.1 cm. The combined two-dimensional scatter is σ_{2D} ≈ 1.5 cm for Configurations A and B, and σ_{2D} ≈ 2.3 cm for Configuration C, a moderate increase of roughly 55 % rather than a severe degradation, indicating that all three height configurations maintain good 2D positional stability.

The geometric explanation for this small increase is found in the structure of the direction-vector matrix H , which relates each anchor's LOS direction to the tag with the resulting position error. Each anchor's direction vector has a horizontal component (in the X-Y plane) and a vertical component (along the Z-axis). In the homogeneous configuration (Configuration A), all anchors are placed at the same height, so their direction vectors are nearly co-planar with a very limited vertical (Z-axis) component; ranging errors are therefore concentrated in, and distributed symmetrically, across the horizontal X-Y plane. In Configuration B, two anchors are raised by differing amounts from the baseline of 2.7 m: Δ of 0.2 m (2.9 m) and Δ of 0.4 m (3.1 m)) and alternated with the two baseline anchors (2.7 m) around the layout rather than grouped together; this interleaved arrange-ment adds a modest vertical (Z-axis) component to the geometry while keeping it evenly balanced across the four anchor positions so the low-scatter behavior of the baseline is preserved. In Configuration C, all four anchors are staggered across a wider 60 cm range. While the configuration remains height-symmetric in the sense that no single anchor stands out as an outlier, the larger spread of vertical (Z-axis) components shifts a small additional share of the ranging error from the vertical direction into the horizontal X-Y plane, producing the slightly larger but still well-controlled increase in horizontal scatter observed for this configuration.

B. Dilution of Precision Analysis

TABLE III presents the computed HDOP values for each configuration, derived from the design matrix H at the mean estimated tag position [32].

Configuration	HDOP
A	1.114
B	1.123
C	1.132

TABLE III HDOP VS ANCHOR-HEIGHT CONFIGURATIONS

HDOP remains nearly constant across all three configurations (1.114, 1.123, 1.132), confirming that the identical horizontal anchor footprint does not meaningfully change horizontal error amplification regardless of anchor-height variation. The marginal increase from Configuration A to Configuration C (ΔHDOP ≈ 0.018) is negligibly small and falls well within the “Excellent” classification (HDOP ≤ 2) throughout [36], indicating that the anchor-height configurations tested in this study do not compromise the horizontal geometric quality of the anchor layout.

C. Practical Infrastructure Guidelines

Synthesizing the static tag position measurements at 0.8 m height, 2D positional scatter and HDOP findings, the following design principles emerge for UWB anchor vertical placement when supporting 2D localization of a sidewalk-based mobile robot.

(1) Prefer uniform anchor-height (Configuration A) where infrastructure permits. This gives the lowest 2D positional scatter (σ_{2D} ≈ 1.5 cm) and the most predictable position estimate.

(2) Symmetric two-anchor-height (Configuration B) is an effective alternative when uniform anchor mounting is impractical. Real sidewalk anchor mounting points (posts, walls, railings) rarely match exactly. Configuration B shows that ±40 cm of alternating height incurs negligible degradation in 2D accuracy (σ_{2D} ≈1.5 cm) and only a marginal increase in HDOP.

(3) Fully staggered anchor-height (Configuration C) is usable but less accurate. A 60 cm height spread, e.g. from sloped terrain or mismatched mounts, raises 2D positional scatter to σ_{2D} ≈ 2.3 cm (≈ 55 % above baseline), acceptable for sidewalk robots.

(4) HDOP is nearly flat across all configurations (1.114-1.132), so it can’t flag Configuration C’s higher 2D positional scatter. Test-field validates actual 2D accuracy, not just HDOP, when anchor height varies substantially.

(5) Keep all anchors above 2.0 m to clear pedestrians, bicyclists, and robots, and avoid ground-reflection bias [14], [15].

(6) Results are static-only. Robot motion, curbs, slopes, and tag-height fluctuations during travel were not tested here and needed separate validation.

(7) The 7 m × 10 m test field is small relative to real sidewalk networks; results should be validated at larger scale before generalizing.

VI. CONCLUSION

This paper presented a static experimental study of the influence of UWB anchor vertical placement on 2D localization accuracy using Qorvo DWM3000-based beacons at HAW Hamburg. Three anchor-height configurations (A to C) were evaluated over a 7 m × 10 m outdoor test field, with the tag held at a fixed height of 0.8 m to simulate the sensor platform of a sidewalk-based mobile robot.

The results show that 2D positional scatter remains low and comparable for uniform (Configuration A) and moderately alternating anchor-height (Configuration B), with σ_{2D} ≈ 1.5 cm for both. A fully staggered height configuration (Configuration C, 60 cm spread) increases scatter moderately to σ_{2D} ≈ 2.3 cm, an increase of approximately 55% over the baseline. HDOP increases only marginally across all three configurations (1.114, 1.123, 1.132), remaining within the “Excellent” classification throughout, and does not by itself predict the scatter increase observed in Configuration C, indicating that vertical height diversity redistributes a small share of ranging error into the horizontal plane in a way that horizontal-footprint-based HDOP alone cannot capture.

These findings suggest that UWB anchors mounted at uniform or moderately varying heights are well-suited for 2D localization of mobile robots on sidewalks, while larger height disparities introduce a measurable but moderate accuracy cost. As the present results are based on static measurements over a comparatively small test field, they should be regarded as an initial geometric baseline. Future work should validate these findings under dynamic conditions with a moving robot platform, across larger-scale outdoor test sites, and account for tag-height variation caused by curbs, slopes, and uneven sidewalk surfaces.

VII. FUTURE WORK

Several extensions to this study would strengthen and broaden its conclusions. First, the present analysis is limited to static tag positions; future work should repeat these measurements with the tag mounted on a moving robot platform to assess whether the scatter trends observed here hold under dynamic conditions, including motion-induced multipath and Doppler effects. Second, the 7 m × 10 m test field used in this study is small relative to real sidewalk networks; validating the anchor-height effect at larger spatial scales and over longer anchor-to-tag distances would clarify whether the 55% scatter increase observed for Configuration C persists, grows, or diminishes with scale. Third, this study fixed the tag at a constant 0.8 m height; since a sidewalk robot crosses curbs, ramps, and uneven terrain, future measurements should quantify how small fluctuations in tag height – not just anchor-height – affect 2D accuracy. Fourth, the present test field was kept free of obstacles during measurement; future studies should introduce static obstructions (parked vehicles, street furniture, vegetation) and dynamic obstructions (pedestrians, cyclists, other moving robots) between anchors and tag to evaluate accuracy and HDOP under realistic NLOS and multipath conditions. Finally, extending the anchor-height range beyond the 60 cm tested here, and combining UWB with complementary sensing (e.g., IMU or wheel odometry), would help to establish more general design limits for outdoor UWB infrastructure supporting autonomous sidewalk navigation.

VIII. Acknowledgement

This work was supported by the German Federal Ministry of Research, Technology, and Space (BMFTR) under the “Safe Walker” project at HAW Hamburg. The authors gratefully acknowledge the contributions of Markus Kasten, Michel Harnisch, Sven Koch, Justus Gleitzmann, Mohammed Obaid, and Mohammad Al-Aloush, whose student research works at HAW Hamburg provided the experimental foundation and hardware platform on which this publication is based.

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Zwischen Zusatzerlösen und Lobbyismus: Die THG-Quote als Instrument und Konfliktfeld der Antriebswende

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Die Treibhausgasminderungsquote (THG-Quote) ist ein zentrales marktgestütztes Instrument zur Dekarbonisierung des Verkehrssektors in Deutschland. Dabei werden Inverkehrbringer fossiler Kraftstoffe verpflichtet, ihre THG-Emissionen in ihrem Kraftstoffmix um eine jährlich steigende Quote zu senken. Die ökonomische Attraktivität der THG-Quote für verschiedene Erfüllungsoptionen der THG-Quote (dies sind insbesondere die sogenannten konventionellen, fortschrittlichen und abfallbasierten Biokraftstoffe, erneuerbare Kraftstoffe nicht biogenen Ursprungs (RFNBOs) und Strom) hängt wesentlich von der politischen Ausgestaltung der THG-Quote sowie der Höhe der Quote ab. Dabei sind die möglichen Erlöse aus der Einbringung in die THG-Quote schwankend: 2022 waren Erlöse von 0,19 €/kWh für Netzstrom und rund 9 €/kg für grünen Wasserstoff möglich, diese sind 2024 auf 0,03 €/kWh für Netzstrom und rund 3 €/kg für grünen Wasserstoff deutlich gesunken. Grund dafür war insbesondere eine Überfüllung durch fortschrittliche Biokraftstoffe, bei denen Betrugsvorwürfe im Raum stehen [1]. Mit der *Zweiten Weiterentwicklung der Treibhausgasminderungsquote* (2026) wurden diese Schwächen durch insbesondere Betrugsprävention adressiert. In dem Zusammenhang hat sich die Höhe der THG-Quote im Jahr 2026 wieder erhöht und entsprechend sind auch Erlöse von rund 0,14 €/kWh (PV-Strom 0,29 €/kWh) und rund 10 €/kg für grünen Wasserstoff möglich.

Das Competence Center for Energy Transition (CC4E) der HAW Hamburg setzt sich mit verschiedenen Aspekten der THG-Quote auseinander (bspw. [2]–[5]). Auf dem Themenkongress Mobilität 2026 wurde ein Paper vorgestellt, in dem analysiert wurde, welche Interessenvertreter welche Interessen im Gesetzgebungsverfahren der Bundesregierung zur *Zweiten Weiterentwicklung der THG-Quote* geäußert haben und inwieweit sich diese Interessen in den Änderungen zwischen Referentenentwurf und Regierungsentwurf widerspiegeln [6]. Methodisch kombiniert das Paper dabei eine strukturierte qualitative Inhaltsanalyse mit einer quantitativen Korrelationsanalysen. Grundlage sind dokumentierte Stellungnahmen aus der Verbändeanhörung des Bundesministeriums für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (BMUKN) sowie einschlägige Interessenvertretungs-Aktivitäten im Lobbyregister im Zeitraum zwischen Juni und Dezember 2025. Insgesamt sind 84 Interessenvertretungen mit 92 Stellungnahmen bzw. Aktivitäten identifiziert und anhand ihrer Positionen zu den zentralen Erfüllungsoptionen der THG-Quote gruppiert worden. Das Paper kommt zu dem Schluss, dass sich in der untersuchten Phase des Gesetzgebungsverfahrens der Bundesregierung ein strukturelles Ungleichgewicht zugunsten ressourcenstarker Interessen aus den Bereichen Biokraftstoffe und RFNBOs und zu Lasten der Erfüllungsoption Strom erkennen lässt. Diese asymmetrische Interessenrepräsentation spiegelt sich auch in den Änderungen vom Referenten- zum Regierungsentwurf wider, indem alle Erfüllungsoptionen außer Strom (-0,13) eine positive Korrelation (0,06 bis 0,13) zwischen Positionierung ihrer Interessenvertreter und der tatsächlichen rechtlichen Umsetzung aufweisen.

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Use of supercapacitors for inland ferries in Germany based on empiric resistance calculations

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Abstract **To achieve the CO_2 reduction target, it is necessary to electrify the entire mobility sector, including inland waterway transport. For this reason, electrical ferries are being deployed around the world to decarbonize maritime transport. With their high energy density, lithium-based batteries are the dominant electrical energy storage (ESS). However, due to their inherent technological disadvantages with a comparatively slow charging rate and limited cycle life, their areas of application are limited. Therefore, the project aims to evaluate the potential of supercapacitors in ferries. Supercapacitors offer a high-power density with a long cycle life, making them a promising technology for ferries with a short charge time, high load power peaks or as part of a hybrid ESS during the acceleration phases of the ferry crossing. An empiric simulation of the German inland fleet is conducted to validate the application of supercapacitors.**

Keywords— ferry, supercapacitor, empiric ship resistance, load profile

I. INTRODUCTION

The impact of the maritime transportation greenhouse gas emission worldwide is estimated to be around 3 % of the global emissions and expected to rise to 15 % according to a study from the International Maritime Organization (IMO) [1, 2]. Therefor a reduction of the CO_2 emissions of 40 % by 2030 and 70 % by 2050 is set for the entire fleet, while the goal is to achieve net-zero in 2050 [3]. Although inland ferries fall under the regulation of their respective countries the goal should remain the same.

In Germany 113 inland passenger ferries and 161 car ferries with an installed power of 12,145 kW and 44,935 kW (in total 57 MW) in 2022 are listed [4]. With an average age of 39.9 years respectively 48.8 years most inland ferries are using a diesel engine to power the propulsion and passenger related systems. A study from 2022 regarding costal ferries listed 105 vessels in Germany (77 under German flag) with a total emission of approx. 309,000 t of CO_2 per year and an average age for the European fleet of 35 years [5]. As a result, laws have been passed to speed up the electrification of the ferries. For example, in Hamburg all motorboats and ferries must be equipped with emission-free motors by 2030 to be allowed to run on the Alster [6].

Supercapacitors (SC) are already widely discussed for peak shaving and recuperation in electric cars and busses where they are used to support acceleration and braking [7, 8]. With an energy density of 1 – 10 Wh/kg and a power density of several kW/kg supercapacitors are highly suitable for hybrid energy storage systems (HESS) in onshore vehicles. As maritime vehicles have different power profiles and driving dynamics, the application of SCs is a current subject of research [9-11].

Up to this date only two ferries have been completely equipped with supercapacitors: the Ar Vag Tredan [12] and the New Ecology [13]. The French ferry was decommissioned in 2019 due to technical issues and currently retrofitted with batteries to be launched again in 2026 [14] while the current status of the Chinese ferry is not public.

This study aims to identify the potential for the electrification of the German inland ferry fleet using supercapacitors based on publicly available data.

The paper starts with an analysis of energy storage systems with requirements for HESS for ferries and shore-side HESS for grid-serving purposes. Afterwards the energy consumption for the German inland ferry fleet is conducted by acquiring available data, developing speed profiles and calculation with different empiric ship resistance methods. Finally, the paper concludes with the result that superconductors ESS are feasible for the German fleet with only a few exceptions and with recommendations for future developments in the field of ESS and the demand of new empiric ship resistance for shallow waters.

II. ENERGY STORAGE SYSTEMS FOR INLAND FERRIES

A. Energy storage analysis

As the energy density of electric storage systems (EES) is significantly lower than their fossil counterparts, the decision for the optimal technology depends on the scope of application.

An important aspect in developing electric operated ferries is to implement a suitable storage system for the specific task [15]. In a study from the European Maritime Safety Agency (EMSA) 16 commercial and 13 future ESS were rated for their possible application in the maritime sector [16]. The most applicable for the use in ships were *Nickel manganese cobalt oxide* (NMC), *Lithium iron phosphate* (LFP), *Nickel Cobalt Aluminum* (NCA) and *Lithium Titanate Oxide* (LTO) with mentioning supercapacitors as suitable for low-energy peak shaving.

For Ferries LTO is the preferable battery choice as this chemistry has a high cycle life, fast charging capabilities and durability [15]. The relatively high specific cost per capacity on the other hand is a disadvantage [15, 17]. Compared to the charging rate of the supercapacitors, which can be fully charged in under a minute, the C-rate of LTO with 4.3, which equals to a full-charge cycle in around 14 minutes, is comparable low and results in a deficit for many inland ferries.

Further important properties are the calendar life, usability as a second life ESS for the shore-side charging station, operation temperature range, the investment cost, safety requirements, and overall sustainability evaluated in a life-cycle assessment (LCA). These aspects need specific knowledge of the individual application and should be conducted as such. Compared to batteries supercapacitors have a regulation gap that hinders their market entry [18].

B. HESS Requirements for ferries

Both inland and coastal ferries offer possibilities for the implementation of supercapacitors as a part of a HESS. Inland ferries often operate between two destinations with a fixed schedule, high frequency, relatively small energy consumption and a very short time span to recharge the electrical storage. ESS only based on batteries are facing the issue of low recharge rates, which are typically between 0,25 h and 2 h, and a cycle lifetime from 5000 up to 7000 full cycles. An inland short-distance ferry has a typical lifetime of over 30 years with over 100.000 crossings resulting in numerous replacements of a battery only ESS.

In comparison, coastal ferries have longer crossing times, higher energy consumption per crossing and more time to recharge the electrical storage. These differences make batteries or fuel cells with a high energy density more suitable than supercapacitors. In this case, supercapacitors can be used to support the main ESS with peak shaving during high load phases for example while the ferry is maneuvering in the port. In the project “V-Access” the load profile is divided in a high energy and a high-power profile using a low-pass filter [17]. With this approach the ESS can be optimized for a high-energy ESS and a high-power ESS separately resulting in a smaller HESS overall.

C. Grid-serving charging of ferries

Similar to electric cars, the charging of E-ferries has to be done without violating the grid directives of the middle or low voltage grid. Especially for ferries in rural areas this can lead to significant obstacles in the implementation, if no further adjustments are considered [19]. Demand-Side-Management (DSM) is only a feasible option for certain time slots of ferry schedules, as it results in lower charge rates and can affect the crossing capability of the vessel. The over scaling of the HESS of the ferry is not a practical solution as the weight and/or volume is limited.

Hence, an additional onshore HESS is often installed to reduce the stress of the grid. To optimize costs, the onshore HESS can be combined with renewable energies (photovoltaic and wind energy) to decrease the size and costs of the storage and also decrease the costs of investments in the local grid. The costs of the shore-side HESS with a photovoltaic power plant combined with the investment in the charging infrastructure can offer a decrease of the overall cost for ferries with multiple stops as every charging opportunity reduces the size of the HESS of the ferry and offers a greater flexibility of load distribution in the grid.

III. CALCULATION OF THE INLAND FERRY CONSUMPTION IN GERMANY

A. Data acquisition of the German inland ferry fleet

Although the information of all ferries in Germany is published anonymized by the administration the data is mostly inaccurate and, in several cases, incomplete or false [20]. In addition to this obstacle, detailed knowledge about the ship dimensions and hull form or a test of a model of the ship in a towing tank is needed for an accurate calculation of the ship resistance. Inland Ro-Ro-ferries can differ significantly from the usual given parameter length-overall as the ramps on both sides of the ship can increase the length by over 20 % while not being relevant to the resistance calculation. First the false data had to be identified, for example if the volume of the ferry based on the multiplication length, width and depth were greater than the displacement volume and corrected. Secondly missing or unusual data had to be corrected using characteristic coefficient values for ferries [21, 22]. The third and last step was to balance corrected values evenly on the depended values. For example, if the block coefficient c_B is corrected which is defined as the ratio between the displacement volume and the block volume, the deviation is evenly proportional distributed on all values to reduce the statistical error in the calculation. After these corrections steps 239 of 274 ferries were useable for further calculation.

B. Speed profiles

Speed profiles of inland ferries mostly have a typical trapezoidal shape with a linear acceleration and deceleration phase. The maximum energy consumption occurs mostly during the steady-state crossing part of the journey while the highest load appears during the acceleration part. For inland ferries with a short crossing, e.g. few hundred meters, the speed profile can change similar to an exponential function without a plateau [23]. In this case the maximum energy consumption can also happen during the acceleration.

Double-ended inland ferries with two destinations usually do not show high power peaks caused by maneuvering in the harbor compared to ferry types with only one exit. Efficient mooring locations directly on the opposite side of the river are essential for reduced daily energy consumption.

C. Empiric calculation of ship resistance

Several different methods are known in the literature for the empirical calculation of ship resistance R_T (for a comprehensive overview refer to [22]). The ships resistance is a complex problem to calculate consisting mostly of the frictional and residual resistance depending not only on the ship's hull form and speed but also of the water conditions (waves, shallow water) [24]. As a result, each method is specific to certain type of ship and field of application (inland, coastal). An approach to reduce the deviation from the true value is to use multiple methods to calculate a mean resistance value [22]. For inland ferries and combination of Holtrop-Mennen [22], Zwankow [25] and the Leningrad Design-Office-Method [25] showed better results compared to Hollenbach [22], Guldhammer-Harvald [22], Van Oortsmerssen-Helmore [26] and Wróblewska-Sirotina [25].

D. Energy-saving operating profiles

The main disadvantage of supercapacitors is the low energy-density compared to state-of-the-art battery technologies which limit their use to short-

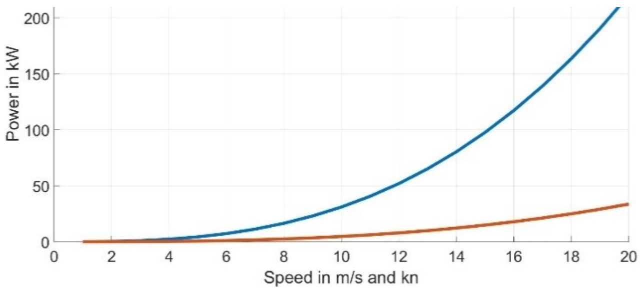

FIG. I EXAMPLE SPEED-POWER CURVE OF A FERRY

distance inland ferries routes. To expand the field of application the power load profile of the ship must be as energy efficient as possible. As the amount of energy saving is mainly dependent on the maximum speed of the vessel during the trip because the propulsion power is exponentially connected to the speed (Error: Reference source not foundFormula 1 and Fig. I).

$$P_{load} = R_T \cdot v^3 \cdot \eta \tag{1}$$

To calculate the power load of the ferry P_{load} the overall specific ship resistance R_T, the ship speed v and the efficiency of the propulsion η is necessary. With this simplified formula it is possible to extrapolate generic load profiles for each vessel and optimize for energy savings while keeping the same transportation profile by reducing the berthing time. [27] shows that the most efficient speed-profile is achieved by minimizing the maximum speed and acceleration as both are exponentially connected to POWER consumption. A gliding phase during which the thruster propulsion is zero offers less benefit than a lower maximum speed at the same total crossing time.

E. Calculation of the German ferry fleet energy consumption

With the public data gathered and the empirical calculation methods the resistance of each ferry can be approximated. For the electrical retrofit of the ferries several assumptions need to be made:

- Shipboard system efficiency $\eta_b = 0{,}85$
- Ship propulsion efficiency $\eta_p = 0{,}6$
- Max. ESS weight = 80 % of ship's deadweight
- Ship lifetime = 20 years
- Long berthing = 10 min berthing, 8 min charging
- Short berthing = 2 min berthing, 1 min charging
- Operation period = 6 AM to 10 PM, all seasons

	300 m	600 m	900 m	1200 m	1500 m	1800 m	2100 m	2400 m	2700 m	3000 m
1 m/s	0,92	1,06	1,22	1,35	1,52	1,65	1,81	1,95	2,13	2,23
2 m/s	0,85	0,92	0,99	1,06	1,13	1,22	1,28	1,35	1,44	1,52
3 m/s	0,82	0,87	0,92	0,97	1,02	1,06	1,11	1,16	1,22	1,26
4 m/s	0,81	0,85	0,88	0,92	0,96	1,00	1,03	1,06	1,10	1,15
5 m/s	0,80	0,83	0,86	0,89	0,92	0,95	0,98	1,01	1,04	1,06

FIGURE II: COST COMPARISON FOR SUPERCAPACITORS/LTO-BATTERIES FOR LONG BREAK TIME FOR DIFFERENT SPEEDS AND DISTANCES

	300 m	600 m	900 m	1200 m	1500 m	1800 m	2100 m	2400 m	2700 m	3000 m
1 m/s	0,58	0,83	0,98	1,11	1,26	1,41	1,56	1,70	1,88	2,04
2 m/s	0,37	0,58	0,76	0,83	0,90	0,98	1,05	1,13	1,20	1,28
3 m/s	0,31	0,44	0,58	0,72	0,78	0,83	0,88	0,93	0,98	1,03
4 m/s	0,28	0,38	0,48	0,58	0,69	0,76	0,80	0,83	0,87	0,91
5 m/s	0,26	0,34	0,43	0,51	0,59	0,67	0,75	0,78	0,80	0,83

FIGURE II: COST COMPARISON FOR SUPERCAPACITORS/LTO-BATTERIES FOR SHORT BREAK TIME FOR DIFFERENT SPEEDS AND DISTANCES

Two berthing options were chosen to highlight the influence of the charging time and the number of trips per day for the decision of the ESS. The short berthing time favors the high-power density of the supercapacitors whereas the longer berthing time the high energy density of the LTO battery. The amount of daily trip varies from 16 to 86 (long berthing time) to 18 to 299 (short berthing time) depending on crossing speed and distance.

An operation period 16 hours per day for all seasons is chosen as an example of a high-frequency year-round ferry. Lower frequency seasons (e.g. winter season) do not reduce the ESS size but have an impact on the electricity costs which is out of the scope for this paper. The reduction of energy density due to colder temperatures in the winter season is considered by the safety margins.

Characteristic	***LTO***	***Supercapacitor***
Gravimetric energy density in Wh/kg	100	3.5
Gravimetric power density in W/kg	100	4,180
Depth of discharge (DoD) in %	80	90
End of Life (EoL) in %	80	100*
Costs per capacity in €/kWh	700	20,000
Max. equivalent cycles	20,000	Up to 1,000,0000

Table I Characteristics for the comparison of LTO and SCs for inland ferries (*EoL-capacity of SCs set to 100 % due to high cycle life)

The characteristics for both ESS types are listed in Table I [15, 28]. The values for ship components are typical for ferries whereas the specifications of the supercapacitor are based on a commercially available component.

The simulations show that with the exception of only 13 at the highest speed, all inland ferries of the catalogue can be fully powered with supercapacitors without reducing the crossing speed or violating the maximum weight limit of the ESS. If the maximum speed is reduced to 4 m/s all the ferries can be retrofitted with supercapacitors.

The cost comparison (Fig. II and III) shows the relative cost savings between an ESS based on LTO-batteries and supercapacitors for all 239 ferries. The relation is cost of SCs to cost of batteries so that for values below 1 supercapacitors are the more cost-effective option and vice versa. For short charging times the SC-solutions is up to four times cheaper than the state-of-the-art battery option. Even for the long charging use case supercapacitors are shown as a viable option for very short distances.

IV. CONCLUSION

Germany has a high potential to reduce the CO_2-emissions by electrifying the inland ferries. Most of the vessels are older than 30 years and use diesel engines. By developing operational profiles, the necessary energy consumption can be reduced and improve the usage of a supercapacitor ESS/HESS. With an empirical resistance calculation approach the scope of application for supercapacitors is determined. The result shows that with small adjustments of the ship maximum speed all of Germany's ferries can be electrified and fully equipped with supercapacitors. Especially for short distances at high speed with a high daily crossing frequency supercapacitor ESS show promising market potential.

For a broad implementation in the field the regulation gap has to be closed, and more field tests must prove the market readiness of the whole system. In the near future new developments or improvements of battery types and supercapacitors in the aspect of energy density, power density, cycle life and costs per capacity can significantly change the choice of the optimal ESS. A general approach for use cases with high energy or high power demand combined with an optimization of the ferry schedule based on passenger traffic is therefore recommended for future studies as well as more in depth studies for empirical resistance methods for shallow water and short distance ferries.

V. Acknowledgement

This work was part within the project ASAP (03EMF0401B), funded by the German Federal Ministry for Digital and Transport.

VI. Declaration Use of AI

I acknowledge the use of DeepL Translator and DeepL Write (https://www.deepl.com/de) to improve the writing of this publication. The final written text, analysis, and verification of original sources remain solely the responsibility of the authors.

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Umweltsimulationsprüfstand als Multi-Exciter zur gezielten Strukturverformung der Traktionsbatterien

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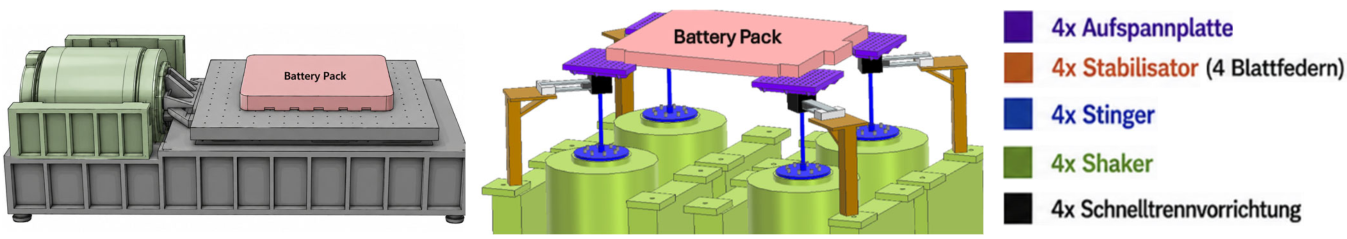
Mit der zunehmenden Integration der Traktionsbatterie in die tragende Fahrzeugstruktur zukünftiger Elektrofahrzeuge (BEV) gewinnen realitätsnahe Prüfverfahren an Bedeutung. Insbesondere bei Cell-to-Chassis-Konzepten werden die großflächig im Fahrzeugboden verteilten Zellen und Zellverbünde stärker durch Umwelteinflüsse beansprucht. Das Forschungsprojekt GRISU fokussiert bei der Umweltsimulation auf die realitätsnahen mechanischen Beanspruchungen der Batterie. Diese umfassen lokale Schwingungen sowie globale Strukturverformungen durch Biegung und Verwindung. Als Grundlage der Prüfstandsauslegung wurden hierzu Beschleunigungen an verschiedenen BEVs im Fahrbetrieb entlang des Übertragungswegs von der Fahrbahn in die Batterie erfasst, hinsichtlich repräsentativer mechanischer Beanspruchungen ausgewertet und die vertikale Richtung als maßgeblich identifiziert.

Konventionelle Vibrationsprüfstände leiten die dynamische Anregung in eine starre Grundplatte ein, auf der die Batterie montiert ist. Diese starre Kopplung sperrt Freiheitsgrade, die eine Strukturverformung der Batterie ermöglichen. Das entwickelte Multi-Exciter-Konzept aus mehreren unabhängig ansteuerbaren Schwingerregern (Shaker) verzichtet auf die Grundplatte und leitet die Anregung über vier Shaker vertikal direkt an die Anbindungspunkte der Batterie ein. Dadurch werden gezielte Verformungen durch Biegung und Verwindung zugelassen und die zuvor im Fahrbetrieb erfassten Beanspruchungen unter kontrollierten Laborbedingungen und realitätsnäheren mechanischen Randbedingungen reproduziert.



Prinzip eines konventionellen Prüfstands mit starrer Kopplung (links) und des Multi-Exciter-Konzepts mit direkter Batterieanregung ohne starre Kopplung zur gezielten Strukturverformung (rechts).

Der Verzicht auf die Grundplatte schafft neue konstruktive Anforderungen an Krafteinleitung, Stabilisierung und Anbindung der Batterie. Dabei sollen Wechselwirkungen zwischen Prüfstand und Batterie das zu untersuchende dynamische Strukturverhalten möglichst wenig beeinflussen. Die als CFK-Rohre ausgeführten Stinger übertragen die Shakeranregung spielfrei auf die Batterie und schützen durch gezielte Verformung die Shaker vor unzulässigen Biegemomenten. Die als Blattfedern mit Elastomerelementen ausgeführten Stabilisatoren begrenzen und dämpfen unerwünschte Querbewegungen, ohne die vertikale Anregung wesentlich zu behindern. Eine hydraulisch klemmende Schnelltrennvorrichtung zwischen Stinger und Lochrasterplatte ist Teil des Brandschutzkonzepts und ermöglicht im Brandfall die schnelle Trennung der vollgeladenen Batterie vom Prüfstand zur anschließenden Löschung und sicheren Lagerung.

Der entwickelte Ansatz soll eine Grundlage schaffen, zukünftige Batteriekonzepte als Komponente ohne fertiges Fahrzeug bereits in einer frühen Entwicklungsphase, jedoch unter möglichst vergleichbaren mechanischen Einwirkungen und Wechselwirkungen, realitätsnah zu untersuchen, abzusichern und gezielt weiterzuentwickeln.

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A Geospatially Informed Governance Framework for Cross-Boundary Mobility in the Kuala Lumpur–Selangor Metropolitan Region

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Abstract

Cross-boundary commuting between Kuala Lumpur and Selangor has created a functional metropolitan mobility region that extends beyond formal administrative boundaries. Yet responsibility for transport planning, feeder services, land-use decisions, and mobility data remains divided among multiple jurisdictions and agencies. This paper proposes a conceptual framework for understanding how geospatial intelligence can strengthen coordination in metropolitan mobility governance. Drawing on literature on functional urban regions, accessibility, public transport integration, and cross-jurisdictional governance, the framework brings together five key elements: functional mobility demand, geospatial evidence, governance diagnosis, coordinated action, and metropolitan outcomes. Rather than presenting completed GIS or origin-destination analyses, the paper outlines how network mapping, accessibility assessments, land-use overlays, and institutional mapping can be used to identify first- and last-mile gaps, strategic mobility corridors, and barriers to inter-agency coordination. In the Kuala Lumpur-Selangor context, the framework offers a structured foundation for shared data practices, joint corridor planning, coordinated investment, and future empirical testing based on transparent mobility and institutional evidence.

Keywords— cross-boundary mobility, metropolitan governance, geospatial intelligence, conceptual framework, first–last mile integration

I. INTRODUCTION

Rapid urbanisation has pushed metropolitan travel well beyond the administrative boundaries of central cities. Housing, employment, education, commercial activities, and public services are increasingly spread across broader functional regions, creating daily travel patterns that link multiple municipalities and transport systems (Tian et al., 2024; Yasin et al., 2022). As a result, the geographical scale of mobility often extends beyond the administrative scale at which transport, land-use, and infrastructure decisions are planned and implemented.

This mismatch is especially evident in the Kuala Lumpur–Selangor metropolitan region. Kuala Lumpur continues to function as a major centre for employment, education, administration, and services, while neighbouring areas in Selangor accommodate large residential populations, employment hubs, and rapidly developing growth corridors. Travel occurs in both directions, with commuters relying on rail, buses, feeder services, private vehicles, walking, and ride-hailing. Halim et al. (2023, 2025) show that the effectiveness of rail-based mobility depends heavily on reliable feeder services, accessible stations, and smooth connections between different modes of transport. Similarly, Yusoff et al. (2021) stress the need for an integrated transport policy framework across the Klang Valley. Thus, despite significant investment in public transport, the overall network may still underperform when rail services, feeder coverage, pedestrian access, transfer facilities, and land-use development are planned and managed under separate institutional responsibilities.

Cross-boundary mobility is not simply an infrastructure challenge. It is also a matter of metropolitan governance, shaped by fragmented responsibilities, uneven access to information, differing planning cycles, and limited opportunities for joint priority-setting. Carvalho et al. (2023) argue that urban mobility should be planned at the metropolitan scale, while Miharja et al. (2021) emphasise the importance of sustained collaboration among the authorities responsible for regional transport planning. In a similar vein, Weinreich and Skuzinski (2021) show that weak institutional coordination can lead to disconnected services, overlapping responsibilities, and investment decisions that favour individual jurisdictions rather than the needs of the wider functional travel region.

Geospatial intelligence can help bridge the gap between functional mobility patterns and administrative decision-making. Tools such as network mapping, indicative origin-destination analysis, accessibility measures, land-use overlays, and institutional mapping can reveal where mobility gaps occur and identify the organisations responsible for the affected corridors (Delloye et al., 2026; Hersperger et al., 2024). Against this background, the paper focuses on a central question: how geospatial evidence can support a shared understanding of governance challenges and inform coordinated action. It is therefore presented as a conceptual contribution rather than a completed empirical GIS assessment.

Research question: How can geospatial intelligence support the identification of cross-boundary mobility gaps and inform more coordinated metropolitan mobility governance in the Kuala Lumpur-Selangor region?

The paper introduces a five-stage framework that links functional mobility demand, geospatial evidence, governance diagnosis, coordinated action, and metropolitan outcomes. It aims to clarify the types of evidence needed, explain how spatial and institutional gaps can be examined together, and illustrate how agencies can turn a shared diagnosis into coordinated, corridor-based decisions. The framework also provides a clear and transparent foundation for future empirical testing.

II. CONCEPTUAL FOUNDATIONS

A. *Functional Mobility Beyond Administrative Boundaries*

A functional mobility region is shaped by recurring travel patterns rather than by a single legal or administrative boundary. Daily commuting flows connect residential areas with employment centres, educational institutions, commercial districts, and major interchange nodes across the wider metropolitan area. Rodríguez et al. (2022) illustrate how mobile-positioning data can be used to identify such functional areas, while Zhang et al. (2022) show that cross-boundary urban regions often extend beyond officially defined municipal territories. Similarly, Bogomolov et al. (2024) demonstrate that intraday commuting patterns can reveal urban structures that are broader and more dynamic than administrative boundaries suggest. This distinction is important because a transport corridor may function as one integrated travel system even though its stations, roads, feeder routes, and surrounding development are managed by several different authorities.

For public transport users, what matters most is the quality of the entire journey, not the administrative area in which each part of it takes place. Even where rail capacity is sufficient, practical accessibility can still be limited by poor pedestrian connections, inadequate feeder services, inconvenient transfer points, or inaccessible station environments. Ramli et al. (2022) emphasise the importance of walkability and first- and last-mile conditions in making public transport genuinely accessible, while Halim et al. (2023) highlight the role of feeder services and station catchment areas in strengthening rail connectivity. The analysis should therefore consider the full journey from origin to destination, rather than ending at an administrative boundary.

B. *Metropolitan Governance and Institutional Fragmentation*

Metropolitan mobility governance refers to the way public authorities, transport operators, planning agencies, and other stakeholders coordinate decisions across administrative boundaries. Fragmentation arises when responsibilities are divided among different organisations without effective systems for aligning plans, sharing data, coordinating services, or funding cross-boundary initiatives. Weinreich and Skuzinski (2021) show that formal institutional structures alone are not enough to ensure integrated services across jurisdictions, as effective coordination also depends on stable relationships between organisations. Likewise, Zimmermann et al. (2023) stress the need for shared metropolitan priorities and governance mechanisms that can align responsibilities across different levels of administration.

In practice, governance gaps may take the form of uneven feeder-service coverage, disconnected pedestrian routes, poorly coordinated timetables, conflicting land-use decisions, or uncertainty over which agency is responsible for addressing problems in boundary areas. Adopting a metropolitan approach does not mean removing the authority of local governments. Rather, it involves creating a coordinating layer that connects local responsibilities with regional travel patterns and enables joint decision-making for corridors whose costs and benefits extend across several jurisdictions. Carvalho et al. (2023) highlight the importance of planning mobility at the metropolitan scale, while Hersperger et al. (2024) show how interconnected planning frameworks can align policies, responsibilities, and decisions across jurisdictional boundaries.

C. Geospatial Intelligence as Shared Evidence

Geospatial intelligence brings together location-based data, analytical techniques, and visualisation tools to support interpretation and informed decision-making. In mobility planning, it allows transport networks, station locations, travel flows, land use, population distribution, and accessibility conditions to be examined within a single analytical framework. Hardi and Murad (2023) show that spatial accessibility analysis can reveal areas that are physically close to public transport but remain difficult to reach because of weak pedestrian connections, limited feeder services, or inadequate transfer facilities. Farooq et al. (2026) similarly demonstrate the value of GIS-based methods in identifying accessibility gaps within congested urban transport systems. Geospatial analysis can also be strengthened through the integration of multiple data sources. Graells-Garrido et al. (2023), for example, show how mobile-phone data can complement conventional travel surveys, while Lemonde et al. (2021) highlight the value of combining multimodal traffic data to develop a more complete understanding of urban mobility patterns.

The main governance value of geospatial evidence lies in its ability to provide a shared spatial reference for decision-making. A mapped transport corridor or accessibility gap can be examined by transport operators, local authorities, land-use planners, and funding agencies within the same geographical context. Attah et al. (2024) note that GIS and data analytics can strengthen public-sector decision-making by providing spatial evidence for urban planning and infrastructure management. However, maps alone cannot resolve institutional fragmentation. The evidence must also be linked to agency mandates, decision-making procedures, and implementation responsibilities. The proposed framework therefore positions geospatial analysis as part of a broader metropolitan governance system rather than as a standalone solution.

III. METHODOLOGY

A. Conceptual Research Design

This paper uses an integrative conceptual approach. It draws together the 20 peer-reviewed and scholarly sources cited in the manuscript, selected for their relevance to functional urban regions, cross-boundary commuting, public transport accessibility, first- and last-mile integration, metropolitan governance, and geospatial decision support. The Kuala Lumpur-Selangor region serves as the applied context for organising the relationships among these themes. The review is interpretive rather than systematic and does not aim to provide exhaustive coverage of the literature. The study also does not collect primary mobility data, calculate accessibility indicators, or present completed origin-destination or GIS analyses.

The framework was developed in four stages. First, the literature was reviewed to identify recurring mobility challenges linked to administrative fragmentation. Second, different forms of geospatial evidence were grouped according to the planning questions they could help address. Third, institutional issues were organised into a governance diagnosis covering agency mandates, service responsibilities, data availability, and coordination capacity. Finally, these elements were linked to possible governance actions, monitoring needs, and metropolitan outcomes. Together, the stages trace a clear progression from identifying the mobility problem to gathering evidence, diagnosing governance gaps, designing interventions, and evaluating their results.

B. Kuala Lumpur–Selangor Study Context

The study focuses on Kuala Lumpur and its cross-boundary mobility connections with neighbouring local authority areas in Selangor, including Petaling Jaya, Subang Jaya, Shah Alam, Selayang/Gombak, Ampang Jaya, and Kajang/Cheras. Together, these areas form an interconnected metropolitan system in which commuting patterns, transport services, and urban development regularly extend across administrative boundaries. Figure 1 presents the Kuala Lumpur administrative boundary, selected surrounding jurisdictions, major rail corridors, key interchange nodes, and indicative directions of cross-boundary movement. The arrows are not intended to represent measured commuting volumes. Instead, they illustrate the spatial relationships that support a metropolitan approach to mobility planning.

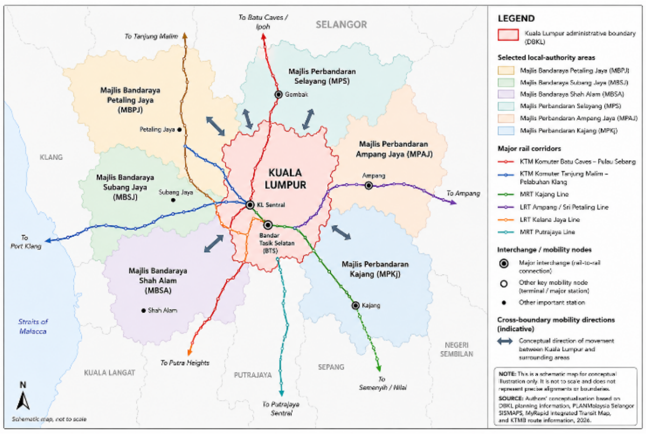

Fig. 1. Schematic Kuala Lumpur–Selangor metropolitan study context showing selected local-authority areas, major rail

corridors, key mobility nodes, and indicative cross-boundary mobility directions. Source: Authors' conceptualisation based on DBKL planning information, PLANMalaysia Selangor SISMAPS, MyRapid Integrated Transit Map, and KTMB route information, 2026.

C. Analytical Domains

The framework is organised around five analytical domains. The examples provided are indicative and do not suggest that all relevant datasets have already been collected. Each domain is connected to a specific planning question and governance purpose, helping to align the conceptual approach with the analysis presented in the following sections.

i. **Functional demand**: Origin-destination patterns, trip purposes, and peak travel flows help define the functional scale of the metropolitan region and identify priority mobility corridors.
ii. **Network and access**: Rail, bus, feeder, walking, and transfer connections are examined to identify gaps in coverage, interchange quality, and first- and last-mile accessibility.
iii. **Land use and activity**: The distribution of residential areas, employment centres, educational institutions, and public services helps determine whether transport provision matches the locations that generate travel demand.
iv. **Jurisdiction and mandates**: Administrative boundaries, agency responsibilities, planning documents, and funding arrangements are used to identify overlapping roles, unclear ownership, and barriers to coordination.
v. **Monitoring**: Indicators relating to accessibility, service quality, equity, data sharing, and implementation progress support the evaluation and ongoing refinement of joint interventions.

D. Framework Construction

The proposed framework consists of five interconnected stages, as shown in Figure 2. It begins with functional mobility demand, which defines the actual scale and pattern of metropolitan travel. Geospatial evidence is then used to examine how transport networks, accessibility, land use, and administrative boundaries interact. The governance diagnosis stage connects the spatial gaps identified to agency mandates, service responsibilities, data constraints, and coordination challenges. These findings then inform coordinated action, including shared data arrangements, corridor-based planning, first- and last-mile priorities, and better alignment of investment decisions. Finally, metropolitan outcomes are assessed in terms of efficiency, equity, accessibility, and climate responsiveness, while ongoing monitoring provides feedback for refining the framework over time.

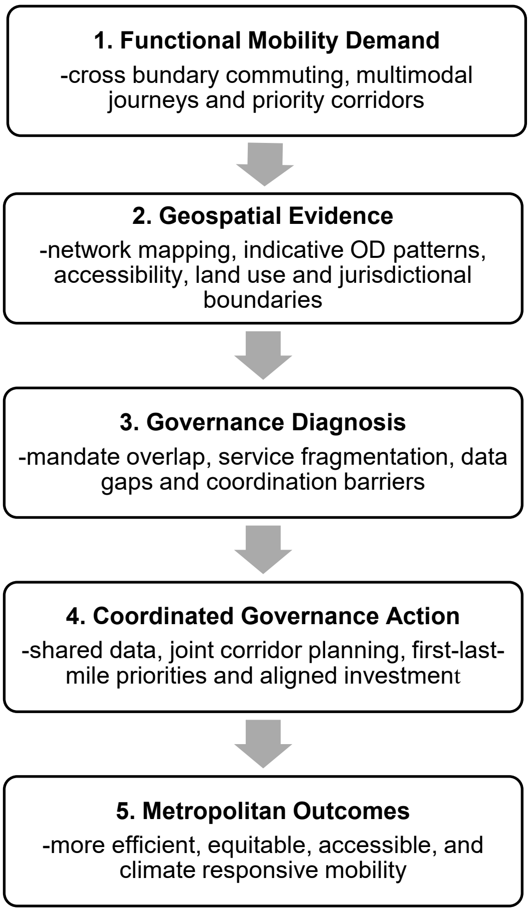

Fig. 2. Proposed geospatially informed metropolitan mobility governance framework. Source: Authors

IV. CONCEPTUAL SYNTHESIS AND DISCUSSION

A. Functional Demand Should Define the Planning Scale

The first proposition is that metropolitan mobility planning should be shaped by actual travel demand rather than jurisdictional boundaries. In the Kuala Lumpur–Selangor region, priority corridors are those that connect residents to employment, education, services, and major interchange nodes in both directions. This approach does not overlook administrative boundaries. Instead, it reveals where those boundaries divide journeys that function as part of the same travel system. It also provides a clearer and more transparent basis for prioritising corridors with substantial cross-boundary movement, frequent transfers, or a strong reliance on feeder services.

B. Geospatial Evidence Can Create a Common Diagnosis

The second proposition is that geospatial evidence can provide a shared language for diagnosing mobility problems. Network mapping can expose gaps between rail, bus, feeder, and pedestrian systems, while indicative origin-destination patterns can highlight areas with strong travel demand. Accessibility assessments can identify poorly connected communities, and land-use overlays can reveal whether transport services align with concentrations of housing, employment, education, and public services. Taken together, these spatial layers turn a broad mobility concern into a more precise corridor-level diagnosis by showing where the problem occurs, which connections are missing, and which organisations are involved.

C. Spatial Gaps Must Be Linked to Institutional Responsibilities

The third proposition is that a spatial diagnosis remains incomplete unless it is tied to institutional responsibility. A single accessibility gap may involve several actors, including a transport operator, a local authority responsible for pedestrian infrastructure, a land-use planning agency, a road authority, and a funding body. Institutional mapping should therefore clarify who manages the relevant assets, who holds the necessary data, which plans apply to the area, and where responsibilities overlap or remain uncertain. By making these relationships visible, a descriptive map becomes a practical coordination tool. It also helps explain whether a mobility gap persists because of limited evidence, fragmented responsibilities, competing priorities, or the absence of a joint decision-making mechanism.Figure 3 operationalises this relationship by connecting illustrative mobility gaps with their geospatial diagnosis, governance implications, and coordinated responses

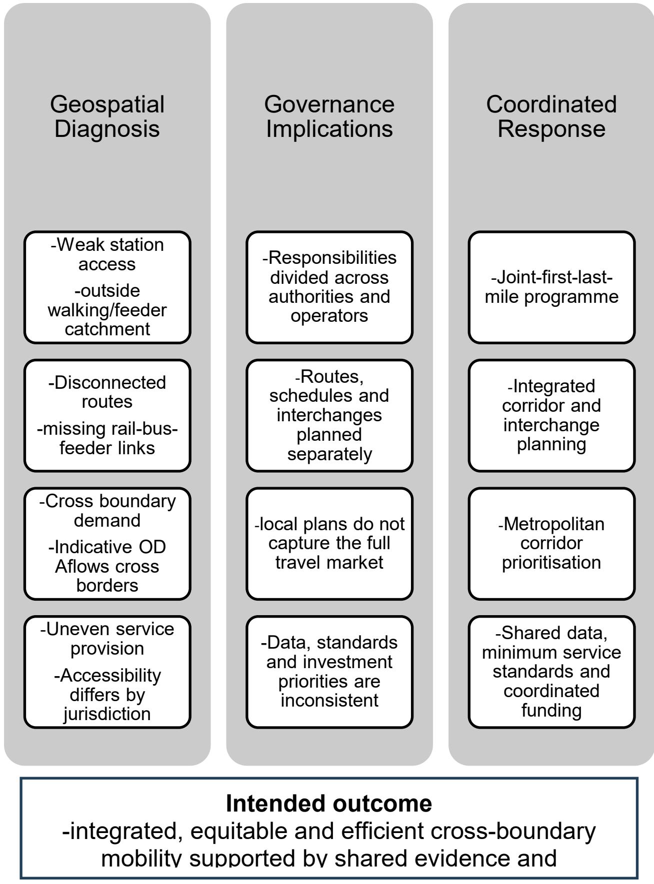

Fig. 3. Translation of geospatially identified mobility gaps into governance and planning responses. Source: Authors'

D. Coordinated Action Should Be Corridor-Based and Iterative

The fourth proposition is that coordinated action should be organised around functional corridors and supported by continuous monitoring. A corridor-based approach allows agencies to coordinate feeder services, station access, pedestrian improvements, interchange design, service schedules, and surrounding land-use decisions across the entire journey. It also provides a practical basis for agreeing on responsibilities, budgets, timelines, and performance indicators. The framework is designed to be iterative, as implementation generates new evidence on service use, accessibility, transfer performance, and institutional cooperation. This evidence can then be used to refine the shared diagnosis and adjust priorities over time.

V. IMPLEMENTATION PRIORITIES AND FUTURE RESEARCH

A. Shared Metropolitan Mobility Data

A practical starting point would be to establish a shared metropolitan mobility data arrangement. This does not necessarily require the immediate creation of a single centralised database. Instead, agencies could begin by agreeing on common data definitions, update schedules, metadata standards, access protocols, and a shared spatial reference for priority corridors. The resulting evidence base should bring together information on transport provision, station access, feeder-service coverage, land use, jurisdictional boundaries, and selected indicators of travel demand, with clear responsibility assigned for managing each dataset.

B. *Joint Corridor Planning*

Priority corridors should be identified using clear and transparent criteria, including the level of cross-boundary demand, reliance on transfers, accessibility gaps, equity concerns, and the feasibility of implementation. Corridor-based working groups could then bring together the relevant local authorities, transport operators, planning agencies, and infrastructure bodies to develop coordinated packages of interventions rather than pursuing isolated projects. Adjusting a feeder service, for instance, may also require safer pedestrian access, better interchange design, consistent passenger information, and more closely aligned land-use management.

C. *Monitoring, Validation, and Empirical Testing*

As this paper is conceptual, its propositions will need to be tested empirically. Future research could apply the framework to selected corridors across Kuala Lumpur and Selangor using clearly documented datasets, study periods, spatial units, indicators, and analytical procedures. Possible methods include network-based station catchment analysis, multimodal travel-time accessibility assessment, origin-destination flow mapping, land-use and population overlays, as well as interviews or document analysis focused on institutional mandates. Such research would help determine whether the relationships proposed in the framework adequately explain observed mobility gaps and coordination challenges.

Evaluation could draw on indicators such as access to public transport, transfer times, feeder-service coverage, pedestrian connectivity, service reliability, user equity, data-sharing performance, and the completion of jointly agreed actions. The study is also limited by its non-systematic review of the literature and the absence of measured mobility and institutional data. However, these limitations point to the next stage of research rather than weakening the value of the conceptual contribution.

VI. CONCLUSION

Cross-boundary mobility between Kuala Lumpur and Selangor functions as an integrated metropolitan system, even though planning and service responsibilities remain divided among different jurisdictions and agencies. The central challenge is therefore not simply the provision of transport, but the mismatch between the geography of everyday travel and the geography of decision-making. This paper addresses that mismatch through a five-stage conceptual framework linking functional mobility demand, geospatial evidence, governance diagnosis, coordinated action, and metropolitan outcomes. Its main contribution lies in showing how spatial evidence can support institutional coordination. Network, accessibility, indicative origin-destination, and land-use data can help identify where mobility gaps are likely to occur, while institutional mapping can explain why those gaps persist and which organisations need to work together.Shared data arrangements, corridor-based planning, coordinated investment, and continuous monitoring provide a pathway from diagnosis to implementation. The paper does not present completed empirical findings, and future research will need to test the framework using transparent mobility datasets, spatial indicators, and institutional evidence. Even at this conceptual stage, however, the framework offers a structured basis for organising mobility decisions around the journeys people make rather than the administrative boundaries they cross.

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Developing Sustainable Spatial Plan Decisions Based On Digital Data From The Turkish Traffic Safety And Density Analysis Platform

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Abstract **Rapid urbanization and increasing motorized mobility create interrelated challenges concerning density, traffic safety, accessibility, and spatial sustainability. This study examines how digital data generated by Türkiye's Traffic Safety Analysis Platform (TSAP) and Traffic Density Analysis Platform (TDAP) can be integrated into sustainable spatial planning decisions. The research adopts a qualitative case-study approach consisting of three stages: a structured review of the platforms, an analysis of their visual outputs at different planning scales, and a data–spatial problem–decision analysis. The findings show that TSAP provides data on accident severity, type, location, time, and high-risk areas, whereas TDAP provides segment-based information on speed, density, queues, peak hours, and travel time. When evaluated together, these datasets can support decisions concerning safety-prioritized corridors, speed management, pedestrian continuity, access management, transfer areas, logistics conflicts, and the equitable distribution of transportation investments. The study proposes a framework for transforming digital traffic data into traceable spatial planning decisions and intervention priorities.**

Keywords— Traffic Safety Analysis Platform, Traffic density analysis platform, safe system approach, sustainable spatial planning, Türkiye.

I. INTRODUCTION

Increasing urbanization, population concentration in metropolitan areas, and the rise in motor vehicle use are driving up demand for road mobility. This process gives rise to numerous challenges in urban transportation systems, including capacity and accessibility, traffic safety, conflicts among road users, traffic density, and the quality of public spaces. Furthermore, the density, delays, speed disparities, and accident risks emerging in road networks affect not only the technical performance of transportation systems but also the sustainability of spatial planning decisions. Consequently, safety assessments in transportation systems are becoming an increasingly important area of research. Particularly in developing countries, it is crucial to link road traffic safety to planning issues such as land use, accessibility, public space, and social justice in relation to accident risks.

Globally, traffic accidents result in approximately 1.19 million deaths and 20–50 million injuries each year [1]. Most of these fatalities and injuries involve vulnerable road users such as pedestrians, cyclists, and motorcyclists. More than 90% of traffic-related deaths occur in low- and middle-income countries [1]. In Türkiye, which ranks among the countries with the highest traffic risks globally, approximately 288,000 traffic accidents resulting in fatalities or injuries occurred in 2025 according to TUİK data, resulting in over 6,000 fatalities [2]. These indicators highlight the importance of developing various safety measures and planning decisions aimed at reducing accident risks using traffic safety data.

In the road traffic safety literature, various modeling approaches are used to examine the likelihood and severity of traffic accidents, as well as the factors that determine them. These approaches often reveal safety issues only after an accident has occurred. However, problems such as incomplete or inconsistent accident records, underreporting of minor accidents, failure to reflect the cause-and-effect relationships of incidents, and the inability to make the data directly usable at the planning scale limit the use of these methods as decision-support tools. At the same time, traffic accidents are not events that can be explained solely by road geometry and traffic volume. Numerous spatial variables—such as pedestrian access, intersection layout, the location of public transit stops, roadside land uses, speed behavior, density distribution, and the organization of public spaces—influence accident risk. For this reason, road traffic safety assessments must be based not only on historical accident statistics but also on multidimensional traffic data generated spatially and temporally.

These modeling approaches evaluate traffic safety performance through indicators such as total number of crashes, crash records, traffic volume, and geometric characteristics. However, these indicators provide only a limited explanation of the spatial distribution of crashes, risks that vary by user type, behavioral factors, the relationship between land use and transportation, and the long-term effects of planning decisions. Furthermore, among other factors, measurement inconsistencies, changes in parameters over time, and unobservable socioeconomic effects reduce the reliability of model results [3].

In recent years, technological advancements have enabled the development of more comprehensive and proactive approaches to traffic safety and traffic density assessments. Road safety audits, the safe system approach, pedestrian safety audits, traffic conflict techniques, automated image processing systems, natural driving data, and microsimulation applications contribute to the identification of high-risk areas before accidents occur [4] [5] [6] [7]. These approaches reveal not only where past accidents occurred but also interactions among road users, changes in traffic density, speed differences, potential conflict points, and intervention priorities. Thus, traffic safety assessment evolves from a reactive analytical process into a proactive decision-support tool that informs planning decisions.

Particularly from the perspective of sustainable spatial planning, digital traffic data serves as a crucial tool for creating safe transportation networks, protecting vulnerable road users, enhancing the quality of public spaces, and establishing a more balanced relationship between transportation and land use. In this context, this study aims to discuss the integration of digital traffic data generated by the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP)—both developed in Türkiye—into sustainable spatial planning decisions.

This paper addresses the following four research questions: (I) What types of digital traffic data do traffic safety and traffic density analysis platforms generate? (II) For which planning tools can the visual materials obtained from these platforms be used? (III) What spatial issues do the data obtained from these platforms reveal? (IV) How can digital traffic data be integrated into sustainable spatial planning processes?. To answer these questions, the paper first establishes the conceptual relationship between traffic safety, the built environment, and spatial planning. It then reviews the data and analytical capabilities of TSAP and TDAP. Finally, the platform outputs are linked to spatial problems, planning scales, and potential planning decisions.

II. CONCEPTUAL FRAMEWORK

A. *Traditional Traffic Safety and Safe Systems Approach*

The traditional approach to traffic safety relies on estimating the impact of certain measures taken to improve traffic safety on the frequency and severity of accidents. This approach aims to change the behavior of road users, reduce human errors by enforcing traffic laws, and develop strategies to improve road infrastructure [8] [9] [10]. Accident-based assessments, a fundamental component of traditional traffic safety analyses, utilize existing accident data to identify high-risk areas, examine the spatial distribution of accidents, and interpret accident outcomes according to their severity levels [11] [12]. Accident-based assessment methods are classified into four groups. Firstly, accident black spot analysis is one of the most common applications of this approach [13]. This analysis identifies road sections and intersections where high accident, injury, or death rates are observed in a specific time period. In identifying these areas, road geometry, traffic characteristics, environmental conditions, and accident records are used. Geographic information systems, Bayesian methods, and clustering approaches are used to increase the accuracy of the analysis. Another group of methods are before-and-after observation studies, which evaluate the impact of intervention by comparing traffic safety conditions before and after the implementation of specific safety measures [14] [15]. Changes in the number and severity of accidents after intersection redesign, speed reduction applications, road signage, and inspection programs are examples of this method.

The third group of methods consists of statistical models that strengthen the quantitative aspect of the traditional approach and address safety performance in detail. These include descriptive statistics that describe current safety conditions, risk exposure and accident outcomes; statistics that predict future accident probabilities by considering the relationship between road geometry, traffic volume and environmental characteristics and the number of accidents; risk statistics that measure the effect of different safety measures on risk reduction; accident outcome statistics that affect injury and death outcomes; and multiple linear regression analyses that address the problems of distribution, extreme zeros and data heterogeneity in accident data [16] [17].The final group of methods is expert opinion and engineering assessments. Traffic safety experts make adjustments to address safety issues by identifying field conditions, road geometry, user behavior, visibility distances, and infrastructure deficiencies. This method offers a solution, particularly in areas with data deficiencies. However, expert opinions may contain subjective interpretations, institutional pressure, or methodological limitations. Therefore, they need to be evaluated in conjunction with data-driven analyses [18] [88].

The traditional approach to traffic safety has some limitations. These include: (I) It is based on data generated after an accident occurs, (II) safety problems become visible only after the number of accidents increases in a particular location, (III) accident records are incomplete and small-scale accidents are not reported, (IV) it considers human error as a significant cause and fails to explain the conditions that lead to this error. These limitations have increased the need for proactive, holistic, and systems-based approaches in the field of traffic safety. In this context, the safe systems approach has emerged as a significant paradigm shift in the field of traffic safety. Its origins lie in the Class Vision program developed in Sweden and the Sustainable Safety approaches developed in the Netherlands [19] [20]. The safe systems approach aims to identify and reduce risks before accidents occur, and to design a system where human error does not result in death or serious injury. Road design characteristics, speed behavior, traffic density, pedestrian-vehicle collisions, and intersection arrangements are analyzed within the system. Thus, safety assessments are not limited to improving black spots, but become a holistic planning tool for risk reduction. This approach is based on some fundamental principles [21]:

- Accepting that traffic accidents will never completely disappear, severe consequences must be prevented. - Transportation systems should be designed taking into account the possibility of road users making mistakes. - The force that the human body can tolerate during a collision is limited. Therefore, design decisions that manage speed and reduce collision severity should be made. - A safe road transportation system requires shared responsibility among road managers, planners, designers, implementers, maintenance units, inspection agencies, emergency response teams, vehicle manufacturers, civil society, and academic stakeholders. Examples of safe systems approach practices include the widespread use of speed control cameras, the conversion of four-way intersections into roundabouts, the promotion of technologies that enhance vehicle safety, and prioritizing the protection of vulnerable road users in urban areas [22][23]. These practices demonstrate that traffic safety should be addressed through system-level policy and planning decisions, in addition to engineering interventions. Therefore, it is important to consider traffic safety together with spatial determinants that affect accident risk.

B. Spatial Determinants of Traffic Safety

Traffic accidents and pedestrian-vehicle collisions are related to spatial factors including land use, road network type, road function, speed, population density, pedestrian mobility, and socioeconomic characteristics. Therefore, in the traffic safety literature, it is important to consider the built environment characteristics and social structure together with accident risks. Research in this context focuses on injury and fatal accidents and examines all modes of transportation. Pedestrian and cyclist accidents are particularly prominent. The built environment is considered in two ways: land-based and street-based. Land-based includes the location, layout, and density of land use, as well as the physical design aspects related to streets. Street-based includes the design of adjacent streets, intersections, and street networks. In addition, it is considered in the social dimension, which includes employment and population density and the demographic characteristics of users. The impact of the built environment on traffic safety is primarily discussed through land use. Land use is one of the strategies used to prevent and reduce accidents [24]. Land use types generate different levels of journeys and influence user behavior. This situation increases the potential for traffic accidents. In the literature, commercial and mixed-use areas are identified as high-risk areas for pedestrian and cyclist accidents [25][26][27][28]. In contrast, single-family residential areas and areas with low activity density are reported to have a lower risk of accidents. However, higher rates of collision and injury accidents have been found in social infrastructure areas such as schools [29][30].

Both the type of land use and the level of mobility generated by these uses increase the risk of accidents. Vehicle-to-vehicle collisions are concentrated in commercial and industrial areas, as well as manufacturing and industrial zones. Vehicle-pedestrian and vehicle-bicycle collisions are higher in areas with tourist accommodations and public services, and high pedestrian activity [31]. [32], in their research, found that housing-population density, commerce and service sector were positively correlated with the number of traffic accidents. [33] found that the number of bars, shops selling alcoholic beverages and restaurants per kilometer along the road was related to pedestrian injuries. In general, it shows that the risk of accidents is affected by the spatial location, density and land use of the surrounding activities. Therefore, the proximity of activities that generate and attract travel can offer a planning approach that reduces the need for vehicle travel and encourages pedestrian and bicycle use [34].

Land use-related mobility patterns become important in terms of traffic safety when evaluated together with road network density and street layout. Road network density, level of connectivity, number of intersections and block structure affect both the level of mobility and the probability of encounters between vehicles and vulnerable road users. High accessibility density increases the probability of collisions. and increases the risk of accidents [35][36]. Similarly, more accidents occur in areas with dense road networks or intersections [27][37][38][39][40]. In their study examining the effect of street layout on accident frequency, [38] classified street layouts into four categories: grid, skewed parallel, loops and lollipops, and mixed. They found that skewed parallel, loops and lollipops, and mixed layouts, which provide limited access, were safer and had lower accident rates compared to grid layouts [38][41][42][43]. This shows that highly interconnected road networks increase accessibility but also increase points of conflict.

However, findings regarding the road network are not always one-sided. [42] state that increased intersection density is less associated with accident rates, but increased street connectivity is more strongly associated with accidents. At the same time, the difference in intersection types affects the severity of the traffic safety impact [27]. For example, in an area with a high density of three-way intersections, the number of injury-related accidents decreased while the total number of accidents increased. Cities with narrow streets and small blocks have a lower risk of fatal traffic accidents. This supports high-density and mixed-use neighborhood designs for pedestrians and cyclists in line with sustainable development goals [44][45][46][47][48].

Another variable related to road network type is the function and speed level of the road. Main arteries, multi-lane streets, and high-speed limit roads are associated with serious injuries and high accident risks [27][49][50][51]. In this context, it has been found that more accidents occur in areas with main arterial roads, and pedestrian and bicycle accidents are particularly prevalent on such roads [52][53]. This is because main arterial roads are designed to accommodate high traffic volumes. As vehicle speed and traffic volume increase on these roads, the risk to vulnerable road users also increases. This situation is explained by the fact that pedestrians and cyclists do not have protection inside vehicles, increasing the risk of injury and death under high-speed conditions [54][55]. The speed variable is a factor that affects the severity of accidents more than the number of accidents. [56] states that the pedestrian and bicycle accident rate is lower in areas with high traffic speeds. However, bicycle and pedestrian accidents cause more serious injuries on roads with high-speed limits [57]. Therefore, traffic safety should be evaluated together with accident severity, user type, and exposure level. The impact of sidewalks on vulnerable road users, bicycle lanes, traffic accidents and injuries, and traffic safety is a controversial area in the literature. While some studies find that sidewalks reduce the risk of accidents for pedestrians [58][59][60][61], others show that there are more pedestrian and cyclist accidents in areas with longer sidewalks, more pedestrian crossings, or more bicycle lanes [62][63][64]. This indicates that the density of pedestrians and cyclists should also be considered in areas where infrastructure is available. Similarly, [65] found that pedestrian accidents involving elderly individuals were higher at signalized pedestrian crossings compared to intersections without signalized crossings. [42] found that injury-causing bicycle accidents increased in areas with a high density of bicycle lanes. [66] stated that bicycle lanes on main arteries increase collisions, while accident rates are lower in bicycle lanes on side streets.

Spatial determinants of traffic safety, including characteristics of the built environment, social structure, and demographic composition, play an important role in shaping the spatial distribution of accident risk. Higher population and employment densities are generally associated with greater pedestrian and vehicular activity, which may increase exposure to traffic conflicts and, consequently, the number of recorded accidents. Accordingly, several studies have reported lower accident frequencies in areas with low population density [27][67], while higher numbers of accidents have been observed in areas with greater population and employment density [68]. Positive associations have also been identified between density and pedestrian injury collisions [33][69][70][71]. However, higher density does not necessarily correspond to greater accident severity. Dense urban environments are often characterized by lower operating speeds, shorter travel distances, and more constrained road conditions, which may reduce the likelihood of fatal outcomes. This may explain the negative relationship reported between density and fatal accidents [72][73][74]. Therefore, density should be interpreted as a factor that may increase exposure and accident frequency while simultaneously reducing accident severity under certain spatial and traffic conditions.

Demographic structure is also an important determinant, especially in terms of pedestrian safety. Children and the elderly are among the most vulnerable groups to pedestrian accidents. [75][76]; found that the death rate among elderly pedestrians is higher during daytime, weekdays, and winter months. In their research, [75] found that elderly pedestrians cross the road more frequently when vehicles are approaching and use unsafe road crossing strategies. According to [77], elderly pedestrians are exposed to vehicle traffic for longer periods because they walk slower than younger pedestrians. On the other hand, disadvantaged demographic groups also have a higher accident risk rate [56][78][79][80][81]. It is debated whether this situation stems from disadvantaged groups walking, cycling, and using public transport more, or from the fact that the transportation infrastructure and traffic conditions in their environments are riskier [82].

In general, the literature shows that traffic safety can be explained by considering land use, road network type, road function, speed, transportation infrastructure, and social vulnerability variables together. High population density, average daily traffic and number of intersections per kilometer, vehicle speed and types, vehicle characteristics and conditions are directly related to accident risks. However, it is stated that the risk of accidents is higher in city centers and low-to-medium density commercial areas compared to villages and city center periphery areas [33][83][84][85]. Therefore, it is important to consider traffic safety not only as an engineering-focused road arrangement, but also as a holistic spatial planning problem that must be addressed together with land use decisions, urban density, accessibility, speed management, and social vulnerability.

III. METHOD

This research is based on a qualitative case study examining the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP) as digital decision support tools that can be linked to sustainable spatial planning decisions. The data sources used in the research include the interfaces of the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP), the official websites and reports of the Ministry of Environment and Urbanization, the types of decisions included in zoning plans, implementation zoning plans, and transportation master plans published in the official gazette, and the implementation tools used in urban design guidelines. The research methodology consists of three main stages. The first stage is a digital platform review analysis that evaluates the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP) through a structured review framework. In this stage, the platforms are systematically examined and defined. This definition is evaluated within the framework of the platforms' purpose, analysis method, filtering tools, visualization methods, data type used, target users, limitations, and decision support potential. The second stage is a visual material analysis examining how digital traffic data obtained from the platforms can be used as input for different planning scales (master zoning plan, implementation zoning plan, transportation master plan, and urban design guidelines). Map layers, thematic visuals, accident density representations, speed and queue analyses, time-space distributions, and graphical outputs from the platforms were evaluated. The final stage is a data-space-decision analysis where the data obtained from the platforms are related to planning decisions within the framework of spatial problems identified at different planning scales. In this stage, inferences regarding spatial planning decisions based on spatial problems identified at different planning scales in the literature are discussed.

IV. FINDINGS

A. *Digital Platform Review Analysis in Türkiye*

The traffic safety analysis platform was developed within the Ministry of Environment, Urbanization and Climate Change as part of the “2020-2023 National Smart Cities Strategy and Action Plan” and the “2021-2023 Road Traffic Safety Action Plan”. It is a big data-driven, web-based software platform that provides decision support for traffic safety analysis and planning on urban road networks using information on accidents and their underlying mechanisms [86]. The platform centrally collects data on accidents resulting in death and injury from the IVME (Ministry of Interior Data Center) project, which was put into use by the Ministry of Interior in 2022, and data on accidents resulting in material damage from the Insurance Information and

Monitoring Center. The data can be filtered for parameters such as accident severity, accident types, weather conditions, accident causes, location information, road characteristics, and time, and can be displayed on a map using heat maps, point mapping, and clustering methods. Thanks to traditional traffic engineering methods and an artificial intelligence algorithm, the platform enables the calculation of Accident Black Spots and High Accident Density Areas. The platform allows for the identification and analysis of factors causing accidents in a defined region and period, areas requiring improvement, and potential situations that may arise under specific conditions. Furthermore, statistics obtained from the data are visualized and reported on the panels within the platform. Launched in 2023, the platform is used by local governments on a national scale [86]. Figure I presents the distribution of traffic accidents across Türkiye and the layers of the platform.

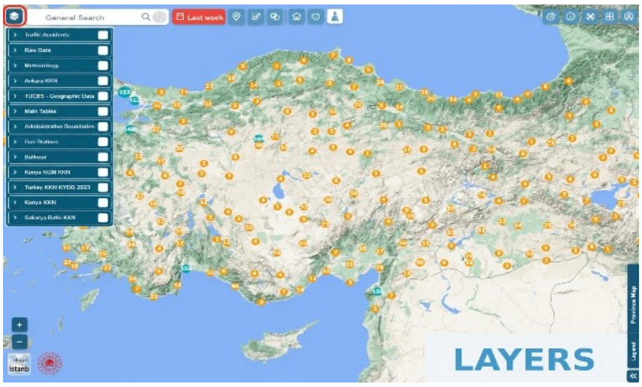

FIG. I TRAFFIC SAFETY ANALYSIS PLATFORM LAYERS

Traffic density analysis platform was developed within the Ministry of Environment and Urbanization under the scope of the "National Smart Cities Strategy" and Action Plan. Its aims are: (I) to display, compare, and report current and historical data on urban traffic density, queue lengths, and peak traffic hours in all 81 provinces on the web; and (II) to enable the sharing of data with other platforms supporting appropriate infrastructure. The platform utilizes mobile vehicle data from 2020, 2021, 2022, 2023, and 2024 to determine traffic flow speed on road networks. It also provides segment-based speed data in 5-minute intervals between 06:00 and 23:00. The platform is used by local governments on a national scale [87] [Fig. II].

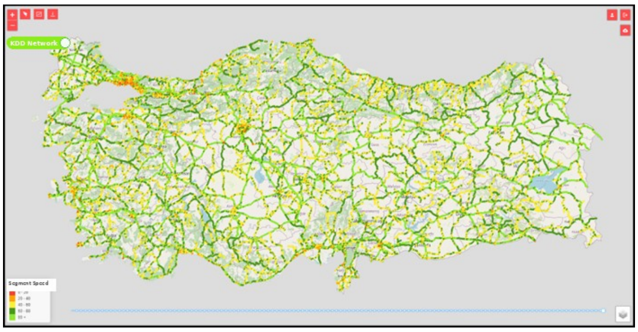

FIG. II TRAFFIC DENSITY ANALYSIS PLATFORM INTERFACE

B. *Visual Material Analysis*

The potential of digital traffic data generated by the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP) was evaluated in relation to different spatial planning scales. At the master zoning plan scale, accident density, traffic congestion, segment-based speed, queuing, and travel-time data can be used as analysis and synthesis inputs for strategic decision-making. These indicators make it possible to identify corridors where traffic safety and accessibility problems overlap and to define safety-prioritized corridors, public transport-prioritized axes, and areas requiring further transportation investment.

At the implementation zoning plan scale, platform data can support more detailed and location-specific planning decisions. Information on pedestrian accidents, intersection accidents, queue lengths, local speed reductions, and roadside congestion can be associated with decisions concerning sidewalk continuity, safe pedestrian crossings, parking and parcel access, intersection arrangements, and target speed regulations. In this way, traffic safety indicators can be translated into plan notes and implementation provisions rather than remaining solely as descriptive analytical outputs.

At the transportation master plan scale, digital traffic data can be used both as a model input and as a tool for determining intervention priorities. Peak-hour congestion, bottlenecks, queue lengths, travel times, speed variations, and accident concentrations can support decisions on public transport corridors, intersection improvements, traffic calming, speed management, freight movement, and logistics organization. The simultaneous evaluation of safety and traffic performance data also allows transportation investments to be prioritized according to both operational efficiency and accident risk.

At the urban design guideline scale, the platforms can inform micro-scale design decisions affecting the daily experience and safety of road users.

Local accident patterns, pedestrian movements, vehicle approach speeds, stopping conditions, and congestion around public transport stops can guide decisions concerning sidewalk width, pedestrian waiting areas, crossing locations, lighting, bus stop arrangements, street furniture, and street cross-sections. Therefore, the visual outputs of TSAP and TDAP can contribute to the development of measurable and location-specific design principles at different planning scales.

C. Data – Spatial – Decision Correlation Analysis

Digital traffic data generated from the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP) were related to spatial planning decisions through a data–spatial problem–decision framework. Within this framework, accident type, severity, location, and density data were evaluated together with traffic volume, speed, queue length, peak-hour congestion, and travel-time indicators. The combined evaluation of these datasets makes it possible to move beyond the identification of individual accident locations and to reveal broader spatial problems related to road hierarchy, land use and density, vulnerable road users, access management, social vulnerability, roadside activities, transfer areas, and logistics mobility.

Path Hierarchy

The safety of main transportation corridors (highways and main arterial roads, urban main arterial roads, local connecting roads) and pedestrian axes accessing public transport stops and transfer points are included. In the traditional planning approach, road hierarchy is defined in terms of vehicle capacity, connectivity level, and road function. However, when road hierarchy is evaluated using indicators such as accident black spots, pedestrian and vehicle accidents, serious injury and fatal accidents, and corridor-based traffic volume, low speed, queues, bottlenecks, and travel time, it provides input for a safety and accessibility-focused planning decision that identifies priority intervention areas.

Land use – the relationship between density and transport capacity

Decisions regarding building density and spatial arrangement (building density, building regulations, ground floor use, setback distance, and building approach limit), as well as commercial and mixed-use decisions, encompass issues related to development area decisions. The relationship between land use and transportation is defined as building regulations and density decisions. However, when evaluated using indicators that highlight safety risks, such as pedestrian accidents, intersection accidents, and accident density, and analyze transportation capacity, such as peak hour density, queues, low speeds, and travel times, it provides input for a holistic planning approach that considers multimodal transportation accessibility and traffic safety components together.

Safety for vulnerable road users

Urban accessibility decisions (schools, hospitals, parking lots) and issues related to pedestrian, cyclist, elderly, child, and disabled user decisions are included. The safety of vulnerable road users is classified as accessibility and post-accident response decisions. However, when evaluating accident events such as visible road user accidents, cross-traffic accidents, and the relationship between accident risk and transportation performance, such as peak hour density, approach speed, queuing, slowdown during stops, and passenger density, the development of planning decisions ensures the inclusion of safe access planning decisions. Preventive decisions include combining design reports focusing on lane width and continuity, ramp and safe pedestrian distance location, lighting, target speed decisions, barrier-free walkways, and pedestrian waiting areas.

Access management

This includes issues related to intersection and signal decisions (pedestrian crossing time, turning restrictions, signal phase) and target speed and traffic calming decisions (speed management in school, hospital and residential areas, low-speed zones). Access management is defined as engineering interventions aimed at accelerating vehicular flow and as nodal points of transportation networks. However, when evaluated with indicators such as side impacts, turning accidents, intersection accidents, pedestrian accidents, which reveal safety problems around the intersection, and queuing, delay, peak hour density, and intersection approach speed, which relate these problems to operational performance; it provides input for safety-oriented design decisions in terms of speed control and pedestrian access.

Social vulnerability and security inequality

In low-income neighborhoods, the inadequate pedestrian infrastructure in areas inhabited by children, the elderly, and individuals with disabilities leads to poor accessibility and high traffic, creating inequality. Injury accidents, pedestrian accidents, and accident densities at the neighborhood/district level, along with indicators analyzing mobility in vulnerable neighborhoods such as peak hour density, queues, and low speeds, highlight safety inequalities. These indicators provide input for planning decisions that prioritize safety investments and focus on the equitable distribution of safe transportation infrastructure.

Parking and roadside use

This includes issues related to access management decisions (parcel entry/exit, parking lot entrance, service access) and roadside usage decisions (short-term stopping, sidewalk encroachment). These decisions are generally defined as parcel and property regulations. However, when side collisions, turning accidents, pedestrian accidents, and indicators of traffic density such as slowing down, queuing, low speed, and narrowing, which reveal accidents caused by roadside and visibility restrictions, are evaluated, they provide input for planning decisions focusing on public road safety and pedestrian access.

Transfer and station area safety

Public transport access includes issues related to stop-pedestrian crossing relationships, waiting areas, sidewalk width, vehicle-pedestrian separation, and speed conditions around stops. When evaluating safety risks such as pedestrian accidents around stops, transfer area accidents, and vulnerable user accidents, as well as indicators measuring transportation performance such as passenger density, slowdown around stops, queuing, low speed, and peak hour, planning and design decisions focusing on pedestrian access and road user safety around stops and transfer areas are provided input.

Logistical mobility and conflicts

Industrial, warehousing, and large-scale commercial use involve freight and heavy vehicle mobility, truck parking, and loading and unloading issues. Indicators such as heavy vehicle accidents, side-impact collisions, and pedestrian-vehicle accidents, which highlight safety risks, as well as peak hour density, low speed, queuing, and access time indicators analyzing the pressure of logistics mobility on the road network, are evaluated. This provides input for planning decisions aimed at reducing conflicts between logistics corridors and scheduling policies and urban living spaces.

V. CONCLUSION

This study aims to discuss the integration of digital traffic data produced by the Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP), developed in Türkiye, into sustainable spatial planning decisions. First, the platforms were systematically examined according to specific review criteria, and then aspects where digital traffic data could serve as input for different planning scales were evaluated. Subsequently, the generated data was linked to planning decisions within the framework of specific spatial problems.

When the research questions presented in the study are evaluated within the scope of the research results: (I) What types of digital traffic data do the traffic safety and traffic density analysis platforms produce? The platforms offer significant potential in terms of producing traffic data in a digital environment. In this context, Traffic Safety Analysis Platform (TSAP) produces data on traffic safety risks with accident black spots, high accident density areas, accident severity, accident type, time, and location data. Traffic Density Analysis Platform (TDAP), on the other hand, reveals the density and accessibility in the urban transportation system with speed, queue, peak hours, traffic density, travel time, and segment-based performance data. (II) For which planning tools can the visual materials obtained from the platforms be used? The digital traffic data generated by the platform contribute to spatial planning processes at three levels. Firstly, platform data can make existing traffic safety and density problems visible in analysis and synthesis maps. Secondly, it can provide input for plan explanation reports, plan notes, transportation master plan strategies, and urban design guides. Thirdly, with new analysis tools to be added to the platform, it can produce concrete planning outputs such as direct intervention priority, target speed decision, safe access area, pedestrian continuity, access management, lighting priority, logistics conflict area, and development area traffic pressure. (III) Which spatial problems do the digital traffic data obtained from the platforms make visible? They make visible the safety problems of pedestrian axes accessing the main transportation corridor and public transport stops and transfer points, problems related to construction and spatial settlement, commerce and mixed use, development area, urban infrastructure access and problems related to pedestrian, cyclist, elderly, child, and disabled users, intersection and signal decisions, and problems related to target speed and traffic calming decisions. (IV) How can digital traffic data be integrated into sustainable spatial planning processes? The platforms function as decision-support tools that provide input for the identification of safety-prioritized corridors and public transport-prioritized axes. The development of decisions regarding sidewalk continuity, safe pedestrian crossings, parking access, and target speeds, prioritizing intersection improvements, speed management, and traffic calming policies, and the creation of micro-scale design principles such as street cross-section, bus stop surroundings, pedestrian waiting areas, lighting, and crossing safety.

In conclusion, Traffic Safety Analysis Platform (TSAP) and the Traffic Density Analysis Platform (TDAP) offer significant potential for integrating urban transportation and traffic safety data into planning processes in Türkiye. For this, it is necessary to develop the platforms not only as data-generating systems but also as decision support infrastructures that carry data to the levels of spatial problems, analysis tools, planning decisions, and implementation priorities. When this integration is achieved, planners, transportation experts, and urban decision-makers will be able to support traffic safety, accessibility, density management, and sustainable mobility goals with stronger, data-driven, and traceable decisions. In future studies, the data obtained from these platforms should be tested practically through specific cities, corridors, or problem areas; It is suggested that the impact of planning decisions be measured and the relationship between traffic safety and spatial sustainability be evaluated with more concrete indicators.

Funding: This paper was produced from Büşra ERTAŞ's Doctorate (PhD) thesis conducted at Istanbul Technical University Institute of Graduate Education under the academic supervision of Assoc.Prof.Dr. Fatih EREN. The theoretical framework of this paper was produced as part of the ‘Aquatic Urban Ecosystems Alive (AQUAlive)' project with the international code: "F-DUT-2024-0260" and the national TÜBİTAK code: "225N983". The AQUAlive project is being conducted officially under the leadership of Fatih EREN and the postgraduate student scholarship of Büşra ERTAŞ, and is funded under the European Commission's Horizon Europe Programme Driving Urban Transitions (DUT 2024). DUT projects are supported by the European Commission and funded under the Horizon Europe (HORIZON-CL5-2021-D2-01-16) programme. Fatih EREN is the Corresponding Author of this paper. The funding sources had no role (were not involved) in the production of this paper.

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Kommunale Regulierung plattformbasierter Mobilität: Governance-Instrumente zur Sicherung fairer Wettbewerbsbedingungen und der Daseinsvorsorgefunktion des Taxis

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Abstract - Digitale Vermittlungsplattformen verändern den Taxi- und Mietwagenmarkt tiefgreifend und stellen Kommunen vor neue regulatorische Herausforderungen. Der Beitrag untersucht, wie Städte ihre Steuerungsfähigkeit sichern, faire Wettbewerbsbedingungen herstellen und Anforderungen kommunaler Daseinsvorsorge gewährleisten können. Methodisch basiert der Beitrag auf einer vergleichenden Analyse aktueller kommunaler Gutachten, regulatorischer Instrumente, ausgewählter Fallbeispiele und einschlägiger Fachliteratur. Betrachtet werden insbesondere Preisinstrumente wie Mindestbeförderungsentgelte, Festpreise und Tarifkorridore, Kontrollinstrumente sowie weitere Steuerungsoptionen des novellierten Personenbeförderungsgesetzes (PBefG). Der Beitrag analysiert rechtliche und institutionelle Rahmenbedingungen ebenso wie praktische Umsetzungsherausforderungen kommunaler Regulierung. Im Fokus stehen Governance-Fragen zwischen kommunaler Handlungskompetenz, digitalen Plattformlogiken, ÖPNV-Integration und verkehrspolitischen Zielsetzungen. Ziel ist es, Handlungsspielräume, Grenzen und Erfolgsfaktoren kommunaler Regulierungssysteme aufzuzeigen und Schlussfolgerungen für eine nachhaltige und sozial ausgewogene urbane Mobilität abzuleiten.

Keywords – plattformbasierte Mobilität; kommunale Regulierung; Taxi; Mietwagen; Mindestbeförderungsentgelt; Governance; Daseinsvorsorge; Personenbeförderungsgesetz

I. EINLEITUNG

Digitale Vermittlungsplattformen haben den Gelegenheitsverkehr mit Pkw nicht nur um neue Buchungs- und Bezahlprozesse erweitert, sondern die Wettbewerbslogik zwischen Taxi- und Mietwagenverkehr strukturell verändert. Im Fokus dieses Beitrags steht dabei insbesondere der plattformvermittelte Mietwagenverkehr, der aus Fahrgastsicht taxiähnlich erscheint und hinsichtlich Fahrtanlass, Nachfragemustern und Leistungsangebot unmittelbar mit dem Taxi konkurriert. Davon zu unterscheiden sind spezialisierte Mietwagenverkehre wie Schüler- oder Krankentransporte sowie neue Mobilitätsformen wie Ridepooling oder Carsharing, die im Beitrag nur insoweit berücksichtigt werden, wie sie Governance-Fragen öffentlicher Mobilitätsversorgung berühren.

Mobilität ist zugleich ein Grundbedarf, dessen Befriedigung über öffentliche Infrastruktur und Regeln kollektiv organisiert werden muss; digitale Mobilitätsdienstleistungen verschieben deshalb nicht nur Buchungs- und Kundenprozesse, sondern auch das Verhältnis von öffentlicher und privater Mobilität (Weber 2020b). Aus Sicht der Fahrgäste werden digital vermittelte Taxi- und taxiähnliche Mietwagenfahrten größtenteils als gleichwertig hinsichtlich der wichtigsten Kriterien für eine Fahrtentscheidung wahrgenommen: Preis, Wartezeit, Transparenz und Bedienkomfort. Damit wird eine vormals komplementäre Marktordnung mit spezialisierten Fahrtangeboten des Mietwagens in vielen städtischen Räumen zu einem substitutiven Wettbewerb um dieselben Fahrtanlässe.Die politische Brisanz dieser Entwicklung ist nicht neu. Bereits im Vorfeld der PBefG-Novelle 2021 wurde die Neuordnung des Taxi- und Mietwagenmarktes als bundesweiter

Konflikt zwischen Taxigewerbe, Plattformanbietern und kommunalen Steuerungsinteressen beschrieben (Delhaes 2020). Seitdem wurde in mehreren Städten die Einführung von Mindestbeförderungsentgelten mit dem Ziel fairer Wettbewerbsbedingungen diskutiert (Köstner 2026). Der Beitrag knüpft an diese Debatte an, betrachtet sie jedoch nicht als Schutzkonflikt einzelner Anbietergruppen, sondern als Frage kommunaler Governance.

Im Zentrum steht somit nicht, ob einzelne Geschäftsmodelle geschützt oder verdrängt werden sollen. Entscheidend ist vielmehr, ob Kommunen unter Plattformbedingungen weiterhin öffentliche Verkehrsinteressen durchsetzen können: ein ausreichendes und verlässliches Verkehrsangebot, Mobilitätsteilhabe, Preis- und Verbraucherschutz, faire Wettbewerbsbedingungen sowie die Sicherung der besonderen Daseinsvorsorgefunktion des Taxis. Das Taxi ist im deutschen Regulierungsverständnis mehr als ein gewerbliches Beförderungsangebot; es übernimmt durch Betriebs-, Beförderungs- und Tarifpflichten eine öffentliche Versorgungsfunktion, die gerade in nachfrageschwachen Zeiten, Randlagen und für mobilitätseingeschränkte Personen relevant bleibt.

Mit dem Aufstieg plattformvermittelter Mietwagenangebote geraten diese Steuerungsmechanismen zunehmend unter Druck. Entscheidend hierbei ist, dass Taxiunternehmen an den örtlichen Taxitarif gebunden sind, während Vermittlungsplattformen grundsätzlich in der Preissetzung nicht eingeschränkt sind und daher mithilfe von komplexen Preis-/Nachfragemodellen Taxifahrten systematisch unterbieten können. Daraus entstehen Wettbewerbsasymmetrien, die langfristig nicht nur die wirtschaftliche Tragfähigkeit des Taxigewerbes beeinflussen können, sondern auch die Fähigkeit der Kommunen, öffentliche Verkehrsinteressen durchzusetzen.

Die Leitfrage dieses Beitrags lautet daher: Wie können Kommunen unter den Bedingungen plattformbasierter Mobilität ihre Steuerungsfähigkeit im Taxi- und Mietwagenmarkt sichern, faire Wettbewerbsbedingungen herstellen und die Daseinsvorsorgefunktion des Taxis als Bestandteil öffentlicher Mobilitätsversorgung erhalten?

II. Regulatorischer und wissenschaftlicher Hintergrund

Die Novellierung des PBefG im Jahr 2021 hat die Veränderungen im Gelegenheitsverkehr rechtlich aufgegriffen und kommunale Handlungsmöglichkeiten erweitert. Neben der Modernisierung des Taxitarifs durch Festpreise und Tarifkorridore eröffnen die neuen Regelungen insbesondere die Möglichkeit, Mindestbeförderungsentgelte für Mietwagen festzulegen. Diese Instrumente sind jedoch keine automatisch wirksamen Lösungen. Sie verschieben die Steuerungsfrage vielmehr auf die kommunale Umsetzungsebene: Städte und Landkreise müssen Instrumente auswählen, fachlich begründen, rechtssicher ausgestalten, kontrollieren, evaluieren und gegebenenfalls nachsteuern (Deutscher Bundestag 2021).

Die etablierte taximarktökonomische Literatur zeigt, dass Digitalisierung klassische Begründungen der Taxiregulierung teilweise verändert. Apps, Routeninformationen, Vorabpreise und bargeldlose Bezahlung reduzieren Informationsasymmetrien zwischen Fahrgästen und Anbietern (Pape und Wein 2014). Der Wissenschaftliche Beirat beim BMVI (2017) leitete daraus eine stark liberalisierende Reformperspektive ab: digitale Vermittlung könne Leerfahrten verringern, Produktivität erhöhen, flexible Preise ermöglichen und zugleich die Kontrolle durch Kunden und Behörden verbessern. Diese Position bildet einen wichtigen Gegenpol zur kommunalen Daseinsvorsorgeperspektive: Digitalisierung schafft Effizienzpotenziale, ersetzt aber nicht automatisch öffentliche Steuerungsziele. Zugleich bleibt ein zentraler Regulierungsgrund bestehen: Die Bereitstellung verfügbarer Taxis erzeugt eine positive Externalität, weil Fahrgäste von einer Option auf kurzfristige Beförderung profitieren, ohne diese Vorhaltefunktion vollständig über den einzelnen Fahrtpreis zu vergüten (Pape und Wein 2014).

Wettbewerbsökonomisch werden Plattformmodelle häufig mit Effizienzgewinnen, niedrigeren Suchkosten und höheren Auslastungsgraden begründet. Haucap et al. (2017) argumentieren für urbane Mobilitätsmärkte, dass digitale Plattformen Wettbewerb intensivieren, Angebotsausweitung und Preisvorteile ermöglichen können. Ergänzend zeigt Weber (2020a), dass neue Mobilitätsangebote vor allem dort attraktiv werden, wo sie die Lücke zwischen eigenem Pkw, klassischem ÖPNV und Taxi schließen und per App niedrigschwellige Tür-zu-Tür-Optionen schaffen. Diese Perspektive ist für die Bewertung kommunaler Regulierung wichtig, weil sie daran erinnert, dass Steuerung nicht pauschal Innovation blockieren sollte. Sie erklärt jedoch nicht hinreichend, wie öffentliche Versorgungsfunktionen, arbeits- und sozialpolitische Standards sowie kommunale Verkehrsziele unter asymmetrischen Regulierungspflichten gesichert werden können.

Aus Governance-Perspektive zeigen Pernicka und Schüßler (2022), dass digitale Plattformen bestehende Personentransportmärkte nicht automatisch disruptiv auflösen. Ihre Wirkung hängt vielmehr von lokalen und nationalen Schutzvorrichtungen, institutionellen Feldstrukturen, rechtlichen Deutungen und Machtbeziehungen ab. Für Deutschland ist dabei bedeutsam, dass die Grenze zwischen Taxi- und Mietwagenverkehr rechtlich fortgeschrieben wurde, während Wien Plattformangebote stärker in das Taxigewerbe integrierte (Pernicka und Schüßler 2022; Kluge et al. 2020). Kommunale Regulierung ist damit als Aushandlung zwischen Marktöffnung, Integration und Daseinsvorsorge zu verstehen.

III. Methodisches Vorgehen

Methodisch basiert der Beitrag auf einer vergleichenden Analyse bestehender kommunaler Regulierungsansätze im Taxi- und Mietwagenmarkt. Grundlage der Untersuchung bilden aktuelle kommunale Gutachten, öffentlich bekannte Regulierungsentscheidungen sowie ausgewählte Fallbeispiele deutscher Städte und Landkreise. Ergänzend wird Fachliteratur zu Mobilität als Dienstleistung, Digitalisierung im Taximarkt, Plattform-Governance und Ride-Pooling herangezogen, um den Zielkonflikt zwischen Innovation, Liberalisierung, ÖPNV-Ergänzung und kommunaler Steuerung analytisch einzuordnen (Weber 2020a; Weber 2020b; Wissenschaftlicher Beirat 2017; Knie et al. 2020). Der Beitrag erhebt nicht den Anspruch einer vollständigen Rechtsstandserhebung, sondern ordnet kommunale Steuerungslogiken vergleichend ein.

Die betrachteten Instrumente wurden zunächst aus dem PBefG, der Fachliteratur, kommunalen Gutachten und öffentlich bekannten Regulierungsentscheidungen identifiziert. Anschließend wurden sie entlang eines analytischen Kriterienrasters verglichen, das aus der Leitfrage und der Governance-Perspektive des Beitrags abgeleitet wurde. Die sechs Kriterien sind: Zielrichtung, regulatorische Eingriffstiefe, erwartete Wirksamkeit für öffentliche Verkehrsinteressen, praktische Umsetzbarkeit, Kontroll- und Evaluationsbedarf sowie Governance-Anforderung. Zielrichtung und Eingriffstiefe erfassen die regulatorische Logik der Instrumente; Wirksamkeit, Umsetzbarkeit sowie Kontroll- und Evaluationsbedarf adressieren ihre kommunale Anwendung; die Governance-Anforderung bündelt Fragen der interinstitutionellen Koordination, Datenverfügbarkeit und Nachsteuerung.

Daraus ergibt sich eine funktionale Ordnung in fünf Instrumentenlogiken: erstens Kontrolle und Durchsetzung bestehender Pflichten, zweitens Modernisierung des Taxiverkehrs, drittens Regulierung des Mietwagenmarktes, viertens Integration des Taxi- und Mietwagenverkehrs in die öffentliche Mobilitätsversorgung und fünftens die Verknüpfung kommunaler Regulierung mit ökologischer Transformation.

Die Befunde sind als vorläufige Governance-Bewertung zu lesen. Viele Instrumente sind erst seit der PBefG-Novelle in kommunaler Anwendung, belastbare Langzeiterfahrungen und einheitliche Evaluationsstandards liegen bislang nur begrenzt vor. Aussagen zur Wirksamkeit einzelner Modelle sind daher als begründete Plausibilitätsurteile zu verstehen, die durch lokale Marktdaten, Kontrollstatistiken und Wirkungsanalysen fortlaufend überprüft werden müssen.

IV. Veränderte Wettbewerbsbedingungen im Taxi- und Mietwagenmarkt

A. Vom komplementären zum substitutiven Wettbewerb

Bis etwa zur zweiten Hälfte der 2010er Jahre bestand zwischen Taxi- und Mietwagenverkehr in den meisten Kommunen Deutschlands ein stabiles Marktgleichgewicht. Denn die beiden Verkehrsformen bedienten in der Regel hauptsächlich unterschiedliche Marktsegmente und Geschäftsfelder. Taxis waren im Wink-, Warte- und Standplatzmarkt präsent und unterlagen im Pflichtfahrbereich Tarif- und Beförderungspflichten. Mietwagen waren stärker auf Vorbestellung, Shuttle-, Kranken- oder Vertragsverkehre ausgerichtet. Jedoch verschiebt sich durch die zunehmende Verbreitung der plattformbasierten Vermittlung diese Ordnung in vielen lokalen Mobilitätsmärkten immer weiter. Ausschlaggebend ist hierbei der Zeitpunkt, ab dem sich die Wartezeit von Mietwagen (per App) und Taxis angleichen, da aufgrund der flexibleren Preisgestaltungsmöglichkeiten Mietwagen für viele Fahrgästen bessere Fahrtkonditionen anbieten können.

Gleichzeitig ist der Markt strukturell sensitiv gegenüber Preis- und Nachfrageschwankungen. Simulationen zu Ride-Hailing in Deutschland zeigen, dass deutlich niedrigere Fahrpreise gegenüber Taxis erhebliche Verlagerungseffekte auslösen können (Ennen und Heilker 2020). Bereits geringe Veränderungen der Nachfrage- oder Preisstrukturen können daher erhebliche Auswirkungen auf die wirtschaftliche Tragfähigkeit der Anbieter haben.

Mit der Zunahme des Plattformgeschäfts verändern sich auch die relevanten

Wettbewerbsparameter. Fahrgäste vergleichen nicht primär Genehmigungskategorien, sondern Wartezeit, Preis und digitale Nutzungserfahrung. Aus Sicht der Kommunen entsteht daraus ein Steuerungsproblem: Regulatorisch bleiben Taxi und Mietwagen unterschiedlich verpflichtet, marktlich konkurrieren sie aber zunehmend um dieselben Fahrten.

B. Plattformlogik und strukturelle Asymmetrien

Digitale Plattformen bündeln Nachfrage, steuern Sichtbarkeit, Verfügbarkeit und Preiswahrnehmung und können Kapazitäten datenbasiert lenken. Sie können dadurch Suchkosten senken und Auslastung erhöhen, aber auch marktprägende Netzwerkeffekte erzeugen. Der Wissenschaftliche Beirat (2017) verweist zugleich darauf, dass dieselben digitalen Systeme grundsätzlich auch für lückenlose Fahrtdokumentation, Regelkontrolle und Marktmachtaufsicht genutzt werden können. Ihre Geschäftsmodelle beruhen häufig nicht auf eigener Fahrzeugvorhaltung, sondern auf der Vermittlung angeschlossener Unternehmen. Damit verschiebt sich Kapitalbindung und Betriebsrisiko auf dezentrale Marktakteure, während die Plattform die Kundenschnittstelle kontrolliert.

Taxiunternehmen unterliegen als Bestandteil der öffentlichen Verkehrsversorgung einer Betriebs-, Beförderungs- und Tarifpflicht. Sie müssen grundsätzlich auch wirtschaftlich wenig attraktive Fahrten durchführen und dürfen ihre Preise nicht frei festsetzen. Diese Verpflichtungen dienen der Sicherung eines flächendeckenden und verlässlichen Mobilitätsangebots.

Demgegenüber verfügen Mietwagenunternehmen über größere unternehmerische Freiheiten. Als regulatorisches Gegengewicht besteht die Rückkehrpflicht, wonach Fahrzeuge nach Abschluss eines Auftrags unmittelbar zum Betriebssitz zurückkehren müssen (Bundesgerichtshof 2026), sofern keine Anschlussfahrt vorliegt. Umgekehrt besitzen Taxis exklusive Privilegien, insbesondere die Nutzung von Taxiständen sowie den Zugang zum Wink- und Wartemarkt.

Zudem benötigen Plattformunternehmen für ihre Vermittlungstätigkeit weder eigene Fahrzeugflotten noch umfangreiche Fahrerbelegschaften. Die eigentliche Verkehrsleistung wird von angeschlossenen Unternehmen erbracht. Dies reduziert Kapitalbindung und betriebliche Risiken erheblich.

Aus kommunaler Perspektive sind insbesondere dynamische Preisbildung, plattformseitige Steuerung der Kundenschnittstelle und mögliche Preisunterbietungen gegenüber dem regulierten Taxitarif relevant. Niedrige Preise können kurzfristig Verbraucherinteressen bedienen; zugleich zeigen internationale Untersuchungen zu algorithmischer Preis- und Vergütungssteuerung bei Ride-Hailing-Plattformen, dass dynamische Plattformmodelle Verteilungswirkungen zulasten von Fahrpersonal und Marktbalance entfalten können (Binns et al. 2025; Sherman 2024; Sherman 2025). Kommunale Regulierung sollte daher nicht allein kurzfristige Preisvorteile bewerten, sondern die langfristige Funktionsfähigkeit öffentlicher Mobilitätsversorgung berücksichtigen.

C. Risiko kommunalen Steuerungsverlusts

Die kommunale Steuerungsfähigkeit gerät unter Druck, wenn Regulierung nur noch auf den Taximarkt wirkt, während wesentliche Wettbewerbsprozesse in den weniger stark gebundenen Mietwagen- und Plattformmarkt ausweichen. Sinkt die Taxiverfügbarkeit, können sich Rückkopplungen ergeben: Fahrgäste wechseln zu Plattformangeboten, Taxiunternehmen verlieren Nachfrage, die Erfüllung von Betriebs- und Beförderungspflichten wird wirtschaftlich schwieriger, und kommunale Instrumente verlieren weiter an Reichweite.

Dieses Risiko betrifft nicht nur den städtischen Kernmarkt. Auch die Frage, welche Angebote in Randzeiten, in weniger nachfragestarken Quartieren oder für Personen mit besonderen Mobilitätsbedarfen verlässlich bereitstehen, ist kommunalpolitisch relevant. Die Funktionsfähigkeit des Taxigewerbes ist daher nicht nur ein Brancheninteresse, sondern Teil einer öffentlichen Mobilitätsarchitektur.

V. Kommunale Regulierungsinstrumente im Vergleich

A. Kontrolle und Durchsetzung

Die konsequente Durchsetzung bestehenden Rechts ist die niedrigschwelligste, aber unverzichtbare Form kommunaler Intervention. Dazu gehören Genehmigungsprüfung, Überwachung der Rückkehrpflicht, Schwerpunktkontrollen an Bahnhöfen, Veranstaltungsorten und Flughafenumfeldern sowie die Prüfung, ob digitale Vermittlungspraktiken mit den genehmigungsrechtlichen Pflichten vereinbar sind. Ohne Kontrolle verlieren weitergehende Preis- oder Tarifinstrumente an Glaubwürdigkeit.

Kontrolle allein kann strukturelle Wettbewerbsasymmetrien jedoch nur begrenzt kompensieren. Sie ist vor allem Voraussetzung einer wirksamen Regulierung. Je stärker Plattformverkehre über Verwaltungsgrenzen hinweg operieren, desto wichtiger werden ämterübergreifende Kooperation, digitale Datengrundlagen und abgestimmte Vollzugsroutinen.

B. Modernisierung des Taxiverkehrs

Festpreise und Tarifkorridore reagieren auf eine zentrale Stärke digitaler Plattformen: Preis- und Planungstransparenz vor Fahrtantritt. Sie können das Taxi anschlussfähiger an App-basierte Buchungslogiken machen und die Akzeptanz im Bestellmarkt erhöhen. Bereits die PBefG-Debatte vor 2021 sah Tarifkorridore als kommunales Steuerungsinstrument vor (Delhaes 2020). Vergleichbare Tariffragen werden auch in internationalen Analysen aufgegriffen; Kluge et al. (2020) zeigen am Beispiel Wien, dass Tarifgestaltung zugleich ökonomische Tragfähigkeit, Verbraucherschutz und institutionelle Ordnung des Gewerbes berührt.

Gleichwohl modernisieren Festpreise und Tarifkorridore primär den Taximarkt. Sie lösen nicht die strukturellen Preisunterbietungsmöglichkeiten durch Mietwagen, sondern erhöhen die Preistransparenz von Taxifahrten. Dennoch können Festpreise unter den in vielen Städten bestehenden Wettbewerbsbedingungen bestenfalls einen kleinen Beitrag zur Angleichung der Marktbedingungen schaffen.

C. Mindestbeförderungsentgelte für Mietwagen

Mindestbeförderungsentgelte (MBE) sind das zentrale Instrument, um systematische Preisunterbietung im Mietwagenmarkt zu begrenzen. Sie setzen dort an, wo der Wettbewerb aus Sicht der Fahrgäste unmittelbar wirksam wird: beim Fahrtpreis. Damit können sie einen entscheidenden Beitrag zu faireren Wettbewerbsbedingungen leisten, wenn ihre Höhe, Bemessungslogik und Ausnahmen fachlich tragfähig begründet werden.

Ihre Wirksamkeit hängt jedoch entscheidend von der konkreten Ausgestaltung ab. Liegt ein Mindestentgelt deutlich unterhalb des Taxitarifs, bleibt ein zu großer Unterbietungsspielraum für Mietwagenpreise bestehen. Unter der Berücksichtigung der sonstigen insgesamt ausgeglichen regulatorischen Rahmenbedingungen (insb. Betriebs-/ Beförderungspflicht vs. Rückkehrpflicht) erscheint eine Orientierung an der Untergrenze des Taxitarifs am geeignetsten, um ein Level Playing Field herzustellen. Gleichzeitig erhöhen sich dadurch aber Begründungs-, Kontroll- und Evaluationsanforderungen. Zudem sind Ausnahmen, etwa für Krankenfahrten oder vertraglich gebundene Verkehre, sorgfältig zu prüfen, damit öffentliche Versorgungsinteressen nicht unbeabsichtigt beeinträchtigt werden.

MBE sollten daher weder überschätzt noch unterschätzt werden. Isoliert eingeführt, ohne Kontrolle und regelmäßige Evaluation, bleiben sie anfällig für Umgehungsstrategien. In Kombination mit Vollzug, Taxitarifmodernisierung und Marktwirkungsanalyse sind sie jedoch ein zentrales Instrument kommunaler Steuerungsfähigkeit.

D. Integration in öffentliche Mobilitätsversorgung

Die langfristige Governance-Frage reicht über Preisregulierung hinaus. Kommunen müssen Taxi, Mietwagen, Plattformen, Pooling-Angebote und ÖPNV zunehmend zusammendenken. Weber (2020a) beschreibt öffentliche Mobilität nicht allein als staatlichen Betrieb, sondern als reguliertes Gesamtsystem, in dem unterschiedliche kommunale und private Angebote räumlich, zeitlich und tariflich integriert werden müssen. Baumeister, Benz, Diekmann und El-Zahab (2024) zeigen am Modell des digitalen ÖPNV-Taxis, dass vorhandene Taxi- und Mietwagenflotten als flexible Ergänzung des ÖPNV genutzt werden können und insbesondere im ländlichen Raum wirtschaftliche Vorteile gegenüber ausschließlich bestellten On-Demand-Flotten bieten können.

Empirisch stützt Knie et al. (2020) diese Integrationsperspektive für Ride-Pooling: In der CleverShuttle-Untersuchung wurden 2019 in Berlin, München, Leipzig und Dresden mehr als 1,8 Mio. Fahrgäste erfasst; in drei Städten wurden bei rund der Hälfte der Fahrten weitere Fahrgäste hinzugebucht, in den Nachtstunden stieg der Pooling-Anteil auf bis zu 65 %. Zugleich verweisen die Autoren darauf, dass Pooling-Angebote vor allem als Tür-zu-Tür-Ergänzung zu Bus und Bahn funktionieren, regulatorisch klar von nicht bündelnden Mietwagenangeboten abgegrenzt und bei nachgewiesener Bündelung von hemmenden Rückkehrpflichten entlastet werden sollten. Auch die ökologische Transformation gehört in diesen Rahmen. Tschinibaew et al. (2024) verweisen auf die Bedeutung politischer Rahmenbedingungen, Ladeinfrastruktur und Innovationsförderung für die Emissionsfreiheit des Taxi- und Mietwagengewerbes. Siekermann (2023) betont für das Taxigewerbe regionale Runden Tische und eine vernetzte Infrastrukturentwicklung; das TALAKO-Projekt zeigt mit induktiver Taxiladung, dass die Elektrifizierung des Taxis spezifische betriebliche und infrastrukturelle Lösungen erfordert (Proff, Clemens, Marrón und Schmülling 2023). Kommunale Regulierung sollte deshalb nicht allein als Marktaufsicht, sondern als Bestandteil nachhaltiger Mobilitätsgestaltung verstanden werden.

Instrumentenlogik	Primäres Ziel	Eingriffstiefe	Governance-Bedingungen
Kontrolle und Durchsetzung	Einhaltung bestehender Pflichten sichern, u. a. Rückkehrpflicht, Genehmigungsrecht und Standplatzregeln wirksam machen	niedrig bis mittel	Personal, Datenzugang, ämterübergreifende Kooperation; Wirkung vor allem als Basisinstrument
Modernisierung des Taxitarifs	Taxi an digitale Buchungslogiken anschließen; Preis- und Planungstransparenz erhöhen	niedrig bis mittel	Regelmäßige Tarifprüfung und -anpassung, klare Kommunikation, Evaluation von Festpreisen und Tarifkorridoren
MBE für Mietwagen	Strukturelle Preisunterbietung im Mietwagenmarkt begrenzen; faire Wettbewerbsbedingungen herstellen	mittel bis hoch	Lokale Marktwirkungsanalyse, rechtssichere Begründung, Kontrolle, Ausnahmen und Nachsteuerung
Integration in ÖPNV und Mobilitätsstrategie	Taxi als Bestandteil öffentlicher Mobilitätsversorgung institutionell absichern	mittel	Koordination mit Aufgabenträgern, Verkehrsverbünden, Sozial- und Klimazielen; Finanzierung und Angebotsplanung
Ökologische Transformation	Emissionsfreiheit, Ladeinfrastruktur und betriebliche Alltagstauglichkeit mit Regulierung verbinden	mittel	Infrastrukturplanung, Förderlogik, lokale Energie- und Flottenstrategie, Einbindung des Gewerbes

TABELLE I FUNKTIONALE TYPISIERUNG KOMMUNALER REGULIERUNGSINSTRUMENT

VI. KOMMUNALE FALLTYPEN

Die kommunale Praxis lässt sich idealtypisch in mehrere Ansätze ordnen. Ein erster Typus setzt auf intensive Genehmigungs- und Kontrollpraxis. Er ist besonders dort plausibel, wo Kommunen frühzeitig verhindern wollen, dass sich nicht regelkonforme Marktpraktiken verfestigen. Ein zweiter Typus nutzt Mindestbeförderungsentgelte als frühes Preisregulierungsinstrument; Leipzig gilt hier als wichtiger Referenzfall, weil die Einführung gerichtliche Aufmerksamkeit erzeugte und die rechtliche Belastbarkeit kommunaler MBE in den Fokus rückte.

Ein dritter Typus orientiert MBE an der Untergrenze des Taxitarifs und zielt damit auf eine möglichst weitgehende Angleichung der Preisuntergrenzen. In diese Logik lassen sich Ansätze wie Lörrach und perspektivisch Dortmund einordnen, soweit die jeweilige örtliche Ausgestaltung diese Orientierung bestätigt. Ein vierter Typus setzt MBE unterhalb des Taxitarifs an, etwa in Städten wie Köln, Essen, Heidelberg oder München. Dieser Ansatz reduziert Preisunterbietung, lässt aber weiterhin eine Differenzierung zugunsten des Mietwagens zu.Ein fünfter Typus verfolgt primär die Modernisierung des Taxiverkehrs durch Festpreise und Tarifkorridore, wie sie unter anderem in Berlin, Düsseldorf oder Chemnitz diskutiert oder eingeführt wurden. Hier geht es weniger um direkte Mietwagenpreisregulierung als um die Wettbewerbsfähigkeit des Taxis im digitalen Bestellmarkt.

Die Typisierung zeigt, dass sich bislang kein einheitliches kommunales Regulierungsmodell herausgebildet hat. Vielmehr reagieren Kommunen mit unterschiedlichen Instrumentenbündeln auf lokale Marktbedingungen, politische Zielsetzungen und Vollzugskapazitäten. Gerade deshalb ist weniger die Übertragung eines einzelnen Modells entscheidend als die Frage, ob Ziele, Instrumente, Datenbasis und Kontrollpraxis vor Ort konsistent aufeinander abgestimmt sind.

VII. GOVERNANCE-BEWERTUNG

A. Handlungsspielräume

Die PBefG-Novelle hat den kommunalen Instrumentenkasten erweitert. Kommunen können Taxitarife modernisieren, Mindestentgelte prüfen, Vollzugsstrategien schärfen und Taxi- bzw. Mietwagenangebote stärker in Mobilitätsstrategien einbeziehen. Daraus entsteht ein reales, aber voraussetzungsvolles Handlungspotenzial. Erfolgreiche Regulierung setzt voraus, dass Kommunen ihre Ziele explizit definieren: Geht es um Verbraucherschutz, Daseinsvorsorge, Angebotsstabilität, Wettbewerbsfairness, Klimaschutz oder ÖPNV-Ergänzung? Je klarer die Zielhierarchie, desto belastbarer lassen sich Instrumente begründen und evaluieren.

B. Grenzen

Grenzen kommunaler Regulierung entstehen durch fragmentierte Zuständigkeiten. Taxi- und Mietwagenregulierung ist häufig lokal und ordnungsrechtlich geprägt, während ÖPNV-

Aufgabenträgerschaft, Finanzierung, Verkehrsverbundlogiken und Mobilitätsplanung teils bei anderen Ebenen liegen. Plattformen agieren zudem stadtregional oder national, während kommunale Vollzugskapazitäten begrenzt bleiben. Steuerungsfähigkeit ist daher ein Mehrebenenproblem.

Eine weitere Grenze liegt in der Datenlage. Ohne belastbare Informationen über Fahrzeugzahlen, Einsatzzeiten, Preisentwicklung, Wartezeiten, räumliche Angebotsverteilung, Rückkehrpflichtverstöße und Wirkungen auf den ÖPNV bleiben regulatorische Entscheidungen angreifbar. Die vom Wissenschaftlichen Beirat (2017) geforderte digitale Einzelaufzeichnung von Fahrten verweist daher auf einen wichtigen Vollzugs- und Evaluationshebel, auch wenn seine Ausgestaltung datenschutz- und wettbewerbsrechtlich sorgfältig erfolgen muss. Kommunale Gutachten sollten deshalb nicht nur Instrumente empfehlen, sondern auch Evaluationsindikatoren definieren.

C. Erfolgsfaktoren

Aus der vergleichenden Betrachtung lassen sich fünf Erfolgsfaktoren ableiten. Erstens sollte Regulierung frühzeitig ansetzen, bevor Plattformmärkte stabile Pfadabhängigkeiten ausbilden. Zweitens müssen Kontrolle und Durchsetzung als Grundlage jeder Regulierung verstanden werden. Drittens sollten Festpreise und Tarifkorridore den Taxiverkehr modernisieren, ohne sie als Ersatz für Mietwagenregulierung zu überschätzen. Viertens sollten MBE lokal begründet, datengestützt kontrolliert und regelmäßig evaluiert werden. Fünftens sollte das Taxi stärker als Bestandteil öffentlicher Mobilitätsversorgung und kommunaler Mobilitätsstrategien institutionalisiert werden.

Diese Kombination vermeidet zwei Fehlsteuerungen: eine rein defensive Taximarktpolitik, die Innovation ausblendet, und eine rein marktliberale Plattformpolitik, die öffentliche Versorgungsinteressen unterschätzt. Gerade Pooling zeigt, dass nicht jede Plattformmobilität gleich zu bewerten ist: Bündelnde Angebote können ÖPNV und Taxi ergänzen, während nicht bündelnde Ride-Hailing- und Mietwagenmodelle stärker auf Preis- und Verfügbarkeitswettbewerb mit dem Taxi wirken. Kommunale Governance muss daher digitale Angebotsformen differenziert nutzbar machen und zugleich institutionelle Schutzvorrichtungen für Daseinsvorsorge, faire Wettbewerbsbedingungen und nachhaltige Mobilität sichern.

VIII. Schlussfolgerungen

Plattformbasierte Mobilität stellt Kommunen nicht vor die Alternative zwischen Innovation und Regulierung. Entscheidend ist vielmehr, digitale Angebotsformen so in die lokale Mobilitätsordnung einzubetten, dass Effizienzgewinne, Verbraucherinteressen, faire Wettbewerbsbedingungen und Daseinsvorsorge miteinander vereinbar bleiben.

Bezogen auf die Leitfrage zeigt die Analyse: Kommunen können ihre Steuerungsfähigkeit insbesondere dann sichern, wenn sie Vollzug, lokal begründete Preisregulierung, Modernisierung des Taxiverkehrs und datenbasierte Evaluation miteinander verbinden. Mindestbeförderungsentgelte, Festpreise, Tarifkorridore und Vollzugskontrollen sind dafür keine isolierten Einzelmaßnahmen, sondern Bausteine eines kommunalen Governance-Systems. Dessen Leistungsfähigkeit hängt davon ab, ob Kommunen klare Ziele definieren, lokale Marktdaten nutzen, Instrumente regelmäßig evaluieren und das Taxi als regulierten Bestandteil öffentlicher Mobilitätsversorgung institutionell absichern. Faire Wettbewerbsbedingungen entstehen dabei durch einen angemessenen Ausgleich der unterschiedlichen regulatorischen Pflichten von Taxi und Mietwagen, während die Daseinsvorsorgefunktion des Taxis durch seine institutionelle Einbindung in die öffentliche Mobilitätsversorgung erhalten bleibt.

Langfristig wird die kommunale Regulierung plattformbasierter Mobilität daran zu messen sein, ob sie faire Wettbewerbsbedingungen mit nachhaltigen und sozial ausgewogenen Mobilitätszielen verbindet. Das Taxi kann dabei eine Scharnierfunktion übernehmen: als Tür-zu-Tür-Angebot, als Ergänzung des ÖPNV, als Versorgungsangebot für vulnerable Gruppen, als Baustein emissionsarmer Mobilität und als regulierter Teil einer integrierten Mobilitätsstrategie. Ergänzende Pooling-Angebote können diese Rolle erweitern, wenn sie nachweislich bündeln, in öffentliche Mobilitätsstrategien eingebettet und klar von bloßer App-vermittelter Einzelbeförderung abgegrenzt werden. Kommunale Regulierung sollte diesen öffentlichen Wert sichtbar machen, institutionell absichern und zugleich offen genug bleiben, digitale Innovation in gemeinwohlorientierte Bahnen zu lenken.

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How Feasible is the 15-Minute City Concept in Istanbul: The Case of Beşiktaş District

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Abstract

This study aims to reveal the extent to which accessibility values calculated using digital platforms (15-minute city score) align with the physical, social and environmental realities on the ground—specifically in two distinct areas within Istanbul's Beşiktaş district, representing the polar extremes—the highest and lowest values—of the 15-minute city scores. Supported by field data, this study employing qualitative research methods addresses, in turn: how accessibility values are calculated, a morphological analysis of the selected areas, and an evaluation of the alignment or discrepancies between the calculated 15-minute city scores and the existing field data. Furthermore, the study will discuss the causes and mechanisms behind the observed discrepancies, the extent to which they represent reality, the reliability of remote calculations, and how these calculations should be utilised in official data. The findings contribute to enabling urban authorities to evaluate the data they use in planning and transport studies more accurately.

Keywords—15-minute cities, digital computing, field research, 15-minute city score toolkit, Beşiktaş, Istanbul

I. INTRODUCTION

In a context where traffic problems are making transportation increasingly frustrating, the quality of urban life has begun to depend on the concepts of accessibility and walkability. Among the urban planning approaches developed in this context, the "15-minute city" approach, in particular, has become the focus of academic research and policy debates in recent years. It has achieved this by offering a comprehensive model that aims to ensure the basic needs of daily life can be met quickly on foot or via micromobility. The growing influence of the 15-minute city approach has made the decisive role of physical proximity, service diversity, and accessibility in urban areas more prevalent in shaping user behavior. In this context, recent empirical studies evaluate the sustainability of cities through "minute-based" accessibility analyses of urban services and test the 15-minute city approach using spatial data [1-5].

Some studies in the literature show that accessibility is influenced not only by distance measurements but also by public transportation integration, environmental quality, the condition of infrastructure, functional density, and spatial distribution. Other studies have also developed various methodologies that utilize "x-minute" analyses to measure accessibility [6-8]. These studies reveal that access to functions such as health centers, schools, grocery stores or public transit stops within a specific time threshold directly shapes the daily life practices of city residents. The concept of accessibility has long held a central position in geography, transportation planning, and urban design studies and can be measured using various methods. While normative measures focus on idealized targets, positive measures are based on actual movements [9]. The cumulative opportunities approach [10] and the analysis of the shortest distance to a destination [11] have emerged as common methods for assessing accessibility. In addition, models that account for an individual's sociodemographic characteristics, travel behavior, or public transportation use have also been developed [12-13]. Although efforts related to digital accessibility assessments are on the rise, relatively little attention has been given to research evaluating the alignment of digitally generated accessibility outcomes with the urban conditions observed in the field.

Recent studies in the literature have highlighted certain limitations in digital accessibility assessments conducted for the “15-minute city” concept. In one such study, Mouratidis [14] notes that digital accessibility assessments often fail to fully account for different modes of transportation, public transit stops that facilitate interaction and transportation between city neighborhoods are not sufficiently taken into account in the assessment, uncertainties in identifying boundaries that create accessibility barriers, and the failure to adequately represent different groups in accessibility assessments due to the assumption that people walk at a specific standard speed. Consequently, this situation highlights the need to incorporate field data—which includes site-specific physical, topographic, and morphological conditions—into accessibility assessments calculated via digital platforms.

The aim of this study is to critically evaluate, through field observations, the extent to which the values generated by the 15-minute city score toolkit—a digital accessibility calculation toolkit—accurately reflect real-world urban conditions. The primary objective of this research is not to redevelop the computational model underlying the digital accessibility toolkit or to calibrate its scoring system based on field data. Instead, the study aims to reveal the alignment or misalignment between the units with the highest and lowest accessibility scores—as calculated via the digital platform—and the reality on the ground; it also examines which physical, topographic, and morphological characteristics account for the identified discrepancies. In this way, the strengths and weaknesses of digital accessibility analyses will be brought to light. This approach will provide a critical assessment aimed at enabling the more informed and context-sensitive use of digital calculation tools for walkability in urban planning and transportation policies. In this context, the research seeks to answer the following questions:

- What degree of alignment or discrepancy exists between the digital accessibility scores calculated using the 15-minute city score toolkit and field observations?
- What physical, morphological, and topographical characteristics account for the differences between evaluations based on digital calculations and field observations?
- What approaches do these identified differences suggest for interpreting digital accessibility evaluations and applying them in urban planning efforts?

This article is structured as follows: Following the introduction, it discusses the negative impacts of urbanization and efforts toward pedestrian-oriented planning to address them (Section A), as well as general information on the 15-minute (x-minute) city approach (Section B). Next, the methodology for calculating 15-minute city scores is discussed (Section II). Following that, the analysis of the Beşiktaş district’s demographic and physical characteristics and the study area begins (Section III). Subsequently, the cell with the highest 15-minute city score (Section A) and then the cell with the lowest 15-minute city score (Section B) are analyzed. In the final evaluation section, the digital calculations are compared with field analyses, and the reasons for any discrepancies are assessed whilst considering literature. The study concluded with recommendations regarding what should be considered in planning processes within the context of the 15-minute city concept (Section IV).

A. *The problem of modern cities: transportation and accessibility*

Industrialization has brought about rapid urbanization. After World War II, urban development accelerated, and cities have significantly deviated from the principle of proximity, which has long been at the heart of urban planning. One reflection of rapid developments in the fields of economics and technology in cities is the increasing prevalence of automobiles and the construction of wide highways to accommodate this vehicle density. These rapid changes in the urban landscape have become factors that directly affect accessibility. People have begun to live farther away from their workplaces and the amenities needed to meet their daily needs, and urban sprawl has become more prevalent. As urban policies have supported outward urban sprawl, dependence on cars has increased, while the use of public transportation and active mobility has declined [15]. In this regard, the quality of life for urban residents and environmental sustainability in the 21st century are being affected by problems stemming from motor vehicle use—such as the ever-increasing dependence on cars—as well as rapid urbanization and the negative consequences of urban sprawl.

Every situation experienced and taken for granted throughout the day—often without even realizing it—affects city dwellers and their surroundings, and in a sense, shapes them [16-17]. In his essay “Architecture in Everyday Life,” Dell Upton [18] redefines architecture not as a collection of monumental forms, but as a condition of everyday life experienced through the body. According to Upton, architecture is not merely something that is drawn; it is also something that is lived, experienced, and constructed through the body. In this regard, the traffic congestion, sustainability issues, and inequalities in access that we encounter in our surroundings will, at their core, be made possible by changes in "everyday life" [18]. Changes in everyday life will reshape the mobility patterns of cities. Urban planning approaches have now shifted from a car-centric planning approach to a search for a pedestrian-oriented transformation. In this regard, walking behavior is emerging as a key component of sustainable urban life, be it environmentally, socially, or individually [19]. Accordingly, walking-focused planning approaches, such as the "15-minute city" concept that has gained prominence in urban planning literature in recent years, are coming to the forefront.

B. *What is the concept of the 15-minute city (X minutes)?*

The 15-minute city is based on the idea that residents' neighborhood-focused daily needs are met primarily by non-motorized transportation or on foot. Carlos Moreno, who first proposed this idea at a climate conference in 2016, has influenced and enriched global discussions on the quality of urban life, the reduction of the carbon footprint, and sustainable urban development through the 15-minute city concept. Moreno defines the 15-minute city concept through four fundamental principles: (a) density, (b) proximity, (c) diversity, and (d) digitalization [20-22]. The first of these, density, is considered in terms of people per square kilometer—in contrast to the ultra-high-density buildings found in traditional planning. It refers to the optimal number of people that a given area can comfortably support in terms of urban service provision and resource consumption for sustainable urban planning. The principle of proximity refers to a city dweller's access to basic needs and services, both in terms of time and space. The principle of diversity refers to a mixed-use distribution at the neighborhood scale, where building functions—such as housing, workplaces, entertainment, and cultural spaces—meet the needs of city residents. Digitalization, meanwhile, is a principle that encompasses digital solutions designed to meet everyday needs—whether through digital tools inspired by smart city concepts or through real-time services and online interactions. This principle enhances accessibility while reducing transportation needs; in particular, it leads to lower emissions by decreasing automobile use. Consequently, it contributes to making cities more resilient in areas such as sustainability and climate change [20].

The principles identified by Moreno are spatial and functional characteristics that directly influence a pedestrian-focused approach to urban mobility. The concept of walkability, examined within the framework of the "15-minute city" concept [15]—which offers an alternative urban development strategy aimed at designing more livable, sustainable and efficient urban environments, in contrary to traditional, car-centric planning practices—is not shaped solely by these principles. Considering literature, the following elements can also be added to the characteristic features of 15-minute cities: livable public spaces, walkable and cyclable streets, inclusiveness and placemaking, and ubiquity. In this regard, the first step is to design walkable and bike-friendly streets, with the goal of establishing a comfortable, seamless, and barrier-free transportation network for all road users—including pedestrians, cyclists, and non-motorized travelers. This infrastructure is supported by public space designs that prioritize local community participation. These placemaking practices aim to strengthen people's sense of belonging to the area and reinforce local identity at new focal points created within the city. In accordance with the principle of inclusivity, which lies at the heart of this approach, all city residents —regardless of their individual abilities, age, gender, or background—are guaranteed the ability to move safely and without barriers in public spaces and to benefit equally from urban services. Finally, the principle of ubiquity envisions the extension of all these qualities throughout the entire city, ensuring that residents can access these standards seamlessly at every point in the city, regardless of their socioeconomic or demographic status [23]. Therefore, the 15-minute city concept offers a flexible design model that must be considered in all its dimensions.

II. RESEARCH METHODOLOGY, DATA COLLECTION, AND ANALYSIS

The study titled "15-minute city score toolkit – urban walkability analytics [24]" is a design developed by Fondazione Transform Transport ETS to measure cities' compliance with the 15-minute city concept using a quantitative method. This toolkit utilizes Python-based software that runs in the QGIS environment. The objective of this study is to develop a digital calculation method that makes the level of accessibility to services capable of meeting the basic daily needs of a specific area at both micro and macro scales repeatable and standardized. Consequently, this study builds upon walkability score measurements such as Walk Score and presents a calculation framework based on the components of the 15-minute city. The steps followed in the digital calculation method for the 15-minute city score are as follows:

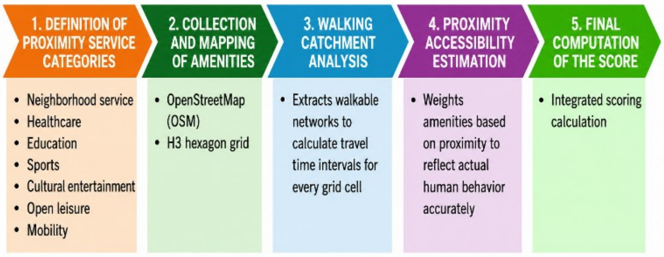

FIG. I STEPS FOLLOWED WHEN CALCULATING THE 15-MINUTE CITY SCORE ,VISUALIZED BY THE AUTHOR USING DATA FROM URBAN MOBILITY METRICS, [24].

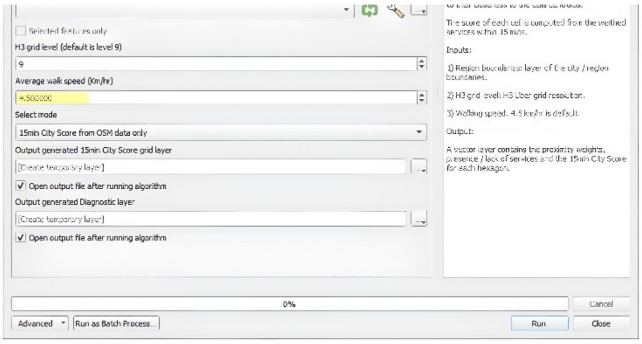

FIG. II INTERFACE OF THE 15-MINUTE CITY SCORE TOOKIT IN QGIS [24]

In the initial phase of designing the digital calculation tool, service categories that meet people's daily needs were identified. These service categories were grouped under eight main headings: "i) Neighborhood services (including personal and community services—e.g., post offices, banks, civic and community centers, police services, water filling stations, local government offices, bars and cafes, tobacco shops, and newsstands), ii) Healthcare: (hospitals, pharmacies, first aid, clinics, and local health services), iii) Neighborhood shops: (grocery stores, retail stores, bookstores, local markets, restaurants, supermarkets, and local non-food shops), iv) Education: (kindergartens, schools, colleges, universities, vocational schools, and libraries); v) Sports: (gyms and sports facilities); vi) Cultural entertainment: (cinemas, theaters, art centers, and museums); vii) Open leisure: (parks, children's playgrounds, and gardens); viii) Mobility: (surface-level public transportation stops, bike parking facilities, bike-sharing and car-sharing facilities, underground metro stations, and railway stations) [24]"

In the second phase of the method, Open Street Map [25] was used as a platform to obtain data containing the spatial counterparts of the identified service categories. One of the primary reasons for choosing Open Street Map [25] is that it is a platform with an open data source. Additionally, it was selected because its ability to host data on different cities holds the potential to enable cross-city comparisons of the scores to be calculated. Furthermore, the system was designed to allow users of this toolkit to add their own spatial datasets. This approach will facilitate the integration of local government data into the system, thereby enabling more precise analyses.

In the third phase of the tool design, a grid system was established to prevent scale discrepancies caused by administrative boundaries, and areas were identified where scores related to the 15-minute city approach would be measured. Spatial boundaries were delineated using the H3 Hexagon Grid System developed by Uber, rather than a traditional grid system. The hexagonal cells are designed to cover an area roughly the size of a neighborhood. The center of each hexagonal cell was configured to serve as the starting point for 15-minute accessibility calculations [24].

In the next phase, it is necessary to measure users' accessibility to the defined service functions within the H3 hexagons. For the pedestrian accessibility analysis, a pedestrian network was created using data from Open Street Map [25] regarding walkable road networks. The starting points created at the cell centers in the previous stage were connected to these networks. In these scenarios, isochrones ranging from 1 minute to 15 minutes were generated. Consequently, the accessibility scenarios for each cell within the grid system were integrated into the pedestrian route networks. The calculation process was carried out based on an average walking speed set at 4.50 km/h. During this process, spatial analyses were performed using Python's built-in libraries as well as libraries such as GeoPandas, NetworkX, OSMnx, Shapely, and PySAL. When establishing the relationship between the pedestrian route networks and service functions, the service area closest to the cell center was taken as the basis for each service category. Separate calculations were performed for each of the 8 categories: neighborhood shops and services, education, healthcare, sports, open leisure, cultural entertainment and mobility. Each category was first calculated as a value between 0 and 1; then, these values were combined across all 8 service categories to yield a value between 0 and 8. These calculated metrics were then converted into percentages. Thus, areas scoring between 90 and 100 indicate that daily needs can be met within a 15-minute timeframe.

The 15-minute city score toolkit is not an assessment tool developed specifically for certain cities and usable only in those cities. The toolkit's adaptable structure allows it to be applied in cities with various spatial, demographic, and transportation characteristics. Indeed, the toolkit has been applied in 112 different cities, primarily located in Europe; it has been used across a broad geographic area stretching from Reykjavík in the northwest, to Umea in the north, Lisbon in the west, Istanbul in the east, and Limassol in the southeast. This broad scope of application demonstrates the method's transferability to different urban contexts and its applicability in new case studies. While this does not, on its own, prove the method's validity or reliability, it does show that it offers a flexible evaluation framework capable of adapting to different urban conditions and being used in comparative spatial analyses [24].

To support the methodological robustness of the study, the principles of construct validity, internal validity, external validity, and reliability proposed by Robert K. Yin [26] for case study research were taken into account. Construct validity was supported by the combined use of multiple data sources. To support the interpretation of accessibility conditions, Open Street Map data used by the 15-minute city score toolkit, Caltopo topographic data, municipal planning data, Google Earth imagery, and field observations were analyzed together. In the process of interpreting the findings, the road hierarchy, topography, block sizes, usable green spaces, pedestrian infrastructure, and other physical environmental characteristics that could affect accessibility were taken into account. Google Earth imagery and street-level photographs were used not as an independent analysis dataset, but to document and illustrate the observed physical conditions. Internal validity was ensured by interpreting discrepancies between the calculated digital assessments and field observations in light of the study area's physical and spatial characteristics (e.g., topography, road hierarchy, block structure, pedestrian infrastructure, and available green spaces) within the context of accessibility. Since the study is based on a single case study, the findings are not statistically generalizable; however, they offer analytical insights applicable to similar urban contexts. Finally, the study's reliability is supported by a clear definition of the data sources used, the study area selection process, and the analytical approach, thereby strengthening the study's applicability in similar case studies within the same analytical framework.

III. CASE STUDY: ISTANBUL'S BEŞİKTAŞ DISTRICT

The 15-minute city score toolkit's study on Istanbul covers only the European side. Consequently, it is not possible to select a location from the Anatolian side for the study area. For this reason, a district on the European side of Istanbul has been designated as a sample area where a comparative analysis of the digital accessibility score and field data can be conducted. Furthermore, the 15-minute city score toolkit's omission of the "density" parameter—one of the fundamental principles of the "15-minute city" concept—in its digital calculation processes is based on the assumption that the areas the model currently calculates are urban areas with a specific population density. In line with this methodological assumption, a district with medium-to-high population density was selected as the sample area for the study. At the same time, the aim was to exclude areas—such as the Historic Peninsula—that have specific and strict site-specific conservation plans, and where urban interventions and morphological transformations are therefore limited. In this context, and considering the aforementioned constraints and methodological criteria, Beşiktaş—which represents a critical threshold as an intersection point of transportation networks within Istanbul's macro-form and also exhibits a dynamic urban morphology—serves as a unique case study for testing the feasibility of "15-minute city" policies.

According to Endeksa [27] data, the population density of the Beşiktaş district is significantly higher than the national average for Turkey. Furthermore, it has been determined that Beşiktaş's population density is higher than that of Istanbul, a megacity. Consequently, the Beşiktaş district meets the density principle—defined as the number of people per kilometer—which is one of the fundamental principles of the "15-minute city" concept.

Region/Area	***Total Population (People)***	***Population Density (People/ km2)***

Türkiye	85,664,944	109.80
Istanbul	15,701,602	2,869.93
Beşiktaş	167,264	9,265.56

TABLE I COMPARISON OF POPULATION AND POPULATION DENSITY IN TURKEY, ISTANBUL, AND BEŞIKTAŞ, ENDEKSA [26].

Upon closer examination of the Beşiktaş district, it can be stated that it comprises a total of 23 neighborhoods, all of which are fully urbanized [25]. According to calculations based on property ownership across Beşiktaş, residential property accounts for 83.68%, while commercial properties account for 16.32% [27]. Therefore, it can be stated that residential areas are generally predominant. This situation aligns with the residential-focused design of “15-minute cities,” which aims to meet people’s daily needs at the neighborhood level.

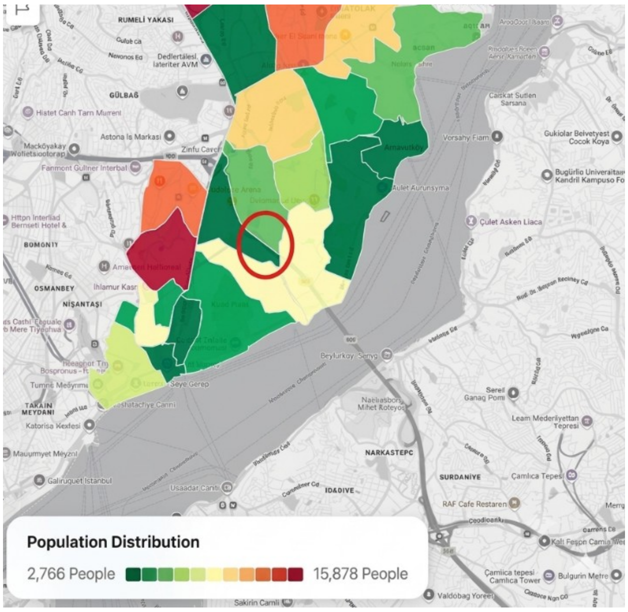

FIG. III POPULATION DISTRIBUTION BY NEIGHBORHOOD IN THE BEŞIKTAŞ DISTRICT AND THE AREA WHERE THE STUDY AREA IS MARKED, ENDEKSA [27].

Another notable demographic point is the age distribution of the population in Beşiktaş district. According to data from Endeksa [27], the population aged 65 and over in the Beşiktaş district is significantly higher than that of other age groups.

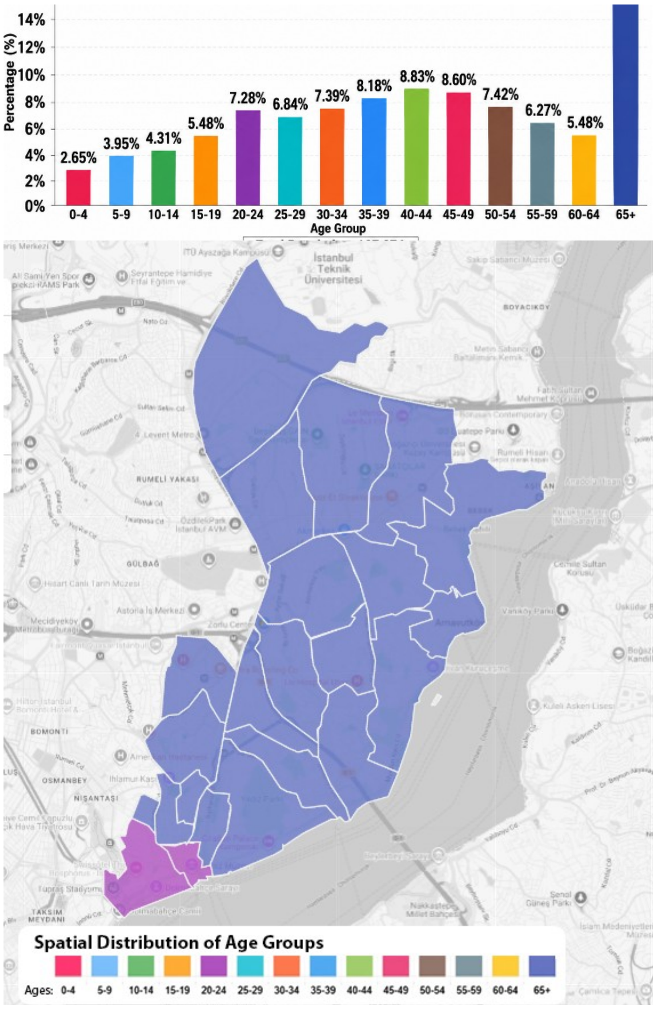

FIG. V ISTANBUL’S BEŞIKTAŞ DISTRICT, THE MAP SHOWING THE AGE DISTRIBUTION OF THE POPULATION IN THE BEŞIKTAŞ DISTRICT, ENDEKSA, [27].

The cells within the Beşiktaş district were analyzed using the 15-minute city score toolkit [24], and five adjacent cells with different scores were identified. The cell with the highest 15-minute city score is 92; the cell with the lowest score is 30; and the others have scores of 87, 63, and 76. Consequently, these five cells were numbered from one to five, and within the scope of the study, cells with scores below 50 were assigned number 5, those in the 50–70 range were assigned number 4, those in the 70–80 range were assigned number 3, those in the 80–90 range are designated as cell number 2, and those with scores over 90 are designated as cell number 1.

FIG. VI THE SCORES FOR ISTANBUL'S BEŞIKTAŞ DISTRICT IN THE 15-MINUTE CITY SCORE TOOLKIT [24] AND THE CELLS WITH THE HIGHEST AND LOWEST SCORES SELECTED FOR THE STUDY AREA

In this study, the H3 hexagonal cell with the highest score of 92 points and the H3 hexagonal cell with the lowest score of 30 points were examined in detail. The study examined the consistency of the cells that yielded extreme (highest and lowest) values in the digital analyses with actual field conditions; the model's capacity to reflect spatial reality and its level of accuracy were analyzed. Since it is methodologically impossible to directly compare and validate the intermediate values generated quantitatively in digital modeling with empirical (field) observations due to their nature, cells numbered two, three, and four were excluded from the scope of the study due to its limitations. The structural and scalar differences between the mathematically generated quantitative intermediate values and the qualitative field observations do not allow for a direct comparison of these two data sets.

A. Cell number 1 (15-minute city score:92) Examining the cell with the highest score

FIG. VII MAP AND IMAGES OF CELL NO. 1 IN THE BEŞIKTAŞ DISTRICT, WHICH HAS A 15-MINUTE CITY SCORE OF 92 (VISUALIZED BY THE AUTHOR USING OPEN STREET MAP [25] AND GOOGLE EARTH [30]).

Cell number 1 is located at the intersection of the Mecidiye, Ortaköy, and Levazım neighborhoods in Beşiktaş. Building heights in the area range from 2 to 10 stories. The average building height is around 6–7 stories. The 15 Temmuz Şehitler Bridge, one of the main transportation arteries of Istanbul's macro-form, is located on the edge of this cell. The ground level is at a height that allows a road to pass under the bridge. Slope levels vary in places. There is a street near the center of the cell (marked in yellow on the map) and side streets connecting to it. Various service functions, such as pharmacies, dining establishments, and grocery stores, are located along this street, which serves the area much like the marketplace of cell number 1. A mosque is located at the section where the street ends at an intersection. The street network includes several dead-end streets, reducing network connectivity and pedestrian permeability. The areas shown in green on the map are the Greek Orthodox Cemetery, an area belonging to the Armenian Catholic Monastery, and the Jewish Cemetery. There is also a children's park in an area near the perimeter of the cell.

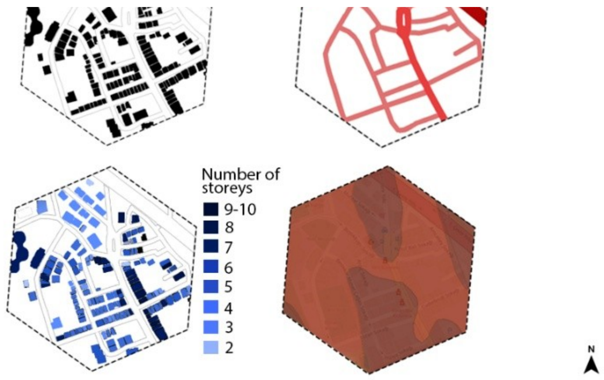

FIG. VIII ANALYSES OF A CELL IN THE BEŞIKTAŞ DISTRICT WITH A 15-MINUTE CITY SCORE OF 92, BASED ON OPEN STREET MAP [25]; BUILT-UP/VACANT AREA ANALYSIS (TOP LEFT), BUILDING HEIGHT ANALYSIS (BOTTOM LEFT); ROAD NETWORK ANALYSIS (TOP RIGHT); SLOPE ANALYSIS (BOTTOM RIGHT).

Based on the analyses conducted, an evaluation of Cell Number 1 revealed that the presence of service areas with various functions along the street near the center of this cell, as well as pedestrian access for meeting daily needs, is more consistent with the 15-minute city approach—a finding also confirmed by digital calculations. However, more in-depth examinations of the area revealed through the road network analysis that some parcels are quite large. Although the service functions are located on a street near the cell's center, pedestrians coming from the periphery to the center must walk around these large parcels to reach the street. Furthermore, the road network analysis revealed that walking continuity is disrupted because some streets end in cul-de-sacs. Another finding from the analyses is that the areas appearing as "green" on digital platform maps do not serve the "open leisure" category within the 15-minute city concept. On the map corresponding to Cell Number 1, the areas appearing in green are the Jewish cemetery and the church garden. One might assume that the church garden is an "open leisure" area serving the public. However, field observations revealed that the church is an abandoned historic structure and its garden is an overgrown, neglected area, and therefore not in use. Consequently, it can be argued that the current status of service categories —which are evaluated on digital platforms based on the presence or absence of a feature in the area —sometimes does not actually reflect the provision of the relevant service in practice.

Another issue identified during the analysis is the absence of contour line data in Open Street Map and the fact that slope is not factored into the 15-minute city score toolkit methodology. The data on contour lines used in the field analyses was retrieved from the Caltopo website [29]. In this regard, it can be argued that a digital calculation that does not account for contour lines does not accurately reflect the actual walkability time of the area.

Analyses were initially conducted using Open Street Map as the data source during the digital calculation phase. However, building floor heights were also unavailable on Open Street Map [25]. Therefore, data on building floor heights was obtained from Beşiktaş Municipality's plans for the area. While reviewing the municipality's plans, it was observed that some structures present in the municipal plans were not found on Open Street Map [25]. This finding was also confirmed using another platform, Google Earth Pro application [30]. Consequently, it was observed that the "empty" spaces in the parcels included in the density analysis were, in fact, so densely built-up that they did not allow for pedestrian passage. The conclusion drawn from all these field analyses and observations is that, despite this area having the highest score on digital platforms, the field analyses reveal the presence of conditions that negatively impact walkability and accessibility.

B. *Cell number 5 (15-minute city score:30) Examining the cell with the lowest score*

Cell Number 5 is located between the Balmumcu and Levazım neighborhoods of Beşiktaş. The number of stories in this cell ranges from 2 to 7. The average number of stories is 3–4. As previously mentioned, the 15 Temmuz Şehitler Bridge—one of the main transportation arteries of Istanbul's macro-form—is situated right in the center of Cell Number 5. The bridge meets ground level in the area where this cell is located. However, there is no direct connection between the main artery and this area. Furthermore, there is only a single axis within the cell that provides an underpass beneath the bridge. The increasing density of contour lines in the northwest direction of the study area indicates that the topographic slope and elevation difference increase in this direction. Streets that can be classified as secondary roads predominate within the cell. The areas shown in green on the map legend represent the surfaces where the bridge piers make contact with the ground. The area consists primarily of residential zones.

FIG. IX MAP AND IMAGES OF CELL NO. 5 IN THE BEŞIKTAŞ DISTRICT, WHICH HAS A 15-MINUTE CITY SCORE OF 30 (VISUALIZED BY THE AUTHOR USING OPEN STREET MAP [25] AND GOOGLE EARTH [30].

Based on the analyses conducted, when evaluating cell No. 5, the presence of the bridge at its center divides the cell into two distinct areas. Since access is provided via a single axis under the bridge, it is not possible to cross from any other location, either on foot or by vehicle. This situation negatively impacts connectivity between these two areas within the same cell. Another issue is that the green spaces—which function as a spatial buffer zone to mitigate the negative effects and risks of high-speed traffic at the point where the bridge meets ground level—are unusable green spaces. In other words, these areas do not serve the “open leisure” function within the 15-minute city concept. Although there is a neighborhood market in the section north of the bridge, it is set up only on certain days of the week and remains closed on other days, so it does not meet people’s daily needs. This is because there are no supermarkets or shopping areas in either of the two districts. The fact that this area—which is primarily residential—lacks the infrastructure to meet its service needs has resulted in this cell receiving a low score. Considering that slope was disregarded in the digital calculations, it is likely that Cell 5’s current score of 30 is actually even lower based on field data. Therefore, in the planning processes to be carried out to integrate this cell into the 15-minute city paradigm, the dynamics of Istanbul’s macro-form must be considered. Designing an optimized H3 hexagonal cell that prevents the bridge from acting as a spatial barrier (dividing element) or defining a holistic perimeter using an alternative grid system, would be a more rational approach that enhances methodological accuracy.

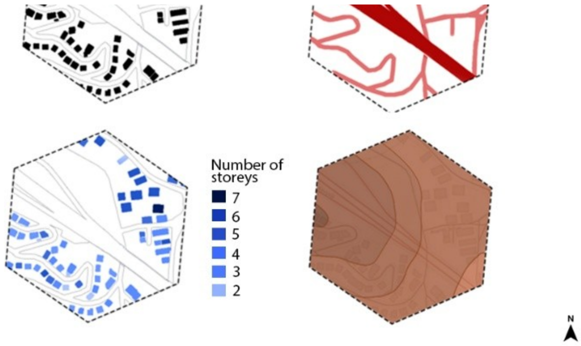

FIG. X ANALYSES OF A CELL IN THE BEŞIKTAŞ DISTRICT WITH A 15-MINUTE CITY SCORE OF 30, BASED ON OPEN STREET MAP [25]; BUILT-UP/VACANT AREA ANALYSIS (TOP LEFT), BUILDING HEIGHT ANALYSIS (BOTTOM LEFT); ROAD NETWORK ANALYSIS (TOP RIGHT); SLOPE ANALYSIS (BOTTOM RIGHT).

IV. DISCUSSION AND CONCLUSION

The study titled “15-minute city score toolkit – Urban Walkability Analytics [24],” conducted by Fondazione Transform Transport ETS, uses quantitative methods to assess cities’ alignment with the “15-minute city” concept and performs a digital calculation. The methodological approach used in this calculation identifies eight distinct categories related to meeting people’s daily needs: neighborhood services, healthcare, neighborhood shops, education, sports, cultural entertainment, open leisure, and mobility. However, it is important to note that all subcategories within each of these categories represent services that people need in their daily lives. For example, the “education” category includes subcategories such as daycare centers, elementary schools, middle schools, and universities. In the calculation, the presence of any of these within a given area indicates that the cell is close to educational services. However, just as the presence of a daycare center does not meet the need for an elementary school, the presence of a pharmacy does not meet the need for a health clinic. Therefore, from a methodological standpoint, organizing service categories into broad headings does not serve the purpose of meeting daily needs within the “15-minute city” concept [31]. In this case, the digital measurements to be conducted will represent a quantitative expression of the number of service categories in the area.

Although the global scale “15-minute city score toolkit,” which utilizes Open Street Map data, provides a macro-scale standard by being applied in different cities, since the topography of each city is different, taking contour lines into account in the calculations will help produce more realistic results. Indeed, in the case of Beşiktaş, the morphological barrier effect created by the suspension bridge axis —which forms the city’s main transportation backbone and connects the two shores separated by the Bosphorus Strait—poses a risk that digital calculations within the relevant H3 cell may produce misleading results if topography and elevation relationships are not taken into account. Therefore, ensuring that the grid system defined by the digital calculations has a flexible structure shaped according to the city's macroform is crucial for integrating the area into the "15-minute city" concept. Furthermore, since performing calculations using a single data source would prevent the inclusion of different paradigms—such as slope—in the calculations, it is necessary to diversify and cross-reference the data sources used and to verify the data.

The slope parameter also affects "accessibility by foot or bicycle," which is a fundamental component of the 15-minute city concept. For this reason, it is critically important that each primary and secondary road in the area have a percentage gradient suitable for vulnerable groups. On the other hand, a different approach, as stated by Mouratidis, is that people generally access local destinations—such as stores, public transit stops, parks, and elementary schools—on foot. Because walking is considered more inclusive—as it can be undertaken by a larger portion of the population compared to cycling—it is deemed more suitable as the foundation of the "15-minute city" approach [29]. On the other hand, equipping the urban fabric with the infrastructure needed to support bicycle use and, at the same time, conducting public awareness campaigns through infographics, billboards and short videos on mass media platforms (social media, television, radio, etc.) are of great importance in terms of the contribution of bicycle use to sustainability. This holistic approach will not only support individuals' established walking habits but also ensure that bicycles play a significant role in urban accessibility scenarios.

When assessing an area's suitability for the "15-minute city" concept, it is necessary to utilize demographic data on the area's residents in addition to physical environmental conditions. This approach is of critical importance for enhancing user experience and spatial equity. Indeed, an analysis of demographic data for the Beşiktaş district reveals that the proportion of the population aged 65 and older is significantly higher compared to other age groups, making it imperative to take into account the specific needs of this demographic in urban mobility calculations. However, the fact that macro-scale digital calculation models treat all segments of society through a single standardized pedestrian profile—in accordance with the principles of inclusivity and ubiquity—can lead to such local demographic vulnerabilities being overlooked. In the 15-minute city score toolkit's digital calculation, the average walking speed was determined to be 4.50 km/h. However, research on walking speed indicates that among different age groups, the lowest walking speed—3.39 km/h—is observed in women aged 80–99, and it has been established that the distance covered in 15 minutes at this speed is 850 meters [31, 32]. Therefore, when determining the urban walking speed parameter, approaches such as establishing a more inclusive speed range that reflects the mobility capabilities of different vulnerable groups —rather than relying on standard and uniform assumptions—and developing alternative scenarios that take climate and weather conditions into account will ensure more realistic and empirical results in planning studies. Thus, this situation will directly contribute to ensuring social justice and spatial equity in access to urban services.

Considering all these assessments, the cells examined in the Beşiktaş district have shown that an area that received the highest score on digital platforms as being most suitable for the "15-minute city" concept may actually perform less well in field analyses. Although field findings indicate that the actual value of this theoretically high-scoring cell is lower, parameters such as the diversity of functions provided by digital calculations and the integration of walking routes into street network analysis also highlight, from a certain perspective, that cell's potential suitability for the "15-minute city" concept. Therefore, directly classifying a cell that receives a high score from digital calculations as "perfectly suitable" does not align with field realities. However, completely disregarding this high score would also be a flawed approach. Similarly, the cell with the lowest score in digital calculation analyses should not be completely disregarded by stating that "no connection can be established with the 15-minute city concept." Instead, a much more realistic and constructive approach would be to thoroughly examine—using field data—the topographic and morphological constraints, spatial barriers, and infrastructure deficiencies that cause the low score; this would help identify the areas that need development and uncover the hidden potential of the site.

The critical framework provided by this study serves as an important methodological foundation for future research on urban accessibility and the "15-minute city" concept, prioritizing the integrated consideration of digital assessments and on-site realities. In this regard, to evaluate accessibility—

specifically the ability to meet people's daily needs—more realistically and accurately at the scale of the "15-minute city" concept (within the boundaries of a neighborhood), future studies should: designing a new grid network (gridal system) shaped by the macroform dynamics of cities and examining the impact of different spatial tessellation approaches on accessibility outcomes are among the priority research topics. Furthermore, incorporating data on user experiences—which cannot be calculated via digital platforms—into the research process by uncovering them through field observations and in-depth qualitative interviews will strengthen the methodology. Additionally, integrating parameters identified through field studies—such as slope, walking speeds specific to user groups, physical infrastructure and amenities designed for groups at a disadvantage due to age or other reasons, needs arising from seasonal variations, and variables in day-and-night usage—parameters that can be determined through field studies—into digital accessibility models can offer significant methodological advancements in reducing the discrepancy between field observations and digital data, thereby enabling context-sensitive urban planning practices. Regarding the technical aspects of the computational process, ensuring that variables obtained from various digital platforms are included in the analysis without omission, and incorporating data from these diverse platforms into the research after comparing and verifying them, will enable more precise and accurate spatial analyses and, in turn, strengthen the reliability of the research findings. It is anticipated that the integration of these empirical and data-driven findings—along with the development and testing of a new computation-based algorithm—will ultimately lead to the generation of region-specific, concrete planning and design recommendations aimed at enhancing urban accessibility, thereby making cities more compatible with the "15-minute city" concept.

Funding: This paper was produced from Hacer TURAN's PhD Thesis conducted at Istanbul Technical University Institute of Graduate Studies under the academic supervision of Assoc.Prof.Dr. Fatih EREN. The theoretical framework of this paper was produced as part of the 'Aquatic Urban Ecosystems Alive (AQUAlive)' project with the international code: "F-DUT-2024-0260" and the national TÜBİTAK code: "225N983". The AQUAlive project is being conducted officially under the leadership of Fatih EREN and the postgraduate student scholarship of Hacer TURAN, and is funded under the European Commission's Horizon Europe Programme Driving Urban Transitions (DUT 2024). DUT projects are supported by the European Commission and funded under the Horizon Europe (HORIZON-CL5-2021-D2-01-16) programme. Fatih EREN is the Corresponding Author of this paper. The funding sources had no role (were not involved) in the production of this paper.

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From Political Adoption to Implementation: Governance and Dialogue Formats for the Municipal Mobility Transition

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Abstract — With its Sustainable Urban Mobility Plan (SUMP/NUMP), the Hanseatic City of Lüneburg has established a strategic framework for future mobility development. Yet the political acknowledgement of the plan did not end the process; it opened a demanding implementation phase in which measures must be prioritised, coordinated across administration, politics and stakeholders, and aligned with limited resources. This paper presents a practice-oriented single-case analysis of how a dialogue-oriented support format developed by the Hanseatic City of Lüneburg and IGES Mobility can address the governance gap between strategic planning and operational implementation. Drawing on the Lüneburg case, the accompanying conference presentation, public committee documents, structured practitioner reflection and SUMP implementation literature, the paper discusses changing roles, participation expectations, annual prioritisation, monitoring requirements and links to municipal budget and committee cycles. The findings should be read as analytical propositions from an early implementation case, not as a completed impact evaluation. The paper argues that recurring dialogue formats can stabilise mobility transition processes if they combine transparent prioritisation, stakeholder knowledge, administrative feasibility, political decision-making and a clear learning logic.

Keywords— Sustainable Urban Mobility Planning, SUMP, governance, implementation, participation, monitoring, municipal mobility transition

I. Introduction: From Strategy to Implementation

Sustainable Urban Mobility Plans (SUMPs) have become a central reference point for integrated urban mobility planning in Europe. Compared with more traditional transport planning approaches, SUMPs shift the focus from traffic flow and infrastructure provision towards accessibility, quality of life, social equity, environmental quality and the integrated development of all transport modes (Wefering et al. 2013; May 2015; Backhaus et al. 2025). The current European SUMP guidelines define a SUMP as a strategic plan that addresses the mobility needs of people and businesses while building on existing planning practices and taking account of integration, participation and evaluation principles (Backhaus et al. 2025). In this sense, SUMPs are not merely lists of measures. They are intended to organise sustainable mobility as a long-term, evidence-based and participatory planning process.

The relevance of this approach has increased considerably. The revised TEN-T Regulation requires urban nodes to adopt and monitor SUMPs by the end of 2027, and the new German national criteria translate these European requirements into a checklist that can also serve as guidance for municipalities beyond the formally designated urban nodes (European Union 2024; BMV 2026). For German municipalities, the SUMP framework therefore combines a strategic planning opportunity with a growing expectation of measurable goals, transparent implementation pathways and systematic monitoring.

However, the political adoption of a mobility plan does not automatically lead to implementation. In practice, the most demanding phase often begins after the plan has been finalised: measures need to be prioritised, specified, translated into administrative work programmes, aligned with committee and budget cycles, and continuously adapted to changing local circumstances. The accompanying conference presentation summarised this problem in one guiding question: how can a politically adopted mobility concept be translated into continuous, prioritised and budget-relevant implementation?

This paper addresses this question using the case of the Hanseatic City of Lüneburg. Lüneburg's Nachhaltiger Urbaner Mobilitätsplan (NUMP) is aligned with the European SUMP logic and provides a strategic framework for the city's mobility development over a period of around ten to fifteen years, with a perspective towards 2040 *(Hanseatic City of Lüneburg 2025)*. Yet the NUMP did not close the process; it created the basis for a new implementation phase. The paper therefore examines the governance gap between strategic planning and operational implementation and discusses the "Umsetzungsdialog", an implementation dialogue format developed for Lüneburg, as a possible bridging instrument.

Against this background, the guiding research question is: How can a politically acknowledged SUMP/NUMP be translated into a recurring, prioritised and politically connectable implementation process? The paper does not claim to verify final budgetary or implementation outcomes. Instead, it analyses the governance logic of an early implementation format and identifies conditions under which such a format can support the transition from strategic planning to municipal implementation.

The core argument is that SUMP implementation requires more than technical measure management. It requires an implementation infrastructure that can connect long-term goals with annual prioritisation, administrative feasibility, political decision-making, stakeholder expectations and monitoring. This is particularly relevant for medium-sized cities such as Lüneburg, where strategic ambition, limited administrative capacity, strong local networks and complex expectations around participation meet in a very concrete implementation setting.

II. Sustainable Urban Mobility Planning as a Strategic Framework

The SUMP concept has evolved from European guidance into an increasingly formalised planning framework. Early guidelines already emphasised long-term vision, stakeholder involvement, integrated transport and land-use planning, clear responsibilities, funding, monitoring and learning (Wefering et al. 2013). The third edition of the European SUMP guidelines strengthens this logic and reflects the revised European policy context, including climate targets, the TEN-T Regulation, urban logistics, multimodal integration and the need to plan for functional urban areas rather than only administrative boundaries (Backhaus et al. 2025).

The German national criteria further operationalise this approach. They emphasise accessibility, functional urban areas, high-quality mobility offers, road safety, sustainable mobility, low-emission mobility, integrated planning, participation, implementation planning and monitoring (BMV 2026). These criteria are important because they turn a broad planning philosophy into assessable requirements. At the same time, they do not prescribe a single local implementation model. This is a central point for the argument of this paper: SUMPs provide a structured strategic framework, but municipalities must still develop context-specific governance arrangements to make implementation work.

The literature confirms that this local translation is decisive. May (2015) identifies a range of barriers to effective SUMP development and implementation, including pro-car and infrastructure-oriented planning traditions, weak cooperation between transport and land-use planning, insufficient funding, inadequate coordination between tiers of government, demanding stakeholder involvement and political conservatism. Mladenovič, Plevnik and Rye (2022) similarly show that SUMP development and implementation take place in complex multi-level governance settings. National support programmes can help, but they do not fully remove the practical barriers municipalities face, particularly lack of funding and public opposition to contentious measures.

This argument is reinforced by research on the German mobility transition. Reichenbach and Fleischer (2023) show that the shift from ambition to implementation is not only a technical or behavioural challenge, but also a question of institutionalisation. Sustainable mobility transitions require organisational routines, responsibilities and institutional arrangements that can carry ambitious goals into everyday decision-making. For SUMP implementation, this means that the post-adoption phase needs dedicated governance structures rather than relying on the strategic plan alone.

Evidence from Germany points in the same direction. Arndt and Drews (2019) show that integrated transport development planning is highly relevant for German municipalities, but that implementation is constrained by long planning and participation processes, limited financial and personnel resources and insufficient binding force. Their survey also highlights an ambivalent role of participation: it can support acceptance and improve understanding of citizens' concerns, but it can also become challenging when different target visions and mobility interests strongly diverge (Arndt and Drews 2019). This finding directly resonates with the Lüneburg case, where participation remains important after plan completion but needs to be reframed for implementation.

The specific situation of smaller and medium-sized cities adds another layer. Guidance on SUMP in smaller cities and towns stresses that such municipalities often have fewer financial and personnel resources, less specialised mobility planning expertise, stronger car dependency and weaker public transport systems than larger cities. At the same time, they may benefit from shorter distances, more walkable and bikeable structures, well-connected social communities and lower institutional complexity under favourable conditions (Brand, Böhler and Rupprecht 2021). For Lüneburg, this means that implementation governance cannot simply be copied from large metropolitan administrations. It needs to be lean, recurring, understandable and closely linked to existing municipal routines.

A further strand of research points to the limits of SUMP as a transformation instrument. Hartl, Harms and Egermann (2024) compare SUMP with transition management and argue that sustainable urban mobility planning could become more transformation-oriented by using transition theory, collaborative formats, backcasting approaches and experiments. Their analysis is particularly relevant for the implementation phase: transformation requires more than a sound plan. It requires formats that enable learning, adaptation, conflict management and the translation of long-term goals into actionable steps.

This also connects with mobility management as a field of integrated transport planning. Schwedes and Rammert (2020) argue that sustainable transport development cannot be reduced to infrastructure provision, but must address mobility behaviour, social participation and the possibility of enabling more mobility with less traffic. This perspective strengthens the argument that implementation is not only about delivering projects, but also about shaping mobility options, routines, communication and institutional responsibilities.

This creates a productive tension. On the one hand, the SUMP framework standardises important quality criteria. On the other hand, successful implementation depends on local institutional conditions, political windows, administrative capacity and the ability to manage conflicts. The Lüneburg case illustrates this tension and shows why an additional governance format can be useful after the completion of the strategic plan.

III. METHODOLOGICAL APPROACH AND CASE BASIS

This paper is designed as a practice-oriented single-case analysis. It uses the Lüneburg case to analyse a specific governance challenge that often emerges after the completion of strategic mobility plans: the translation of long-term goals into prioritised, administratively feasible and politically connectable implementation steps. The aim is not to provide a statistically representative evaluation of SUMP implementation, nor to test causal effects of the implementation dialogue.

The analysis combines five source types of insight. First, it draws on the European and German SUMP framework, including the revised TEN-T Regulation, the European SUMP guidelines and the German national criteria. Second, it uses selected academic and practice-oriented literature on SUMP implementation, governance, participation, monitoring and mobility transitions. Third, it builds on the NUMP final report of the Hanseatic City of Lüneburg, which documents the plan's integrated structure, stakeholder and public participation formats, measure profiles, prioritisation, cost estimates, resource requirements and evaluation concept (Hanseatic City of Lüneburg 2025). Fourth, it considers public committee documents from the first implementation dialogue cycle, especially the submissions on the measure profiles F1 “Netzkonzeption Fuß”, M1 “Netzkonzeption Kfz”, S4 “50 Knotenpunkte und Querungen für Lüneburg” and S5 “Sichere Schulumfelder”. Fifth, it reflects the authors' direct practitioner experience in the Lüneburg NUMP process and the subsequent development of the implementation dialogue.

The case perspective is based on two complementary roles. The municipal perspective reflects the experience of coordinating the NUMP during its preparation and subsequently carrying responsibility for implementation within the city administration. The external process perspective reflects the former project management of the NUMP and later strategic support for the implementation phase. This double perspective is relevant because the governance gap appears precisely at the interface between strategic planning, municipal administration, political decision-making and external facilitation.

To strengthen analytical consistency, the case is interpreted through five categories derived from the literature and the practical implementation challenge: role shifts after plan completion, participation in the implementation phase, alignment with municipal budget and committee cycles, monitoring and learning requirements, and limits of transferability. The findings were validated through triangulation between the NUMP final report, public committee documents, the conference presentation, the literature and the two author perspectives. However, the paper remains limited by the early stage of implementation. It cannot yet provide longitudinal evidence on budget allocation, implementation speed or long-term learning effects.

IV. THE GOVERNANCE GAP AFTER PLAN COMPLETION

During the preparation of a SUMP, roles are usually relatively clear. A planning office or external consortium structures the process, provides methodological expertise, develops analyses and measures, facilitates participation and prepares outputs for political discussion. The municipal administration coordinates the process, contributes local knowledge, ensures organisational continuity and connects the planning process with local political bodies. Stakeholders and citizens provide perspectives, identify needs and evaluate proposals. This arrangement can be demanding, but it is usually held together by a defined project structure, a timeline, a contract and a final deliverable.

After plan completion, this structure changes. The final report may provide a strategic framework, but the external planning contract often ends. Responsibility for further specification, internal coordination, political preparation and implementation shifts back to the municipality. This is not a weakness of SUMP guidance; it is a structural feature of the transition from planning to implementation. The European guidelines address implementation and monitoring, but they cannot define the specific organisational arrangements for every municipality (Backhaus et al. 2025). Similarly, action-plan guidance recommends defining measures, responsibilities, timeframes, funding sources, indicators, activities, resources, costs and stakeholder involvement, but the concrete form remains locally contingent (Mattsson and Wennberg 2018).

The topic guide for smaller cities and towns makes this transition particularly clear. After SUMP adoption, the strategic plan provides a framework, but implementation tasks are often taken over by responsible technical planners rather than by the original SUMP team. Therefore, a good handover, continuous coordination and regular status updates are vital to ensure a coherent implementation approach (Brand, Böhler and Rupprecht 2021). This is highly relevant for Lüneburg, because implementation requires the transfer of measure profiles into administrative procedures, political consultation and budget-related decisions.

Lüneburg illustrates this transition clearly. The NUMP final report contains a differentiated action and evaluation concept, including measure profiles, prioritisation, a time horizon towards 2040, financial considerations, personnel requirements and indicators for goal achievement and implementation evaluation (Hanseatic City of Lüneburg 2025). The plan therefore provides more than a general vision. Nevertheless, it does not automatically bring measures into practice. In Lüneburg, implementation depends on further political decisions, administrative specification and budgetary provision. Measures must be translated from a strategic programme into annual priorities, committee submissions, funding applications, staff assignments and operational project steps.

This transition creates a governance gap. The term governance is used here to describe the structured connection between strategic planning, political prioritisation and operational implementation. The gap emerges because the strategic plan has been completed, while the institutional routines required for implementation are not automatically in place. New actors within the administration may become responsible for individual measures. Existing stakeholders may expect continuity from the participation process. Political actors may need to decide on selected measures rather than on the entire strategic plan. Budget cycles may require decisions before all technical details are fully developed. These dynamics require a new type of coordination.

The literature suggests that such implementation challenges are not specific to Lüneburg. SUMP implementation is shaped by local political culture, institutional structures, funding, evaluation practice and the dominance of established mobility patterns (Okraszewska et al. 2022; Peters and Reisch 2025). Even in a frontrunner city such as Copenhagen, implementation follows city-specific pathways rather than simply applying European guidance, and evaluation, policy learning and representation can remain selective (Peters and Reisch 2025). For Lüneburg, this underlines that a local implementation format must not only reproduce the SUMP logic but adapt it to municipal decision-making realities.

V. PARTICIPATION IN THE IMPLEMENTATION PHASE

Participation is a core principle of SUMP processes. The guidelines emphasise stakeholder and citizen involvement, and the Lüneburg NUMP included a broad participation process. The NUMP advisory board involved around 50 actors from administration, public bodies, transport providers, business, politics and civil society. Public formats included an opening event, online participation, planning walks and cycling tours, district workshops, thematic workshops and stakeholder discussions. The online dialogue alone collected around 1,600 contributions (Hanseatic City of Lüneburg 2025). These formats helped to generate local knowledge, identify conflicts and strengthen public visibility of the planning process.

However, participation changes its function once the plan enters implementation. During plan preparation, participation can still influence the formulation of goals, the development of measures and the overall strategic direction. During implementation, the core task is different. The question is no longer whether the strategic plan should contain a measure, but how a selected measure can be prioritised, specified, sequenced and made feasible. Participation therefore becomes more focused. It moves from broad co-creation towards structured reflection, conflict clarification and prioritisation.

This shift is consistent with participation guidance for SUMP processes. Lindenau and Böhler-Baedeker (2016) argue that planning authorities should reject a "decide–announce–defend" approach and open mobility planning for dialogue. At the same time, they emphasise that participation must be linked to clear stages of the planning process, suitable methods, transparent decision rules, conflict sensitivity, documentation and feedback. For the implementation phase, this means that participation should not be understood as a general promise of co-decision, but as a carefully designed interface between stakeholder input and formal municipal responsibility.

Recent empirical evidence from Germany adds a critical perspective. Mark, Holec and Escher (2024) show that consultative, discursive participation in mobility-related planning is increasingly used, especially in larger and participation-oriented municipalities, but remains the exception in many cities. They also point out two limitations that are highly relevant for implementation dialogues: participation formats often reach only certain groups of the population, and information on the results of participation is frequently difficult to find. This suggests that implementation-oriented participation needs strong documentation, transparency and a realistic understanding of who is represented in the dialogue.

This change creates both opportunities and risks. Stakeholders who were involved in the preparation phase often hold valuable process knowledge and can support practical specification. Their continued involvement can create ownership and continuity. At the same time, it can generate expectations that every measure discussed during the SUMP process will be implemented quickly. If resources are limited, this expectation needs to be managed transparently. Hartl, Harms and Egermann (2024) point out that collaborative formats can strengthen transformation-oriented planning, but they also raise legitimacy concerns. A small, fixed stakeholder group may support depth and continuity, but it cannot replace broader public communication or formal political decision-making.

For this reason, participation in the implementation phase should be designed as an interface rather than as a substitute for democratic decisions. The Lüneburg implementation dialogue follows this logic. It does not reopen the entire NUMP, but selects a limited number of measures for annual discussion. It combines stakeholder knowledge, external moderation, administrative feasibility and preparation for political follow-up. Its contribution lies not in producing final decisions, but in improving the quality, transparency and political connectability of subsequent decisions.

VI. The Implementation Dialogue as a Governance Instrument

The "Umsetzungsdialog" in Lüneburg was developed as a dialogue-oriented support format for the implementation phase of the NUMP. Its purpose is to reduce complexity, make prioritisation transparent, connect stakeholder knowledge with administrative reality and translate strategic goals into politically connectable implementation steps. In the accompanying presentation, the format was summarised as a bridge between strategy, politics, administration, stakeholders and budget planning.

The format is based on four design principles.

First, it is selective. Instead of discussing the entire NUMP each year, a small number of measure profiles is selected for focused discussion. In the Lüneburg format, four measure profiles per year are prepared. This reduction is crucial because implementation capacity is limited. It also reflects the recommendation of action-plan guidance that measures should be described in terms of objectives, responsibilities, timeframe, funding, indicators, activities, resources and stakeholder involvement (Mattsson and Wennberg 2018). Brand, Böhler and Rupprecht (2021) similarly stress that actions should be translated into priorities, timing, responsibilities, budgets, funding sources, risks, contingencies and dependencies.

Second, the format is recurring. A single workshop cannot stabilise a long-term implementation process. Annual repetition creates a rhythm that fits the dynamic character of SUMP implementation. It allows priorities to be reviewed, new developments to be considered and previous decisions to be followed up. This is consistent with the idea that SUMPs should be monitored, reviewed and improved through a structured learning process (Wefering et al. 2013; Backhaus et al. 2025).

Third, the format is connected to municipal decision-making. In Lüneburg, the implementation dialogue is scheduled before budget and committee processes. This timing should not be interpreted as evidence that the dialogue has already secured funding for specific measures. At the time of writing, the first application had not yet passed through a completed municipal budget cycle. The observable contribution is therefore more limited but still relevant: the format creates a structured interface through which prioritised measures, stakeholder feedback and administrative preparation can be made compatible with committee discussion and budget preparation. If dialogue results are produced too late, they cannot inform budget planning. If they are produced too early, they may lack sufficient administrative preparation. The format therefore needs to align with the municipal calendar: preparation of selected measures, implementation dialogue, further administrative specification, committee discussion, budget consideration and subsequent implementation.

Fourth, the format is moderated externally while remaining municipally owned. External facilitation can help structure discussions, make conflicts visible and prevent role conflicts. However, it cannot replace municipal responsibility. The municipality must decide which measures are relevant, organise the link to political bodies and carry the results into the administrative system. In this sense, external facilitation is best understood as strategic implementation support, not as outsourcing of responsibility.

In the first application, the Lüneburg dialogue used a World Café format. This enabled parallel discussion of several measure profiles, lowered entry barriers for different stakeholder groups and generated comparable feedback across topics. The first cycle addressed four NUMP measure profiles: F1 “Netzkonzeption Fuß”, M1 “Netzkonzeption Kfz”, S4 “50 Knotenpunkte und Querungen für Lüneburg” and S5 “Sichere Schulumfelder”. The paper focuses on S4 as an illustrative example because this measure shows particularly clearly how stakeholder feedback, administrative preparation, committee discussion and budget planning interact.

For S4, the dialogue addressed questions such as which junctions and crossings should be prioritised first and which target groups should receive particular attention. Conflicts emerged around limited space, overlaps with construction works and the difference between individual perspectives and the representation of stakeholder groups. At the same time, participants recognised that different actors often pursue similar goals and that prioritisation is more demanding than measure development itself.

The subsequent public committee submission for S4 illustrates both the potential and the limits of this linkage. The administrative proposal (Hanseatic City of Lüneburg 2026) translated the dialogue and the NUMP recommendations into four implementation-related elements: checking improvement measures for junctions and crossings in all civil engineering projects where possible; registering funds from 2027 for the planning and potential construction of at least three crossings or crossing aids per year; registering planning resources for at least two junctions per year; and registering annual funds for the gradual retrofitting of acoustic and tactile signalisation at existing traffic lights. The documents also made clear that the financial means were not yet secured under budget law and that the proposed funds would still have to be addressed within the 2027 municipal budget planning process. This means that the case provides process evidence for political-administrative connectability, but not yet evidence of fully secured funding or completed implementation.

This example shows the specific added value of the format. The implementation dialogue does not merely collect opinions. It structures an intermediate step between a measure profile and administrative/political decision-making. It helps to identify which aspects need clarification, which conflicts may become relevant, which criteria stakeholders consider important and how a measure can be communicated more transparently.

The S4 example also shows why implementation dialogue should not be confused with implementation proof. The format can improve the quality of prioritisation and prepare measures for administrative and political follow-up. However, whether such measures are funded, planned and built depends on subsequent committee decisions, budget adoption, staff capacity, technical planning and, where relevant, external funding opportunities.

The dialogue also has a communicative function. Ruhrort (2023) shows that mobility transitions depend not only on technical measures, but also on narratives that make change appear both desirable and achievable. This is especially relevant in implementation, where abstract goals such as climate protection, liveability or traffic safety need to be translated into concrete, sometimes controversial interventions. A dialogue format can help to build a shared implementation narrative: not every measure will be implemented immediately, but selected steps become understandable, prioritised and politically connectable.

VII. Monitoring, learning and evidence-based adaptation

Monitoring and evaluation are central elements of SUMP implementation. The Lüneburg NUMP includes an evaluation concept, and both the European guidelines and the German national criteria emphasise measurable goals, indicators and regular review (Hanseatic City of Lüneburg 2025; BMV 2026; Backhaus et al. 2025). Yet the literature shows that monitoring is often one of the most difficult parts of implementation.

Gillis, Semanjski and Lauwers (2016) propose a broad indicator perspective that covers environmental effects, economic performance, quality of life and mobility system performance. Their set of indicators includes not only classic environmental and transport indicators such as greenhouse gas emissions, congestion, noise and air pollution, but also mobility space usage, quality of public area, access to mobility services, traffic safety, affordability of public transport, accessibility for mobility-impaired groups, intermodal connectivity, resilience and opportunity for active mobility (Gillis, Semanjski and Lauwers 2016). This supports a broader understanding of SUMP implementation: success cannot be measured only by whether a measure has been built, but also by whether accessibility, safety, equity, quality of public space and sustainable mobility behaviour improve.

The 2025 European SUMP guidelines distinguish between output, result and impact indicators. Output indicators measure what has been delivered, such as kilometres of cycle lanes or number of charging points. Result indicators capture direct effects on behaviour or system performance, such as increased cycling, reduced waiting times or shifts in modal split. Impact indicators address broader long-term goals, such as reduced emissions, improved air quality, lower noise levels or fewer traffic accidents (Backhaus et al. 2025). This distinction is important for Lüneburg because an implementation dialogue can mainly support output and result orientation in the short term, while broader impacts require longer-term evaluation and robust data.

Wołek and Jagiełło (2024) highlight that monitoring and evaluation frameworks need to be flexible enough for cities of different sizes and capacities, but specific enough to reflect local mobility challenges. They also point to persistent risks: inconsistent methodologies, limited data availability and unclear responsibilities for data collection, integration and archiving. For implementation governance, this means that monitoring should not be treated as a separate technical appendix. It needs to be embedded in responsibilities, reporting routines and political communication.

In Lüneburg, the implementation dialogue can complement indicator-based monitoring in three ways. First, it can help interpret monitoring results and relate them to stakeholder experience. Second, it can identify reasons why measures are delayed, adapted or politically contested. Third, it can provide a recurring moment for adjusting priorities without reopening the entire strategic plan. However, the dialogue cannot replace systematic monitoring. Its value lies in connecting quantitative evidence, qualitative feedback and political prioritisation.

VIII. Discussion: tensions and implications for SUMP implementation

The literature and the Lüneburg case point to several tensions that should be addressed explicitly when designing implementation formats.

The first tension concerns standardisation and local adaptation. European and national criteria are valuable because they define quality requirements and create comparability (European Union 2024; BMV 2026; Backhaus et al. 2025). Yet implementation remains highly local. Peters and Reisch (2025) show that even advanced cities interpret and apply SUMP principles through their own institutional and political contexts. For Lüneburg, this means that the implementation dialogue should not be presented as a universal model in a narrow sense. It is better understood as a transferable governance logic: municipalities need recurring formats that connect strategy, prioritisation, participation, monitoring and decision-making.

A further limitation concerns full transferability. The Lüneburg implementation dialogue is embedded in the German SUMP context, municipal budget cycles, local committee structures and a planning culture in which municipalities have a specific role in translating strategic plans into implementation. The format should therefore not be understood as a universal model that can be transferred one-to-one to other national contexts. It is most suitable for strategic and programme-level implementation processes in which prioritisation, sequencing and communication remain open. It is less suitable for legally fixed planning procedures where formal consultation has already taken place and later implementation leaves little room for substantive adaptation.

The second tension concerns participation and legitimacy. Participation can create ownership, reduce opposition and bring local knowledge into planning (May 2015; Backhaus et al. 2025; Lindenau and Böhler-Baedeker 2016). However, focused implementation formats necessarily involve fewer participants than broad public participation.

Mark, Holec and Escher (2024) warn that consultative formats often reach only selected population groups and that results are not always transparently documented. This makes documentation and political embedding essential. A fixed stakeholder group can support continuity, but legitimacy depends on transparent criteria for participation, public communication of results and clear distinction between dialogue recommendations and formal political decisions.

The third tension concerns long-term transformation and short-term feasibility. Hartl, Harms and Egermann (2024) argue that SUMP could learn from transition management, especially through backcasting, experiments and collaborative learning. Ruhrort (2023) adds that mobility transition narratives must make change appear both desirable and achievable. At the same time, municipalities operate within annual budgets, staff shortages, committee schedules and legal procedures. The Lüneburg case suggests that transformation-oriented planning must therefore be translated into manageable annual steps. The implementation dialogue can help by linking long-term goals with selected short-term priorities.

The fourth tension concerns monitoring and learning. SUMP guidance, the national criteria and the Lüneburg NUMP all emphasise monitoring and evaluation (Hanseatic City of Lüneburg 2025; BMV 2026; Backhaus et al. 2025). Okraszewska et al. (2022) highlight that comparable indicators and data transparency are essential, but difficult because cities use different indicators and data availability varies. Wołek and Jagiełło (2024) similarly show that monitoring frameworks need to account for city size, data availability and organisational capacity. Implementation dialogues should therefore not replace indicator-based monitoring. Rather, they can complement it by interpreting monitoring results, identifying reasons for delays and adjusting priorities in light of new information.

The fifth tension concerns resources. The SUMP literature repeatedly identifies lack of funding and capacity as major barriers (May 2015; Mladenovič et al. 2022; Okraszewska et al. 2022). German evidence confirms that financial and personnel constraints, long planning processes and limited binding force are central implementation barriers for transport development plans and SUMPs (Arndt and Drews 2019). The Lüneburg case confirms that implementation depends on administrative capacity, political backing and budgetary decisions. A dialogue format cannot solve resource scarcity on its own. Its value lies in making resource constraints visible, aligning expectations and preparing decisions in a way that increases the chance that selected measures become budget-relevant.

The sixth tension concerns the direction of the mobility transition itself. Ruhrort (2023) identifies competing narratives around green growth versus transport sufficiency, commercial mobility services versus public goods, and urban versus suburban mobility cultures. These tensions are relevant for SUMP implementation because measures are not politically neutral. A measure that appears as a technical improvement for one actor may appear as a restriction or loss of convenience to another. Implementation formats therefore need to make underlying narratives visible: Is a measure framed as improving safety, reducing car dependency, supporting climate goals, increasing accessibility, strengthening public space or enabling fairer mobility? The way such narratives are connected can influence whether a measure appears legitimate and feasible.

IX. Findings from the Lüneburg case

The Lüneburg experience suggests six analytical findings for governance and participation in the implementation phase of strategic mobility planning. These findings are practice-based propositions derived from the case and interpreted through the SUMP implementation literature.

First, political adoption is the starting point rather than the finish line. A SUMP or NUMP provides orientation, but implementation begins only when measures are specified, prioritised and embedded in administrative routines. This requires a dedicated process after the final report.

Second, roles and responsibilities change after plan completion. During plan preparation, the planning office often structures content and communication. During implementation, the administration must carry responsibility for coordination, internal alignment and political preparation. This role shift should be anticipated early, and a clear handover from strategic planning to technical and administrative implementation is essential.

Third, participation remains relevant but changes its function. In the implementation phase, participation should focus on prioritisation, specification, conflict clarification and reflection. It should not reopen the entire strategic plan, but it should make the pathway from strategy to action more transparent.

Fourth, political and administrative connectability is a precondition for effectiveness. Dialogue results need to enter committee discussions, budget planning and administrative work programmes. Otherwise, participation may remain visible but ineffective.

Fifth, recurring dialogue formats can contribute to the stabilisation of mobility transition processes. A repeated annual format can help maintain momentum, support learning and adjust implementation priorities over time. This is particularly important because mobility transition is not achieved through isolated measures but through the consistent combination of many steps over several years.

Sixth, implementation dialogue needs to be connected with monitoring and communication. The dialogue can help translate indicator-based findings into practical and political learning, while communication can make prioritisation more understandable. This is important because successful implementation depends not only on what is decided, but also on whether the pathway appears transparent, legitimate, desirable and achievable.

X. Conclusion

The Lüneburg case shows that the effectiveness of strategic mobility planning depends not only on the quality of the plan but also on the governance arrangements that follow it. SUMPs provide a robust strategic framework, especially when they include clear goals, integrated measures, participation, prioritisation and monitoring. Yet they do not automatically solve the transition from planning to implementation.

The implementation dialogue developed in Lüneburg addresses this transition by creating a recurring, focused and politically connectable format. It reduces complexity by selecting a small number of measures per year, creates transparency around prioritisation, integrates stakeholder knowledge, supports administrative preparation and links the strategic plan with budget and committee cycles. Its value lies not in replacing formal decisions, but in improving the quality and legitimacy of the steps that precede them.

For other municipalities, the main lesson is not that the exact Lüneburg format should be copied. The transferable insight is that strategic mobility plans need a durable implementation infrastructure. This infrastructure should combine strong municipal ownership, clear responsibilities, external facilitation where useful, transparent prioritisation, public documentation, monitoring and an explicit link to political and financial decision-making. It should also be realistic about participation and resources: dialogue can support acceptance, learning and prioritisation, but it cannot replace political decisions, administrative capacity or reliable funding.

At the same time, implementation governance should not become purely managerial. Mobility transition remains a contested socio-technical process. Measures need to be explained as part of a credible and locally meaningful pathway that is both desirable and achievable. In this sense, the Lüneburg implementation dialogue is not only an organisational tool. It is a format for translating a strategic mobility vision into annual, understandable and politically relevant steps. Without such a bridge, even high-quality SUMPs risk losing momentum after adoption. With it, the mobility transition can become a continuous, adaptive and locally anchored process.

Future research should move from exploratory case analysis to systematic evaluation. Comparative studies could examine municipalities with and without recurring implementation dialogue formats and analyse whether such formats increase the likelihood that SUMP measures enter administrative work programmes, committee agendas and budget planning. Longitudinal studies could follow selected measures over several budget cycles and assess whether recurring dialogues improve continuity, learning, conflict clarification, transparency and implementation speed. Further research should also compare different municipal sizes and national planning contexts in order to test how institutional autonomy, legal participation requirements and administrative capacity influence the effectiveness of such formats.

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Evaluating Smart Mobility Ecosystems: Citizen Perspectives from Four Global Cities

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Abstract: Smart mobility has become a critical component of urban competitiveness and sustainable urban development. While smart city rankings frequently assess infrastructure and governance capacity, less attention has been paid to citizens' perceptions of mobility-related innovations. Drawing on survey data from Hamburg, Los Angeles, Shanghai, and Dubai (N = 955), this study examines how residents evaluate digital mobility services, including car sharing, parking guidance, bike sharing, digital ticketing, and real time traffic information. The findings reveal substantial cross regional differences. Shanghai records the strongest smart mobility index (1.78), followed by Dubai (1.91), Los Angeles (2.36), and Hamburg (2.83). Public transport t-ticketing receives the most positive evaluation in Hamburg and Los Angeles, while real-time road traffic information receives the most positive evaluation in Shanghai; both services are rated equally favourably in Dubai. The results suggest that smart mobility serves not only as a transport policy instrument but also as a visible indicator of urban innovation, quality of life, and competitiveness.

Keywords: smart mobility, digital mobility services, citizen perceptions, smart cities, urban mobility, cross-city comparison

1. Introduction

Cities increasingly face the challenge of adapting urban development to growing sustainability demands, technological change, and citizens' expectations regarding quality of life [1]. Smart city research highlights that digital infrastructures need to be complemented by human and social capabilities to improve urban performance [1], [9]. Within this broader context, mobility represents a particularly relevant smart city dimension because citizens experience transport infrastructure and digital mobility services directly through their everyday travel. Smart mobility connects intelligent transport systems, shared mobility, public transport e-ticketing, and real-time road traffic information to improve urban movement [2], [3]. Smart city literature examines these developments from both system-oriented and citizen-centred perspectives. Lyons [4] emphasizes the need to align technological innovation with broader sustainable mobility objectives, while Savastano et al. [5] demonstrate that the digitalization of shared and public mobility services can improve service quality, accessibility, and perceived value, particularly when applications are efficient and user-friendly. Angarita-Lozano et al. [6] further show that combining objective performance indicators with citizens' subjective perceptions can reveal implementation gaps that remain hidden in conventional assessments. Because mobility services are frequently used in everyday life, they constitute a highly tangible manifestation of smart city development and can influence citizens' perceptions of urban quality and performance [3],[7]. Citizens therefore evaluate urban innovation not only through policy initiatives or official rankings but also through their everyday mobility experiences. International comparative research also demonstrates that citizen roles and interactions in smart city initiatives vary across institutional and governance contexts and evolve over time [8]. Taken together, these studies indicate that the effectiveness of digital urban services cannot be assessed independently of citizens' everyday experiences and their specific urban contexts. Building on this perspective, the present study examines how citizens in four international cities evaluate digital mobility ecosystems.

2. Data and Method

The empirical analysis is based on a harmonized citizen survey from Hamburg, Los Angeles, Shanghai, and Dubai. The combined sample includes 955 respondents: Hamburg n = 352, Los Angeles n = 201, Shanghai n = 194, and Dubai n = 208.

Participants were recruited through the authors' academic networks and degree programmes in the four study locations. The study therefore employed a pragmatic convenience-sampling approach rather than probability-based sampling. Participation was voluntary and limited to residents of Hamburg, Los Angeles, Shanghai, and Dubai.

The structured questionnaire was administered online between October 2021 and June 2023. It was available in English and Chinese, with the Chinese version used to facilitate participation in Shanghai. At the beginning of the survey, respondents received standardized written information about the purpose of the study, the voluntary and anonymous nature of participation, and the procedure for completing the questionnaire. Participants completed the survey independently and were instructed to evaluate the statements using a five-point Likert scale, with lower values indicating more favourable assessments.

To reduce the likelihood of duplicate submissions, the survey platform permitted only one completed response per IP address. No names or contact details were collected. Survey responses were stored securely and were accessible only to the authors.

The underlying survey was originally designed to capture citizens' perceptions of multiple smart city dimensions. In addition to smart mobility, respondents evaluated smart governance, smart environment, smart living, smart economy, and digital public services. The survey therefore reflects a comprehensive understanding of smart city development.

Previous analyses using ordered logistic regression across all dimensions indicate that smart mobility, smart environment, and smart governance are among the most significant predictors of overall city ratings and citizens' perceptions of urban smartness [10]. Given the central role of mobility in shaping broader smart city perceptions, this paper focuses specifically on the mobility dimension. Overall perceived smart mobility status refers to respondents' general assessment of their city's mobility system in terms of accessibility, multimodality, sustainability, and the integration of digital technologies. In contrast, the Smart Mobility Index represents the arithmetic mean of five separately evaluated digital mobility services: car-sharing applications, parking guidance applications, bike-sharing services, public transport e-ticketing, and real-time road traffic information. Public transport e-ticketing refers to digital public transport services that provide timetable and journey-planning information and enable users to purchase or use public transport tickets through mobile applications or online platforms. It excludes parking tickets and parking payment services. Real-time road traffic Information refers to mobile information about road conditions, including congestion, incidents, disruptions, and route conditions; it does not include public transport timetable updates.

The mobility-item analysis is based on 818 respondents with valid responses to all five service items. Cases with missing values in the original dataset, were excluded from this analysis; most excluded cases were from Hamburg. Respondents evaluated each item on a five-point Likert scale, with lower values indicating stronger agreement and more positive assessments (1 = very advanced/strongly agree; 5 = very primitive/strongly disagree). Arithmetic means are used exclusively as descriptive summaries to facilitate comparisons across services and cities; no parametric inferential tests are applied to the individual items. Given the relatively large city-specific samples, the identical five-point response format across all items, and the exclusively descriptive purpose of the comparison, mean scores were considered appropriate for illustrating general patterns. Nevertheless, the results should be interpreted as descriptive differences in response patterns rather than as evidence of statistically significant group differences [11].

3. Results

The results indicate clear cross-city differences in the perceived quality of smart mobility systems, suggesting that citizens experience and evaluate digital mobility ecosystems in distinct ways.

Figure 1 compares two complementary measures of smart mobility across the four cities.

Across all four cities, the Smart Mobility Status receives slightly more favourable evaluations than the Smart Mobility Index, suggesting that citizens tend to assess the broader mobility system more positively than individual digital mobility services.

The figure reveals substantial cross-city differences. Shanghai receives the best evaluation on both measures, recording a Smart Mobility Index of 1.78 and a Smart Mobility Status score of 1.56. Dubai follows closely with an index value of 1.91 and a status score of 1.76. In contrast, Los Angeles achieves more moderate evaluations, with a Smart Mobility Index of 2.36 and a Smart Mobility Status score of 2.29, while Hamburg receives the most critical assessments, with corresponding values of 2.83 and 2.42. The distance between Hamburg and Shanghai exceeds one full scale point for the Smart Mobility Index, suggesting notable differences in the perceived maturity, visibility, and integration of digital mobility ecosystems. The parallel ordering of the four city samples across both measures suggests that more favourable evaluations of specific digital mobility services tend to coincide with more favourable assessments of overall perceived smart mobility status. As the present analysis is descriptive, this pattern should not be interpreted as evidence of an individual-level statistical relationship.

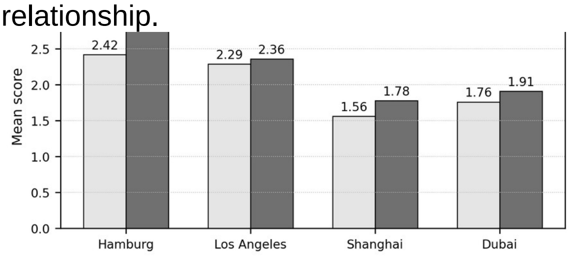

Fig. 1. Overall Perceived Smart Mobility Status and Smart Mobility Index by city. Lower values indicate more positive citizen evaluations. Source: Own figure.

A closer examination of the individual mobility indicators reveals differences in the composition of perceived mobility performance. While Shanghai and Dubai consistently achieve favorable evaluations across all indicators, Hamburg and Los Angeles exhibit a more heterogeneous pattern. Hamburg performs comparatively better in public transport e-ticketing than in parking guidance or car sharing applications, whereas Los Angeles receives relatively balanced evaluations across most mobility services. The consistently more favourable ratings of the Smart Mobility Status measure, which captures accessibility, multimodality, sustainability, and digital integration, compared with the five-item digital service index suggest that respondents distinguished their overall experience of the mobility system from their evaluations of specific digital services.

Figure 2 provides a detailed view of the five mobility service indicators. Public transport e-ticketing receives very positive evaluations across all four cities, indicating that citizens particularly value services that simplify public transport access and trip planning. Traffic information and parking guidance services exhibit the largest variation between cities. Shanghai records the strongest evaluation for real-time road traffic information (1.5), while Hamburg receives the weakest evaluation (2.9). Shared mobility services such as car sharing and bike sharing show greater heterogeneity, suggesting that local mobility cultures and policy frameworks influence user perceptions.

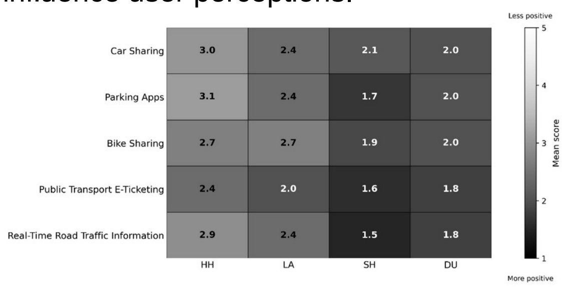

Fig. 2. Mean scores for the five digital mobility service indicators by city. Lower values and darker shading indicate more positive citizen evaluations. HH = Hamburg; LA = Los Angeles; SH = Shanghai; DU = Dubai. Source: Own figure.

4. Discussion

The findings support the view that smart mobility constitutes a strategic component of smart city development. Across all four cities, respondents evaluated overall perceived smart mobility status more positively than the individual mobility services. This difference suggests that their overall assessments may reflect not only experiences with specific digital technologies but also broader perceptions of accessibility, connectivity, and transport quality. However, the present descriptive analysis cannot determine which factors shaped these broader assessments.

Mobility also occupies a distinctive position among smart city dimensions because transport infrastructure and mobility services are encountered directly through citizens' everyday travel. Smart mobility therefore represents a particularly tangible and frequently experienced aspect of smart city development. This interpretation is consistent with Benevolo, Dameri, and D'Auria [2], who conceptualize smart mobility as a citizen-facing domain in which ICT-supported services can contribute to quality of life and public value.

The findings are consistent with Lyons [4], who argues that smart mobility should be assessed beyond technological innovation and aligned with broader sustainable mobility objectives. They also relate to the governance perspective of Docherty et al. [3], who emphasize that realizing the potential benefits of smart mobility requires effective coordination among technologies, services, public authorities, private providers, and other urban actors. The particularly positive evaluation of public transport e-ticketing further supports the findings of Savastano et al. [5], who highlight the importance of accessible and user-friendly digital mobility services.

The four city samples followed the same ordering for both overall perceived smart mobility status and the Smart Mobility Index. At the aggregate city level, more favourable evaluations of individual digital mobility services therefore coincided with more favourable assessments of overall smart mobility development. However, this parallel ordering is descriptive and should not be interpreted as evidence of an individual-level statistical relationship or a causal effect of particular mobility services on overall perceptions.

The findings should also be interpreted considering the pragmatic sampling approach. Recruitment through academic networks and degree programmes resulted in an overrepresentation of younger and highly educated respondents. The results therefore describe the surveyed samples and should not be interpreted as population-representative estimates for the four cities. In addition, the exclusion of incomplete mobility responses, most of which originated from Hamburg, may have affected the city-level comparisons.

The observed cross-city differences should be interpreted cautiously because they may reflect not only differences in local mobility ecosystems but also cultural and linguistic measurement effects. Respondents in Los Angeles and Shanghai, for example, may apply different culturally shaped reference standards when evaluating accessibility, service quality, and technological development. Cross-national research has identified differences in acquiescence, midpoint, and extreme response styles, while the language in which a questionnaire is administered can also influence the use of response categories [12],[13]. Differences in mean scores may therefore partly reflect how respondents interpret and use the Likert scale rather than differences in mobility services alone. Because the present study did not test measurement invariance or employ anchoring vignettes, it cannot fully distinguish substantive differences between the city samples from cultural and linguistic response effects.

Against this background, Hamburg's comparatively fewer positive results should not be interpreted as direct evidence of insufficient mobility innovation. Instead, they may indicate potential limitations in the visibility, usability, or integration of existing services among the respondents surveyed. The comparatively less favourable evaluations of car-sharing applications and real-time road traffic information point to possible opportunities to improve the everyday user experience and increase the perceived value of these mobility offerings. These interpretations nevertheless require confirmation through representative samples and complementary objective indicators of local mobility performance.

5. Conclusion

This study provides comparative evidence on how citizens perceive smart mobility as a visible dimension of smart city development. Across the four cities, citizens evaluate digital mobility services differently, with the most positive assessments observed in Shanghai and

Dubai. Public transport e-ticketing and real-time road information emerge as particularly important components of smart mobility because they reduce friction in everyday travel and improve the user experience. For policymakers, the findings suggest that mobility strategies should focus not only on technological deployment but also on usability, integration, and perceived citizen value. Reliable and accessible digital services that are seamlessly integrated into everyday life can improve citizens' mobility experiences.The individual indicators reveal a consistent pattern across the four cities. Shanghai and Dubai achieve favourable evaluations across all mobility services, while Hamburg and Los Angeles receive more moderate ratings. Public transport e-ticketing receives the most favourable evaluation in Hamburg and Los Angeles, while real-time road traffic Information is rated most favourably in Shanghai and shares the best rating with public transport e-ticketing in Dubai. This pattern suggests that citizens particularly value digital services that facilitate public transport access and provide timely information for everyday travel. In contrast, car sharing applications, parking guidance systems, and traffic information display the largest cross-city differences. Hamburg receives substantially fewer promising evaluations for car sharing applications (3) and real-time road traffic information services (2.9) than Shanghai (2.1 and 1.5, respectively). For policymakers, the results imply that mobility strategies should focus not only on technological deployment but also on usability, integration, and perceived citizen value. In particular, the comparatively weaker evaluations of car sharing applications and traffic information services in Hamburg indicate that improving the visibility and user experience of digital mobility services may contribute to stronger citizen perceptions of mobility performance.

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