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Advancing urban planning and autonomous vehicles integration through scaled models

Avançando no planejamento urbano e na integração de veículos autônomos através de modelos em escala

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ABSTRACT

In the evolving landscape of urban planning and transportation, the integration of autonomous vehicles (AVs) into the urban environment presents a transformative opportunity. This paper explores the potential of scaled models in advancing urban planning and AV integration, highlighting the intricate interdependence of transportation systems, urban planning, and socio-economic factors. The emergence of AVs promises unparalleled efficiency, safety, and environmental sustainability in urban mobility. However, their successful integration necessitates meticulous planning and a comprehensive understanding of the urban landscape. Scaled models offer a dynamic platform for urban planners and policymakers to simulate, assess, and strategize the incorporation of AVs into cities, enabling the visualization of potential changes and the formulation of sustainable and equitable development strategies. Despite the promising prospects of scaled models, challenges such as scaling accuracy and the simplification of complex urban dynamics persists. Addressing these challenges is crucial to bridging the gap between model experiments and real-world urban complexities. By harnessing the power of scaled models, this paper aims to deepen our understanding of the interaction between AVs and urban environments and to strategize their integration, marking a significant step towards smarter, safer, and more sustainable cities.

Keywords: Autonomous vehicles; Urban planning; Scaled models

RESUMO

No cenário em constante evolução do planejamento urbano e dos transportes, a integração de veículos autônomos (AVs) no ambiente urbano apresenta uma oportunidade transformadora. Este artigo explora o potencial de modelos em escala no avanço do planejamento urbano e na integração dos AVs, destacando a intrincada interdependência dos sistemas de transporte, planejamento urbano e fatores socioeconômicos. O surgimento dos AVs promete eficiência, segurança e sustentabilidade ambiental sem paralelos na mobilidade urbana. No entanto, a integração bem-sucedida deles necessita de um planejamento meticuloso e de um entendimento abrangente da paisagem urbana. Modelos em escala oferecem uma plataforma dinâmica para planejadores urbanos e formuladores de políticas simularem, avaliarem e criarem estratégias para a incorporação dos AVs nas cidades, possibilitando a visualização de mudanças potenciais e a formulação de estratégias de desenvolvimento sustentáveis e equitativas. Apesar das perspectivas promissoras dos modelos em escala, desafios como a precisão e a simplificação de dinâmicas urbanas complexas persistem. Abordar esses desafios é crucial para superar a lacuna entre experimentos com modelos em escala e as complexidades urbanas do mundo real. Ao aproveitar o poder dos modelos em escala, este artigo visa aprofundar nosso entendimento da interação entre AVs e ambientes urbanos e as estratégias de sua integração, marcando um passo significativo em direção a cidades mais inteligentes, seguras e sustentáveis

Palavras-chave: Veículos autônomos; Planejamento urbano; Modelos em escala

1 INTRODUCTION

Transportation systems play a crucial role in modern society as they serve as intricate networks that facilitate the movement of people and goods across diverse geographical regions. These systems are designed with the intention of increasing efficiency, ultimately making it easier for individuals and businesses to access different areas and conduct commerce. Furthermore, transportation systems are heavily influenced by land use patterns and local socio-economic factors, presenting a complex interdependence between these systems and the communities they serve. As the population and economy continue to grow, there is a growing demand for increased accessibility and mobility in various modes of transportation (Eckelman, 2013; Sweeting & Winfield, 2012).

In this dynamic context, urban planning emerges as a pivotal discipline, orchestrating the harmonious integration of transportation systems within the urban fabric to address the evolving demands of society. Urban planners employ a holistic approach, considering not just the physical infrastructure, but also the socio-economic and environmental implications of transportation networks. This comprehensive perspective ensures that transportation systems not only facilitate mobility but also contribute to the overall well-being and sustainability of urban areas (Banister, 2008).

The advent of autonomous vehicles (AVs) represents a paradigm shift, promising to redefine urban mobility by introducing unprecedented levels of efficiency, safety, and environmental sustainability (Fagnant & Kockelman, 2015; Xu et al., 2018). However, the successful incorporation of AVs into existing urban landscapes necessitates meticulous planning and foresight, ensuring that these technological innovations align seamlessly with broader urban development objectives and the sophisticated network of urban life (Litman, 2023). The concept of autonomous vehicles encompasses their ability to navigate partially or fully independently, requiring minimal human intervention (Hussain & Zeadally, 2019).

Te integration of autonomous vehicles (AVs) into urban landscapes offers a unique confluence of technology and spatial organization. The advancement of urban planning, in harmony with the deployment of AVs, necessitates a comprehensive understanding of the potential impacts and benefits. In this context, scaled models, which can provide a detailed representation of urban environments and transportation systems, has the potential to serve as crucial tools in this initiative. They enable urban planners and policymakers to anticipate challenges, identify opportunities, and devise strategies that optimize the symbiosis between AVs and urban infrastructure (Kim et al., 2016).

As scaled models can offer a detailed and dynamic platform to simulate changes in the urban environment, they allow planners to assess the impacts of various scenarios and make informed decisions. It can enable planners to visualize these potential changes, providing a basis for strategies that leverage AV technology to promote sustainable and equitable urban development. Therefore, the aim of this paper is to discuss the pivotal role of innovative research methodologies, specifically the use of scaled models, in deepening our comprehension and strategizing the urban landscape for the integration of autonomous vehicles. The objective is to elucidate how these detailed and adaptable scaled models can serve as indispensable tools for urban planners and policymakers

The remainder of this paper is structured as follows: In Section II, autonomous vehicles are defined and discussed; Section III delves into scaled models and urban planning, discussing the technological aspects of scaled urban models and the future of scaled AVs for urban planning; and Section IV presents the conclusions.

2 AUTONOMOUS VEHICLES

The complexity of modern urban life necessitates transport systems that can seamlessly connect different areas, catering to the dynamic needs of urban dwellers and businesses alike. Consequently, transportation planning and infrastructure development become critical in addressing the intricate mosaic of urban accessibility and mobility, ensuring that the movement of people and goods is not just a matter of transit but a pivotal element in enhancing the quality of urban life and economic productivity (Raza et al., 2022).

The rapid societal changes and growing need for efficient, sustainable transportation necessitate transformative upgrades in existing transport systems, emphasizing the adoption of innovative technologies. This pressing need has led to the development and testing of autonomous vehicles (AVs). AVs, such as self- driving cars, are equipped with advanced technology and artificial intelligence, and have the potential to revolutionize transportation by providing a safe, convenient, and environmental-friendly mode of commuting (Caleffi et al., 2023).

Moreover, the implementation of AVs could potentially reduce the number of accidents caused by human error (Xu et al., 2018), increase mobility for people with disabilities and the elderly (Zhang et al., 2019), reduce emissions, alleviate traffic congestion, and improve overall traffic flow (Fagnant & Kockelman, 2015). As we continue to face new challenges and changes in society, the advancement of AVs presents a promising solution in meeting the evolving needs of transportation systems.

The proficiency of autonomous vehicles in comprehending the present traffic conditions and their immediate surroundings, coupled with their capacity to predict and adapt to future scenarios, is crucial for their efficient functionality and safety assurance. Nonetheless, these requisites present intricate challenges, primarily due to the limitations in observing the external environment, and the substantial computational resources necessitated for the execution of predictive algorithms (Mozaffari et al., 2022). Consequently, autonomous vehicles necessitate a range of elaborate features to facilitate their operation in a manner that is both safe and efficient.

Autonomous vehicles (AVs) are currently in the development and testing phases in various countries around the world. However, field-testing of AVs is a demanding and resource-intensive process. While simulations have been utilized as a more cost-effective alternative, they often fall short in precisely replicating real-world scenarios. To address this issue, new methods have surfaced for testing autonomous software-hardware on scaled vehicles (Betz et al., 2022; Caleffi et al., 2023). These scaled vehicles provide a middle ground between simulations and full- sized AVs, allowing for a more accurate representation of real-world driving conditions. This approach not only reduces the time and costs associated with traditional testing methods, but also helps to ensure the safety and reliability of AV technology.

In Brazil, the AV technology is still incipient. Unlike North America, Europe, and Asia, third world countries, such as Brazil, lack legislative frameworks that authorize the field testing of autonomous vehicles. To effectively test and advance AV technologies, a practical approach would be to utilize scaled vehicles in controlled studies. This method allows for the creation of realistic mobility scenarios, while also ensuring the proper safety regulations. By conducting these studies in a controlled environment, researchers can accurately assess the capabilities of AV systems and identify potential challenges and areas for improvement. Furthermore, this method proves to be cost-effective and less risky compared to testing with full-size vehicles on public roads (Betz et al., 2022; Caleffi et al., 2023).

Betz et al. (2022) and Caleffi et al. (2023) provided literature reviews on scaled autonomous vehicles. While Betz et al. (2022) focused solely on autonomous vehicle racing, Caleffi et al. (2023) investigated the current state of the literature surrounding small-scale self-driving cars. They both stated that publications on this topic are relatively new (2012 onwards), with a notable rise in the number of publications only in recent years. The reviews found that most studies involve the development of a path planning system for autonomous navigation. No direct goal of using scaled models for urban planning were found. Most papers deployed a 1:10 scale car, while other notable scales being 1:5 and 1:43.

On trend that is clearly visible from the literature reviews is the design and production of AVs utilizing low-cost and easily obtainable components. This approach has proven to be instrumental in the efficient and effortless construction and operation of AVs. This strategy ultimately facilitates the mass adoption of AVs, as it eliminates the barrier of high costs and technical complexity often associated with the development of such vehicles. Moreover, utilizing inexpensive and readily available components allows for greater flexibility in adapting to technological advancements and environmental factors, leading to the continuous improvement and evolution of AVs. Most studies implemented the proposed F1tenth (O'Kelly et al., 2019, 2020) chassis configuration. This 1:10 scale is broadly used in competitions and has gained a thriving online community (Caleffi et al., 2023).

3 SCALED MODELS AND URBAN PLANNING

Model scaling in urban planning is a meticulous process that aims to replicate the complexities of urban environments in a simplified, yet precise, manner. According to (Bettencourt, 2020), cities are perceived as spatial equilibria, where their aggregate properties emerge from the statistical dynamics at play within the urban environment, including population size and agent interactions. This understanding underscores the relevance of model scaling, as it enables urban planners to analyze and predict the heterogeneous dynamics of urban evolution, infrastructure requirements, and socio-economic transformations. Scaling models necessitates the transformation of intricate elements into a simplified, coherent structure, allowing for the simulation of urban scenarios and the assessment of potential outcomes of urban policies and interventions. Moreover, the implementation of scaled models in urban planning is not just a technical endeavor but also a creative one. It requires an in-depth understanding of urban dynamics and an ability to translate these complex realities into a scaled representation. For instance, the work of (Kee et al., 2022) on fractional modeling of urban growth introduces the concept of memory effects, enhancing the traditional urban growth models by considering the historical trajectory and temporal dynamics of cities. This exemplifies the level of sophistication and thoughtfulness required in model design, extending beyond mere statistical replication to include temporal and spatial nuances that define the urban experience.

In summary, the principles of model scaling in urban planning revolve around the accurate and detailed representation of urban complexities, enabling the simulation and analysis of urban dynamics in a manageable and insightful manner. The meticulous design of scaled models underscores the blend of technical precision and creative interpretation that is essential in capturing the essence of urban environments. As urban planners continue to refine and innovate in model scaling techniques, the potential to enhance urban planning processes and outcomes through these scaled representations becomes increasingly evident.

3.1 Technological aspects of scaled urban models

The development of scaled urban models constitutes a rigorous and complex procedure, where the choice of materials and components plays a crucial role in ensuring the models accurately represent the complexities of urban environments. The selection of materials is guided by the need for durability, detail, and the capacity to reflect real-world textures and colors. High-quality materials such as polymers for

3D printing, fine woods, Styrofoam, or detailed metal components are often used to replicate the intricate architectural features of urban landscapes. Additionally, electronic components are embedded within these models to simulate dynamic elements such as lighting, traffic signals, or moving vehicles, providing a more realistic and interactive representation of urban dynamics (Narazani et al., 2019).

Incorporating technology into scaled urban models transforms them from static representations to dynamic platforms capable of simulating urban behaviors. Advanced scaled models integrate sensors and programmable elements to simulate traffic patterns effectively. These models can replicate the flow of vehicles and pedestrians, allowing urban planners to observe and analyze traffic behavior under various conditions. By adjusting the model's parameters, planners can predict traffic congestion points, optimize traffic light sequences, or evaluate the impact of new infrastructure on traffic flow. This interactive approach provides a tangible and intuitive way to assess and improve urban traffic management strategies (Garcia-Dorado et al., 2014).

Furthermore, scaled urban models serve as valuable tools for simulating pedestrian interactions in urban settings. By designing models with movable components and interactive features, urban planners can study pedestrian flow, understand how urban design influences pedestrian behavior, and identify areas that may lead to crowding or inefficiencies (Bellomo et al., 2012). These models allow for the testing of various scenarios, such as the allocation of public facilities, walkway widths, or the arrangement of public spaces, to create safer and more efficient pedestrian pathways.

The integration of scaled urban models into urban planning goes beyond traffic and pedestrian simulations. Additionally, these models can serve educational and communicative purposes, allowing stakeholders and the public to visualize and understand proposed changes or developments within urban spaces. As urban planning continues to evolve, these sophisticated scaled models can undoubtedly play a pivotal role in shaping the future of urban landscapes.

3.2 The future of scaled model AVs for urban planning

As evidenced by existing literature, no specific objective or purpose has been identified for incorporating scaled models of autonomous vehicles (AVs) in urban planning (Caleffi et al., 2023). Few studies have attempted to assess scaled AVs within contexts that, albeit to a moderate extent, resembles urban settings.

Gao et al. (2022) emphasized the importance of scaled-car platforms for evaluating autonomous driving algorithms, particularly under extreme driving conditions. Their study successfully demonstrated a scaled-car platform's capability to perform complex maneuvers, reflecting the potential of such models in understanding AVs' interaction with their environment and enhancing their adaptability to challenging conditions. Two studies presented an intersection management controller (Ahn et al., 2015; Andert et al., 2017), utilizing cameras to monitor intersections. This system aggregates data such as vehicle positions, speeds, and trajectories. Upon identifying potential collisions, the controller intervenes, adjusting vehicle movements to maintain safety.

Obstacle detection/avoidance and lane tracking were also discussed in some studies (Bae et al., 2013; Hamzah et al., 2022; Hossain et al., 2020; Kannapiran & Berman, 2020; Muraleedharan et al., 2022; Verma et al., 2021). The strategies prioritized identifying viable trajectories for AVs and selecting the optimal path around few static obstacles. Some studies developed software that focuses on a specific task: autonomous car-following (Jahoda et al., 2020); overtaking (Anindyaguna et al., 2016); and platooning (Filho et al., 2020).

Multi-scaled-vehicle interaction also requires further research, as only seven papersaddressed this topic (Williams et al., 2018), (Andert et al., 2017), (Ahn et al., 2015), (Anindyaguna et al., 2016), (Filho et al., 2020), (Hyldmar et al., 2019), (Bae et al., 2013). Most studies deal with a single-vehicle setup, which is not ideal for a realistic urban modeling scenario.

The prevailing literature on scaled AVs has so far neglected to consider the deployment of these vehicles on complex urban environments, where they must navigate a multitude of dynamic elements, including pedestrians, cyclists, and traditional vehicles. In their literature review, Caleffi et al. (2023) stated that studies often present only preliminary results that are tested in a simple environment. Furthermore, little attention has been given to the potential impact of this technology on urban planning. As such, there remains a significant gap in our understanding of how AVs will interact with and reshape urban landscapes. It is essential for future models to explore these crucial aspects, as they have significant implications for the implementation and success of this emerging technology in the modern city. By addressing these overlooked areas, we can better prepare for the future of transportation and ensure a smooth integration of AVs into our society.

The utility of scaled AVs for testing is substantial, offering rapid and secure evaluation across diverse scenarios and settings. This approach ensures model robustness and adaptability to various environments prior to real-world deployment. Additionally, it facilitates the identification and resolution of unforeseen challenges, significantly advancing autonomous vehicle development by confirming safety and efficacy across all operational contexts (Caleffi et al., 2023).

Future research endeavors should encompass more comprehensive experiments within actual urban environments. Addressing intricate urban scenarios, including dynamic elements like pedestrians and cyclists, is crucial for advancing autonomous technology. Small-scale vehicles offer significant benefits in this context, enabling numerous trials in scaled urban environments while mitigating concerns associated with full-scale testing, such as safety, technological maturity, and costs.

3.3 Challenges and limitations

While scaled autonomous vehicle models offer invaluable insights into urban planning and traffic management, they are not devoid of challenges and limitations. One major constraint is achieving scaling accuracy. Translating findings from scaled models to real-world scenarios demands precise calibration, as minor discrepancies can lead to significant divergences in actual urban settings. Moreover, the environment within which these models are tested is often simplified, not fully encapsulating the intricacies of real urban landscapes (Li et al., 2018). This simplification raises concerns about the direct extrapolation of results, as factors in actual urban environments may significantly alter the performance and behavior of AVs.

The theoretical framework linking AV technology to urban planning and traffic management is grounded in the notion of enhancing efficiency, safety, and sustainability. AVs are expected to revolutionize urban mobility by reducing traffic congestion, minimizing the likelihood of accidents, and optimizing the flow of traffic through advanced algorithms and communication technologies. However, ensuring the safety and reliability of these systems necessitates addressing complex, multidimensional challenges, encompassing hardware fault tolerance, resilient machine learning algorithms, and effective interaction with human-driven vehicles (Koopman & Wagner, 2017).

The contribution of scaled AV models to understanding urban dynamics is undeniable. These models facilitate the evaluation of AVs' interaction with various urban elements, including pedestrians, cyclists, and infrastructure, in a controlled and safe environment. Despite this, the transition from scaled models to full-scale urban implementation is complex and necessitates meticulous consideration of the myriad factors influencing AV performance and their integration into the urban fabric.

Along with the scaled AV model, the design of urban scaled models, particularly in the realm of urban planning and architecture, inherently presents a set of challenges and limitations that must be acknowledged and addressed. Scaling accuracy remains a critical concern, as the fidelity of these models in replicating real-world structures and urban layouts is paramount for their effective application in planning and decision-making processes. The constraints associated with the model environment, such as the simplification of complex urban elements and dynamics, further complicate the extrapolation of insights gained from scaled models to actual urban scenarios.

Additionally, the selection and application of materials in constructing these models introduce another layer of complexity. Materials must physically represent the architectural features accurately. Moreover, the challenges extend to manufacturing and assembling scaled models, demanding precise craftsmanship and attention to detail to maintain the model's integrity and reliability.

Therefore, while scaled AV models are instrumental in propelling the development of autonomous technology, the journey from model to real-world is fraught with challenges. These challenges demand an integrated and comprehensive approach that effectively bridges the gap between scaled experiments and the complexities of real-world urban environments. By acknowledging and addressing these challenges, the potential of AVs to transform urban mobility can be fully realized, paving the way for smarter, safer, and more efficient cities.

4 CONCLUSIONS

Scaled models can serve as a pivotal tool in the realm of AV research and development. They provide a safe, cost-effective, and efficient means to simulate real-world conditions, allowing for the comprehensive testing and validation of autonomous driving algorithms and vehicle dynamics. These models bridge the gap between theoretical research and practical application, thereby accelerating the advancement and ensuring the readiness of AVs for urban deployment. As the field of autonomous driving continues to evolve, the role of scaled models in shaping the future of urban mobility becomes increasingly prominent.

By facilitating the simulation of diverse scenarios and visualizing potential transformations, scaled models empower stakeholders to make well-informed decisions. This, in turn, ensures that the integration of autonomous vehicles not only harmonizes with, but also enriches the broader objectives of urban development, crafting a future where efficiency, sustainability, and the intricate dynamics of urban life converge seamlessly.

Despite the increasing interest and investment in AVs, there appears to be a lack of clear direction in how these technologies should be integrated into city planning. This raises concerns about the effectiveness and efficiency of incorporating such models in the first place. Without a clear understanding of their purpose, it is difficult to assess their potential impact on urban infrastructure and the community. As such, it is important for further research to be conducted to establish a solid framework for incorporating scaled models of AVs in urban planning. This will not only aid in the successful integration of these technologies, but also ensure that urban planning and development remains equitable and sustainable for all members of the community.

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