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Towards an integrated framework connecting urban morphology and wind engineering

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SUMMARY

Modern cities across the world support a complex network of social and economic activities and thus carry a relatively unequal burden when it comes to the development of public infrastructure, when compared to their rural counterparts. This unequal and rapid growth of urban centres around the globe, combined with large-scale industrialisation, has led to the development of unique street networks that connect different parts of the city to maximise transit volume and minimise transit time. In this work, we explore a unified understanding of wind flow around urban built environments conditioned on the underlying urban morphology by simulating wind flow for 16 data-rich cities primarily situated in the global North. Using street-network complexity as a central defining feature of the urban morphology we quantify the effect of urban morphology on the wind flow predictions using a Reynolds Averaged Navier-Stokes framework.

Keywords: *Urban Morphology, Street Network Complexity, Reynolds Averaged Navier-Stokes, Computational Fluid Dynamics*

1. INTRODUCTION

Modern cities across the world support a complex network of social and economic activities and thus carry a relatively unequal burden when it comes to the development of public infrastructure, when compared to their rural counterparts (Pandey et al., 2022). This unequal and rapid growth of urban centres around the globe, combined with large-scale industrialisation, has led to the development of unique street networks that connect different parts of the city to maximise transit volume and minimise transit time (Barthelemy & Boeing, 2025). Consequently, major cities can now be uniquely characterised by the complexity of the street network (as illustrated in Figure 1) that has emerged as a consequence of the socio-economic requirements of the given city. This socio-economic imprint on urban morphology not only shapes the movement of people and goods but also governs the way momentum, heat, and pollutants (to name a few) interact with the built environment. Specifically, the configuration of streets, building orientations, and open spaces influences ventilation corridors, turbulence generation, and recirculation zones within a city (Britter & Hanna, 2003; Fernando, 2010). These micro- and meso-scale flow phenomena are of particular importance for urban resilience, air quality management, and thermal comfort, all of which are deeply tied to public health and social equity (Lu, 2020).

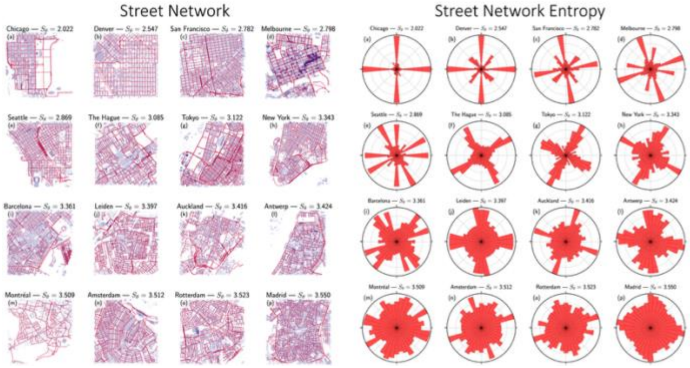

Figure 1: Comparison of 16 urban environments organised in ascending order of street-network entropy, with the street-network shown in red and building footprints shown in purple on the panels on the left. The street-network complexity and street networks were generated using OSMnx (Boeing, 2018, 2019a, 2025). The panels on the right compare the dominant street orientation for the cities shown on the left.

2. METHODOLOGY

Developing reduced-order models to capture the effects of heterogeneous urban morphology requires understanding the influence of numerous independent parameters that govern the flow within these complex canopies (Boeing, 2019b; Fleischmann et al., 2021; Labetski et al., 2023). To that end, a plethora of previous studies have investigated the impact of heterogeneous roughness canopies (not limited to urban morphologies) on the flow statistics as a function of frontal and platform packing density, sky view factors, roughness height distribution, and roughness shape characteristics, etc., (Barlow & Coceal, 2008; Belcher et al., 2012; Chung et al., 2021; Finnigan, 2000; Flack & Schultz, 2010; Jiménez, 2004; Nazarian et al., 2025; Patil & Fringer, 2023). Unlike heterogeneous roughness canopies observed in mechanical and environmental hydraulic systems, urban roughness canopies exhibit subtle differences in geometric characteristics that necessitate a relatively urbanism-based characterisation, such as the one proposed by (Barthelemy & Boeing, 2025), to accurately capture the essential features of these anthropogenic systems. As a result, in this work, we use the street-network complexity as a single quantifiable metric that differentiates the various urban areas around the world. To simulate the wind flow around complex urban environments, we use the neutral atmospheric boundary layer (NABL) flow conditions, which can be accurately modelled using the steady state, incompressible continuity equation ($\partial_i u_i = 0$) , and the incompressible Navier-Stokes momentum equations given by,

$$\partial_j u_j u_i = -\frac{1}{\rho}\partial_i p + \nu \partial_j \partial_j u_i + \ \partial_j u_i' u_j', \tag{1}$$

where u_i is the time-averaged velocity vector, p is the pressure, ν is the kinematic viscosity of the fluid, ρ is the density of the fluid, $\partial_j\langle\cdot\rangle$ is the spatial differential operator in space, and $u_i' u_j'$ is the time-averaged Reynolds stress tensor. The governing equations are solved efficiently using the MPI-parallelised open-source computational framework OpenFOAM-v7.

3. RESULTS

We first begin by understanding the velocity magnitude at various heights above the ground for the city of The Hague, as shown in Figure 2. As seen here, substantial changes are in the wind response as a function of the height above the ground. By comparing these changes across various city morphologies quantified using street-network complexity, we can classify wind predictions within a diverse set of urban environments as a function of urban morphology.

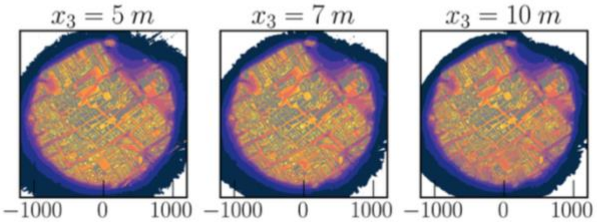

Figure 2: Time- and wind-direction averaged velocity for the city of The Hague at various heights above the ground.

4. CONCLUSIONS

Through a unified complexity framework of the street network, we have developed a single-parameter framework that can be used to characterise various urban built environments. Using this unique characteristic of urban cities, we applied wind simulations at a relatively fine wind incidence to connect the city characteristics and wind speed observed within the urban canopy. These observations can be helpful in further improving the urban canopy parameterisation for large-scale computational models.

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