

Reframing Low-Emission Zones as Adaptive Decision Infrastructures: A Digital-Twin Framework and Lifecycle Methodology for Sustainable Urban Air Quality

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Abstract-

Road transport is a leading source of urban nitrogen oxides (NO_x) and fine particulate matter (PM_{2.5})—a public-health and urban-sustainability challenge—and Low-Emission Zones (LEZs) are Europe’s principal response. Yet most are governed statically, unable to track conditions changing by the hour and the street. A digital twin, treated as decision infrastructure rather than a 3D model, recasts the LEZ as an adaptive decision infrastructure: a closed loop of sensing, modelling and rule-based adjustment. We develop a scalable, five-phase lifecycle methodology with auditability and GDPR-by-design built in, and derive three falsifiable hypotheses—efficiency, data integration, responsiveness—defining a research agenda. We test only the first. A diagnostic reading of London’s ULEZ shows its unimplemented phases are precisely those that close the loop. A proof-of-concept on real hourly NO₂ from five London sites (2023–2024) tests efficiency: at equal abatement effort, adaptive targeting avoids significantly more elevated-pollution hours than a uniformly stricter policy (about 37% versus 27%; 95% CI excludes parity), the advantage rising with forecast quality. This demonstrates the mechanism in reduced form, not a generalizable figure for a deployed system. By making regulation more responsive and accountable, it advances the Sustainable Development Goals on health, sustainable cities and climate (SDGs 3, 11, 13).

Index Terms- low-emission zones; digital twins; urban air quality; adaptive policy; decision infrastructure; smart cities; sustainable urban mobility; environmental governance; Sustainable Development Goals; data integration

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