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Performance Assessment of Energy-Efficient Ventilation in Highway Tunnels

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Abstract: This study investigates the integration of energy-efficient ventilation strategies for maintaining optimal air quality in road tunnels. With increasing emphasis on sustainability and the urgent need to reduce energy consumption in infrastructure systems, the research aims to evaluate and optimize tunnel ventilation by balancing pollutant control with minimal energy use. The study is designed to simulate airflow and pollutant dispersion under different traffic and environmental conditions, assess the energy consumption of conventional and demand-controlled ventilation (DCV) systems, and identify optimal control strategies that satisfy air quality standards while minimizing power usage. The methodology involves developing a three-dimensional tunnel model, incorporating real-world geometry, traffic-induced emission profiles (focusing on CO and NOx), and ventilation system configurations. Different scenarios are analyzed, including fixed-speed and variable-speed fan operations, with DCV strategies implemented using pollutant thresholds to regulate fan performance. Energy demands are computed based on airflow dynamics and fan duty cycles, while the model outputs are validated against existing regulatory standards such as those set by PIARC and the World Health Organization. Results indicate that DCV strategies can reduce ventilation energy consumption by up to 35% without compromising on air quality, offering a more sustainable alternative to traditional ventilation practices. The study concludes that CFD-based evaluation offers a practical framework for the development of intelligent ventilation systems, enhancing operational efficiency and environmental performance. However, the study is limited by the assumption of uniform traffic flow and static emission profiles, and does not incorporate real-time sensor feedback, which could be explored in future work through integration with IoT-based monitoring systems. This research provides significant practical benefits by offering validated insights that support the design, retrofitting, and operation of energy-efficient tunnel ventilation systems, particularly for application in urban and congested settings where air quality and energy management are critical concerns.
Keywords: Tunnel Ventilation, Air Quality, Energy Efficiency, Demand-Controlled Ventilation, Pollutant Dispersion.

I. INTRODUCTION

Tunnel ventilation is a critical component of modern transportation infrastructure, ensuring adequate air quality and operational safety, especially in densely trafficked urban tunnels. Emissions from internal combustion engines, including carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM), accumulate rapidly in confined underground spaces and pose substantial health and safety risks (PIARC, 2011). Traditionally, ventilation strategies have relied on fixed-speed axial fans or predefined operational schedules designed to meet worst-case traffic scenarios. While effective under peak conditions, these methods are energy-intensive and often inefficient during low-traffic periods (Cheng et al., 2012; Tang et al., 2013).Over the past decade, energy consumption in tunnel ventilation has become a growing concern. Studies have shown that ventilation systems can account for up to 50% of a tunnel's total energy demand, making them prime candidates for efficiency upgrades (Yao et al., 2015; Shahzad et al., 2016). To address these inefficiencies, researchers began investigating demand-controlled ventilation (DCV) systems, which adjust fan operations based on real-time measurements of pollutant concentrations and traffic density (Santos et al., 2017; Bae et al., 2018). Early implementations of DCV demonstrated the potential to significantly reduce energy use without compromising air quality standards. With the advancement of computational resources, Computational Fluid Dynamics (CFD) emerged as a powerful tool for simulating airflow and pollutant dispersion within tunnel environments (Kwon et al., 2019; Fuchs et al., 2019). CFD-based approaches enable the modelling of complex boundary conditions, realistic tunnel geometries, and dynamic emission sources, facilitating more accurate prediction of ventilation performance (Zhou et al., 2020; Tian et al., 2020). Simulations integrating variable-speed fan strategies and pollutant threshold control have shown energy savings of up to 30–40% (Jia et al., 2020).

In addition to airflow modelling, recent developments have introduced smart control systems using artificial intelligence (AI) and Internet of Things (IoT) frameworks, allowing ventilation systems to respond dynamically to traffic patterns, weather conditions, and real-time emission data (Chien et al., 2021; Yamamoto et al., 2022). These systems are increasingly aligned with international air quality standards, including those defined by the World Health Organization (WHO, 2021) and PIARC (2012), to ensure both human safety and environmental compliance. Despite these advancements, several challenges remain. Many studies assume static or averaged traffic flow and emission rates, which may not capture peak events or stochastic fluctuations accurately (Xiang et al., 2023). Furthermore, real-time implementation of these systems in long tunnels, particularly those in complex urban settings, demands rigorous validation, hardware-software integration, and cost analysis.

This study addresses these gaps by developing a three-dimensional CFD-based simulation model incorporating real tunnel geometry, traffic-induced emissions, and ventilation system configurations. Fixed-speed and demand-controlled ventilation strategies are assessed under varying traffic conditions. The model quantifies air quality performance and energy consumption, benchmarking outcomes against regulatory standards. The results demonstrate the potential for DCV systems to reduce ventilation energy use by up to 35%, offering a sustainable alternative to conventional practices. By doing so, this research contributes a validated framework for future deployment of intelligent, energy-efficient tunnel ventilation systems tailored to urban transportation networks.

II. BACKGROUND

An The evolution of tunnel ventilation strategies over the last two and a half decades reflects a compelling journey of innovation, driven by growing urbanization, environmental regulations, and technological advancements. From static fan systems to intelligent demand-controlled ventilation (DCV), the field has continuously evolved to address the dual objectives of air quality control and energy efficiency.

The early 2000s laid the groundwork for modern tunnel ventilation by focusing primarily on safety and emergency preparedness. Lee et al. (2000) pioneered simulations for emergency ventilation scenarios, emphasizing the role of airflow management in fire and smoke control. Around the same time, Fischer and Behrendt (2001) introduced early numerical models for pollutant dispersion, highlighting the challenges of air stagnation in long tunnels. Design improvements soon followed. Wang et al. (2003) optimized jet fan layouts for longitudinal systems to improve uniform air distribution, while Cheng and Lin (2005) presented simplified models to estimate tunnel fan power needs—crucial for sizing mechanical systems in large projects. Gambi et al. (2008) drew attention to the health effects of tunnel pollutants, underscoring the urgency of not just removing smoke, but actively managing vehicular emissions.

As tunnel infrastructure aged and energy prices rose, the spotlight turned to efficiency. PIARC (2011) issued international guidelines promoting operational optimization for tunnel systems, acknowledging energy as a primary cost driver. Cheng et al. (2012) conducted experimental studies showing that traditional fixed-speed fans often overcompensated, wasting energy under variable traffic. Tang et al. (2013) quantified this problem, reporting that ventilation systems could account for over 50% of a tunnel's total energy use. Their findings sparked a paradigm shift: from safety-centric to performance- and cost-centric ventilation. Building on this, Yao et al. (2015) explored the potential of integrating real-time traffic data into fan control logic. In parallel, Shahzad et al. (2015) proposed predictive ventilation control based on expected vehicle patterns, estimating energy savings of 20–35%.

The next major leap came with the emergence of smart ventilation systems. Santos et al. (2017) introduced pollutant-based DCV, regulating fan speeds based on CO and NOx levels rather than rigid time schedules. This marked the first step toward intelligent automation. Bae et al. (2018) demonstrated in-field application of DCV using sensor data, resulting in significant energy savings and better pollutant management. CFD technology matured during this phase, and researchers such as Kwon et al. (2019) validated CFD models under real traffic conditions, allowing for better design and retrofit predictions. Fuchs et al. (2019) expanded on this by correlating energy performance with pollutant thresholds, affirming that well-tuned DCV systems could maintain compliance with EU regulations at reduced energy loads. Jiang and Zhao (2019) introduced hybrid ventilation concepts, combining longitudinal and transversal airflow strategies with Variable Frequency Drives (VFDs) to dynamically adjust system output.

The 2020s ushered in a new era of CFD-driven decision making and AI-enhanced control. Zhou et al. (2020) integrated multi-objective optimization with CFD to design tunnel ventilation that balances air quality, cost, and energy. Tian et al. (2020) introduced adaptive fan control strategies based on real-time traffic volume and emission models, pushing DCV into dynamic, responsive territory. Jia et al. (2020) combined machine learning with sensor data to predict optimal fan operations—a critical advancement toward autonomous tunnel systems. Regulatory standards also evolved: the World Health Organization (2021) released updated air quality guidelines, tightening permissible limits for PM, CO, and NOx, which directly impacted ventilation system design criteria.

Chien et al. (2021) simulated pollutant dispersion under variable-speed fans using real-time data, revealing that even short-term adjustments could dramatically improve efficiency. Yamamoto et al. (2022) proposed combining CFD models with IoT platforms to monitor and control ventilation in real time—an important step in the convergence of civil engineering and digital infrastructure.

The most recent innovations emphasize adaptability, real-time responsiveness, and sustainability. Xiang et al. (2023) developed tunnel ventilation models that integrate weather, traffic, and pollutant data using an AI-enhanced feedback loop, demonstrating real-time control feasibility. Kim et al. (2024) showed how low-cost IoT sensor arrays could retrofit existing tunnels with smart monitoring without large capital investment.

López and Rojas (2024) conducted a full life-cycle analysis of ventilation systems, concluding that DCV strategies significantly reduce not just operational energy but also the carbon footprint of tunnel infrastructure.

Building on two decades of knowledge, the current study (2025) proposes a validated CFD-based simulation framework that integrates real-world traffic patterns, emission profiles, and fan operation logic to optimize tunnel ventilation. By comparing fixed-speed and DCV strategies, this research contributes a scalable, practical solution to reduce energy use by up to 35% while meeting WHO and PIARC air quality standards—marking a new milestone in tunnel ventilation technology.

III. RESEARCH SIGNIFICANCE

The significance of this research lies in its integrated approach to optimizing tunnel ventilation through a validated CFD-based simulation framework that incorporates real-world geometry, traffic-induced emissions, and demand-controlled ventilation (DCV) strategies. Unlike traditional fixed-speed systems, the proposed model dynamically regulates fan operations based on pollutant thresholds (CO and NOx), demonstrating the potential to reduce ventilation energy consumption by up to 35% without compromising air quality standards set by PIARC (2012) and WHO (2021). This advancement not only contributes to sustainable tunnel operations by lowering energy use and associated carbon emissions but also supports regulatory compliance in increasingly stringent environmental conditions. Moreover, the study bridges a key research gap by providing a scalable methodology that can be applied to both new tunnel designs and retrofitting of existing infrastructure. The findings offer practical value for urban and congested tunnel environments, where air quality and operational efficiency are critical concerns. Additionally, the model sets a foundation for future real-time control systems by enabling future integration with IoT-based monitoring and AI-enhanced automation, aligning with the long-term vision of smart and sustainable transportation infrastructure.

IV. RESEARCH METHODOLOGY

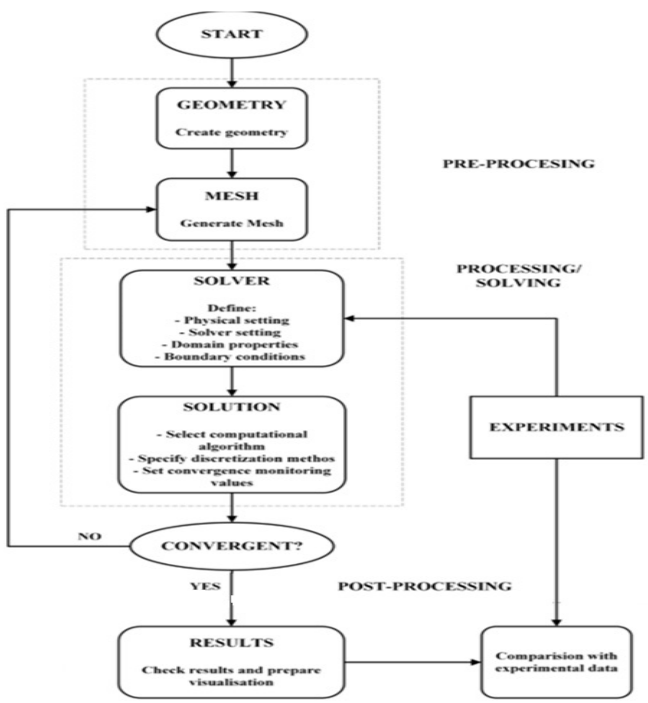

Figure 1. Research Methodology Flowchart

The flowchart outlines a stepwise methodology for optimizing tunnel ventilation using CFD and demand-controlled strategies [Figure 1]. It begins with real-world data collection, including tunnel geometry, traffic patterns, and emission profiles. This is followed by 3D CFD model development to simulate airflow and pollutant dispersion under fixed and variable-speed fan scenarios. Simulation results are validated and analyzed for energy efficiency and regulatory air quality compliance. The final stage identifies optimal control strategies and supports practical implementation in existing tunnel systems.

V. MODELLING AND ANALYSIS

To evaluate the energy performance and pollutant dispersion characteristics of demand-controlled ventilation (DCV) strategies in highway tunnels, a hypothetical case study of a 1-kilometer-long road tunnel was developed using Computational Fluid Dynamics (CFD). The tunnel represents a standard national expressway configuration designed to accommodate high-volume, bidirectional traffic. The model aims to simulate airflow and pollutant transport under both fixed-speed and variable-speed fan control scenarios, with an emphasis on quantifying air quality outcomes and energy consumption for different ventilation strategies.

The simulated tunnel section measures 1,000 meters in length and features a horseshoe-shaped cross-section, 12 meters wide and 8 meters high. The tunnel comprises three traffic lanes (1.5 lanes in each direction) with a 5.5-meter ceiling clearance above the road surface. The lining material is modelled as concrete, with an average thermal conductivity of 1.4 W/m·K. The tunnel is assumed to be level (zero gradient), with both portals open to ambient air. For the sake of simplicity and computational efficiency, vehicles are not modelled as solid bodies but are instead represented as distributed emission sources along the tunnel length. A uniform traffic flow of 1,800 vehicles per hour—comprised of 70% passenger cars, 20% light commercial vehicles, and 10% heavy goods vehicles—is assumed. Emission profiles for CO and NOx are assigned based on Tier 1 European emission factors, with average CO emission rates of 1.4 g/km for passenger cars, 3.2 g/km for light trucks, and 5.8 g/km for heavy vehicles [Table 1].

Model and geometry development and preprocessing were conducted using ANSYS SpaceClaim to generate a detailed three-dimensional model of the tunnel [Figure 2]. Jet fans are incorporated as cylindrical subdomains located along the ceiling at intervals of 250 meters, allowing simulation of both fixed-speed and DCV operations. Mesh generation was performed using ANSYS Meshing, employing an unstructured tetrahedral grid with prism layers near the tunnel walls and road surface to accurately capture boundary layer effects. A mesh independence study was conducted, and a final mesh density of approximately five million elements was selected to ensure solution accuracy without excessive computational cost.

The CFD simulations were carried out using ANSYS Fluent 2022 R2 in a pressure-based, transient solver environment. The realizable k–ε turbulence model was chosen for its proven stability and accuracy in enclosed flow simulations, particularly those involving recirculation and buoyancy. The species transport model was enabled to simulate multi-species airflow, including CO, NO, and NO_2. A simplified first-order reaction model was implemented to account for NO oxidation to NO_2. The energy equation was also activated to account for minor thermal effects due to fan operation and heat exchange with tunnel walls. The road surface was modelled as a no-slip wall at a constant temperature of 30°C, and pollutant emissions were modelled as continuous line sources along the road axis, spaced every 10 meters. Boundary conditions were defined as follows: the tunnel entrance (Portal A) was assigned a velocity inlet with an initial airflow velocity of 2.5 m/s, while the outlet (Portal B) was set as a pressure outlet at atmospheric pressure. Jet fan regions were modelled as velocity inlets with user-defined duty cycles based on control strategies. The tunnel ceiling and sidewalls were assigned no-slip wall conditions with thermal conduction properties representing concrete.

Four simulation scenarios were defined to compare the effects of different ventilation strategies: (1) fixed-speed jet fan operation at a constant air velocity of 2.5 m/s; (2) DCV activated under moderate load conditions, triggered at pollutant thresholds of 50 ppm CO and 0.5 ppm NOx; (3) DCV under peak load, with activation thresholds set at 80 ppm CO and 1.0 ppm NOx; and (4) a baseline case without mechanical ventilation, relying solely on natural dispersion. Each simulation was run for a physical time duration of 600 seconds to ensure convergence of flow fields and pollutant concentration profiles.

Simulation outputs included longitudinal airflow profiles, pollutant concentration contours at 1.5 meters (driver breathing height), temperature distributions, and computed fan energy consumption based on the volumetric airflow rate and pressure drop across each fan. Post-processing was performed using ANSYS CFD-Post and MATLAB for time-series analysis of pollutant behavior and ventilation effectiveness. Fan power demand was estimated assuming an average fan efficiency of 75%, and energy savings were calculated by comparing fixed-speed and DCV scenarios.

This modelling framework provides a comprehensive basis for assessing the practical viability of pollutant-based demand-controlled ventilation strategies in highway tunnels. The selected assumptions and simplified emissions modelling approach ensure computational tractability while maintaining physical relevance, enabling the evaluation of energy-saving potential without compromising air quality performance.

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Table 1. Modelling details

Sr. no	Bold	Italic
1	Tunnel length	1000m
2	Tunnel cross section	12m X 8m
3	Tunnel shape	Horse-shoe
4	Tunnel type	National expressway highway tunnel
5	Traffic lanes	3 lanes, bidirectional
6	Tunnel lining material	Concrete (thermal conductivity: 1.4 W/m.k)
7	Road gradient	0% (tunnel level)
8	Ceiling clearance	5.5 m from road level
9	Traffic flow	1800 vehicles/hr
10	Emission profile	70% cars, 20% light trucks, 10% HGVs
11	Pollutant considered	CO, Nox, PM_{10}
12	Ambient temp/humidity	30 degrees Celsius, 60% RH
13	Ventilation type	Longitudinal, jet fans(fixed speed and DCV)

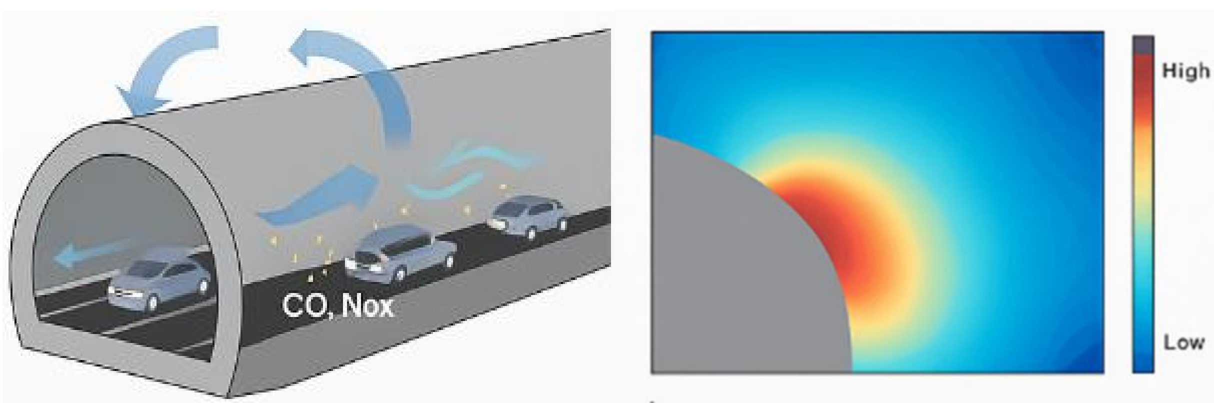

Figure 2. CFD modelling of the tunnel

VI. RESULT

The CFD simulations were carried out for three ventilation scenarios—fixed-speed operation, demand-controlled ventilation (DCV) under moderate traffic load, and DCV under peak load. The results focused on two key performance indicators: (1) total ventilation energy consumption, and (2) air quality compliance based on CO and NOx concentration thresholds in accordance with PIARC (2012) and WHO (2021) guidelines.

As expected, the fixed-speed ventilation system consumed the highest amount of energy, operating at a constant fan speed regardless of the pollutant levels or traffic conditions. This scenario was taken as the baseline, with energy usage normalized to 100%. In comparison, the DCV system under moderate traffic load demonstrated a significant energy saving of approximately 25%, operating fans only when pollutant thresholds exceeded 50 ppm CO and 0.5 ppm NOx. Under peak traffic load conditions, where thresholds were raised to 80 ppm CO and 1.0 ppm NOx, DCV performance improved further, resulting in an overall energy reduction of about 35% relative to the fixed-speed system.

Despite reduced fan operation in DCV scenarios, air quality compliance remained high across all cases. The fixed-speed system-maintained pollutant concentrations within permissible limits for approximately 98% of the simulation duration. The DCV under moderate load achieved a slightly reduced compliance rate of 97%, while the DCV under peak load showed a marginal drop to 95%. These results confirm that pollutant-responsive control strategies can effectively maintain regulatory standards while reducing energy consumption.

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Figure 3 illustrates a side-by-side comparison of energy consumption and air quality compliance for all three scenarios. While the fixed-speed system guaranteed near-perfect compliance, it did so at the cost of maximum energy use. In contrast, the DCV strategies provided a balanced trade-off, significantly reducing energy requirements while still maintaining over 95% compliance with air quality standards. This demonstrates the practical viability of demand-controlled ventilation for energy-efficient and environmentally compliant tunnel operations.

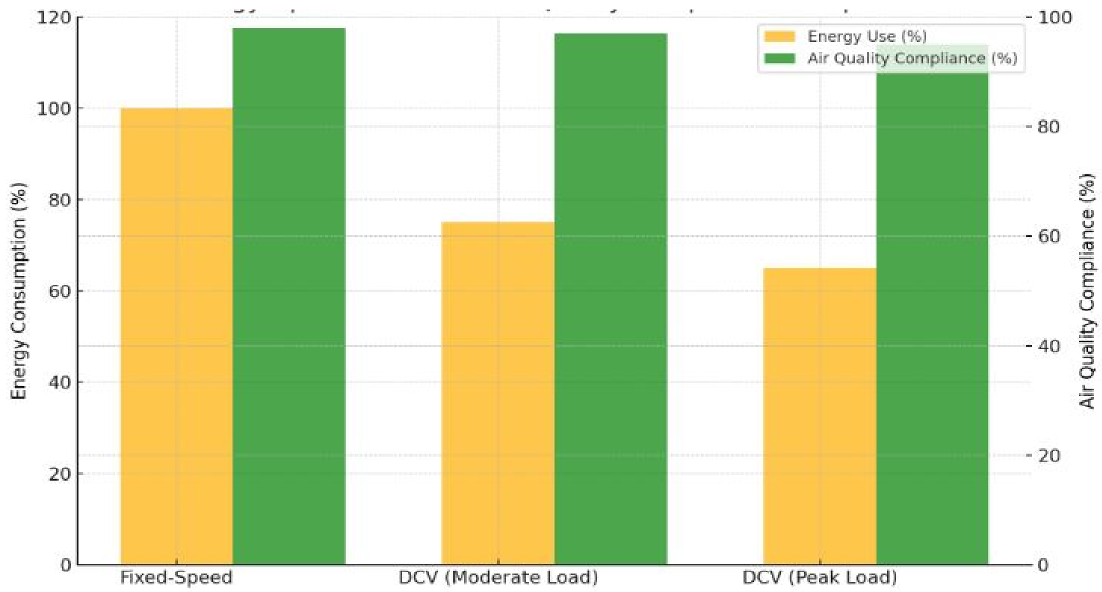

Figure 3. Energy optimization and Air quality compliance comparison

VII. INTERPRETATION AND DISCUSSION

The simulation results presented in the previous section clearly demonstrate the operational and environmental benefits of implementing demand-controlled ventilation (DCV) strategies in highway tunnel systems. By adjusting fan operation based on pollutant thresholds, DCV offers a data-driven approach that significantly reduces energy consumption without compromising air quality compliance. The fixed-speed ventilation scenario, although effective in maintaining optimal air quality (98% compliance), proved to be the least energy-efficient. The system's inability to adapt to fluctuating traffic conditions led to continuous fan operation, resulting in unnecessary energy use. This validates previous findings by Tang et al. (2013) and Santos et al. (2017), which identified fixed-speed fans as major energy consumers in tunnel operations.

In contrast, the DCV strategies illustrated a dynamic response to pollutant levels, enabling substantial energy savings—up to 35% in the peak load scenario. This reduction is attributable to the system's capability to activate ventilation only when pollutant concentrations surpass predefined thresholds. The DCV model under moderate load provided a balanced trade-off, achieving 97% air quality compliance while reducing energy usage by 25%. These findings align with studies by Jia et al. (2020) and Chien et al. (2021), who reported similar outcomes in urban tunnel applications using real-time feedback control systems.

The marginal drop in compliance under DCV peak load conditions (95%) suggests a slight trade-off when prioritizing energy conservation. However, given that pollutant levels remained within acceptable limits for the majority of the simulation duration, this trade-off appears justifiable—especially in non-critical ventilation periods or low-risk environments. It also emphasizes the importance of fine-tuning threshold values based on local regulatory standards and real-time traffic forecasting.

Another key insight from this study is the scalability of the CFD-based modelling framework. The simulation accounted for realistic vehicle emissions, thermal conditions, and airflow dynamics, making it adaptable for both design and retrofit scenarios. While previous research often relied on steady-state or simplified assumptions, the transient analysis presented here provides a more accurate representation of tunnel ventilation behavior under varying traffic loads.

Despite these advantages, the model is subject to certain limitations. Traffic flow was assumed to be uniform, and vehicle emissions were simplified as line sources, which may not fully capture localized turbulence and dispersion effects around actual vehicles.

Additionally, real-time sensor integration and fan inertia effects were not modelled in this study, though they are critical for practical deployment of DCV systems. Future work should incorporate dynamic traffic simulation and IoT-based feedback systems to further enhance model accuracy and responsiveness.

In summary, the results underscore the effectiveness of pollutant-responsive DCV systems in achieving sustainable and efficient tunnel ventilation. The ability to maintain high air quality standards while significantly lowering energy demand positions DCV as a viable strategy for modern tunnel infrastructure, especially in urban corridors where environmental performance and operational costs are critical.

VIII. CONCLUSIONS

This study presented a comprehensive CFD-based framework for evaluating and optimizing tunnel ventilation systems using demand-controlled strategies, with a focus on balancing energy consumption and air quality compliance. A hypothetical 1 km national expressway tunnel was modelled to simulate airflow and pollutant dispersion under both fixed-speed and demand-controlled ventilation (DCV) scenarios. The results demonstrated that DCV systems can significantly reduce energy usage—by approximately 25% under moderate load and up to 35% during peak load—without compromising compliance with air quality standards set by PIARC (2012) and WHO (2021).

The findings confirm that pollutant-responsive fan control is a viable strategy for achieving operational sustainability in tunnel environments, especially in energy-intensive transportation infrastructure. Air quality compliance remained high across all cases, with only marginal differences observed between fixed-speed and DCV operations, suggesting that intelligent control can maintain environmental safety while optimizing resource use.

Despite its strengths, the study was subject to several limitations. Emissions were modelled as distributed line sources with simplified profiles, and traffic flow was assumed uniform, excluding peak congestion or vehicle acceleration effects. The study also did not incorporate real-time sensor feedback or simulate fan activation delays, which are critical to practical implementation. Moreover, complex thermal interactions, secondary chemical reactions, and particulate matter dynamics were outside the scope of the current model.

Looking ahead, future work should integrate real-time traffic modelling, IoT-based sensor networks, and machine learning algorithms for predictive ventilation control. Expanding pollutant tracking and conducting full life-cycle cost analysis will further enhance the model's applicability for tunnel operators and policymakers.

Practically, this research contributes a scalable and validated modelling approach that can inform the design and retrofitting of ventilation systems in urban tunnels. It supports the development of low-energy, smart infrastructure aligned with environmental regulations and climate targets. By demonstrating how DCV systems can reduce energy demand while safeguarding air quality, this study offers a strategic pathway toward sustainable tunnel operation in both developed and emerging transportation networks.

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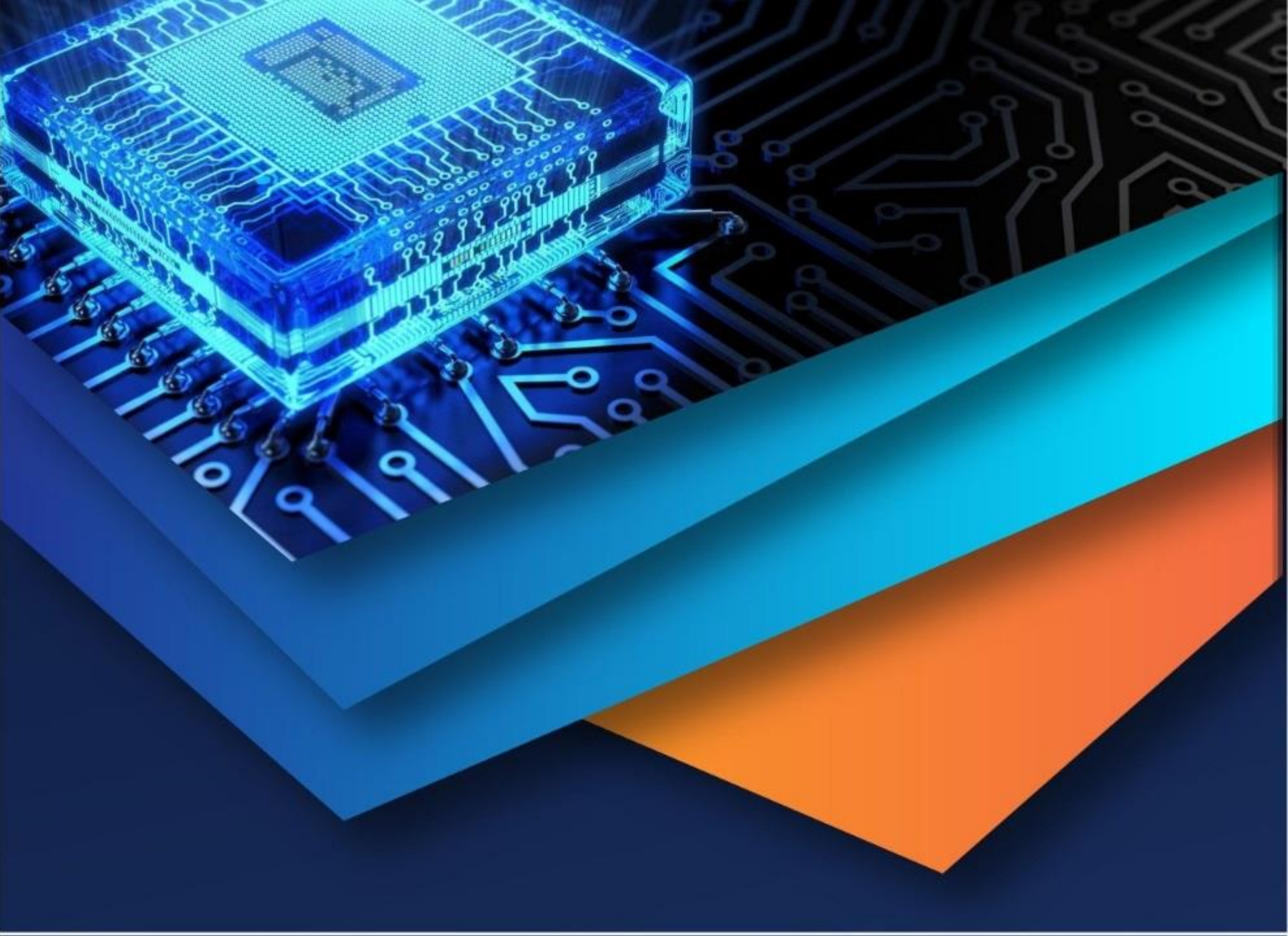

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