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DYNAMIC AIR CONDITIONING LOAD ADJUSTMENT IN A BUSBASED ON PASSENGER COUNT

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Abstract

This project presents the design and analysis of a dynamic air conditioning load adjustment system for a bus based on passenger count. The proposed approach integrates detailed cooling load estimation with airflow and duct design to ensure adaptive thermal performance under varying occupancy conditions. A comprehensive heat load calculation is carried out by accounting for conduction through the bus envelope, solar radiation through glazing, internal sensible and latent heat gains from occupants, ventilation air, infiltration, door opening cycles, onboard electrical loads, and engine heat contribution. For a design occupancy of 25 passengers and peak outdoor conditions of 40 °C, the total cooling load is estimated to be 19.26 kW (5.48 TR), comprising 12.72 kW sensible and 6.54 kW latent loads. The total HVAC electrical demand is estimated at approximately 5.91 kW under steady-state conditions. The study demonstrates that a passenger-adaptive air-conditioning strategy, supported by accurate load modeling and optimized duct design, can significantly enhance energy efficiency while maintaining consistent thermal comfort within the bus cabin.

1. Introduction

Air conditioning is an essential requirement in modern public bus transportation, particularly in hot and humid climates where passenger comfort and service quality are strongly influenced by cabin thermal conditions. Unlike stationary buildings, bus cabins experience highly dynamic thermal environments due to fluctuating passenger occupancy, frequent door

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openings, variable ventilation demand, high solar radiation through glazing, and rapidly changing external conditions. These transient factors cause significant variations in internal heat loads over short time scales, making effective thermal control both complex and energy intensive. Conventional bus air conditioning systems are typically designed for worst-case operating conditions, assuming maximum passenger occupancy and extreme outdoor temperatures. While this ensures adequate cooling during peak demand, it results in inefficient operation during low and moderate occupancy periods. Fixed-capacity operation often leads to overcooling, unnecessary compressor and fan operation, increased energy consumption, and accelerated system wear. Moreover, the inability to respond to real-time changes in internal heat gains frequently causes discomfort during sudden increases in passenger load. The passenger occupancy is one of the most dominant contributors to the cooling load inside a bus, influencing both sensible and latent heat gains as well as ventilation requirements for maintaining indoor air quality. Despite this strong dependence, most existing bus HVAC systems do not incorporate occupancy variation into their control strategy, leading to a mismatch between cooling supply and actual demand. This inefficiency is further compounded by rising fuel costs, stricter emission norms, and the growing emphasis on sustainable public transportation systems. To address these limitations, this project proposes a passenger-adaptive air conditioning approach for buses based on detailed cooling load estimation and optimized air distribution design. The work focuses on accurately accounting for all major heat gain components and developing an airflow distribution system capable of maintaining uniform thermal conditions under varying occupancy levels. By establishing a strong analytical foundation for load calculation and duct design, the study provides a pathway toward intelligent, demand responsive HVAC systems that enhance energy efficiency, ensure passenger comfort, and reduce environmental impact in public transport applications. The remainder of this paper is organized as follows: Section 2 reviews related literature on bus HVAC systems and passenger-adaptive cooling strategies. Section 3 presents the proposed methodology, including cooling load estimation and airflow design. Section 4 defines the evaluation metrics used for performance assessment. Section 5 discusses the results obtained from analytical and simulation studies. Section 6 describes the system implementation and practical considerations. Section 7 concludes the paper and outlines future research directions, followed by the References section.

2. Literature Review

The thermal management of passenger compartments in public transportation vehicles has attracted sustained research attention over the past two decades, driven by escalating energy costs, heightened passenger comfort expectations, and increasingly stringent environmental and emission regulations. Among various modes of public transport, urban buses present particularly demanding HVAC design challenges due to their large enclosed volumes, high glazing ratios, compact installation constraints, and highly variable passenger occupancy. Unlike stationary buildings or rail-based systems, buses operate in continuously changing environments characterized by fluctuating ambient temperatures, varying solar radiation, stop-and-go driving cycles, and frequent door opening events. These factors lead to rapidly changing internal thermal loads, necessitating HVAC systems that are not only capable of meeting peak cooling demands but are also responsive, energy efficient, and robust under transient operating conditions. Early research on bus air-conditioning systems largely adopted steady-state cooling load estimation approaches derived from conventional building HVAC design methodologies. These studies typically accounted for conductive heat transfer through the vehicle envelope, solar radiation incident on glazed surfaces, and internal heat gains from passengers and onboard electrical equipment. Simplified conduction models were employed to estimate heat transfer through roof, sidewall, and floor structures, while solar heat gains were calculated using glazing area, incident solar irradiance, and solar heat gain coefficients. Across multiple investigations, passenger sensible heat and solar radiation through glazing were consistently identified as the dominant contributors to total cooling load during summer operation, particularly in tropical and subtropical climates. While these steady-state models provided useful first-order estimates for system sizing, their applicability was limited by the inherent assumption of constant operating conditions. Recognizing the limitations of steady-state analysis, subsequent studies introduced dynamic and transient thermal modeling frameworks to better represent real bus operating conditions. These models incorporated time-dependent variations in ambient temperature, solar intensity, vehicle speed, route characteristics, stop frequency, and door opening duration. Results from such studies revealed substantial deviations between steady-state predictions and actual transient cooling loads, particularly during passenger boarding and alighting. Door opening events were shown to introduce significant quantities of hot and humid ambient air into the cabin, leading to sharp increases in both sensible and latent loads. Experimental validation efforts further demonstrated that ventilation, infiltration, and door exchange loads can be comparable to, or even exceed, envelope conduction losses on heavily trafficked routes. These findings highlighted the importance of explicitly accounting for transient air exchange processes in bus HVAC design. Passenger occupancy has been consistently identified as one of the most influential parameters governing the thermal behavior of bus cabins. Each passenger contributes both sensible heat, which raises the cabin air temperature, and latent heat, which increases moisture content and directly affects perceived thermal comfort. In addition, higher occupancy levels demand increased ventilation rates to maintain acceptable indoor air quality, further amplifying the cooling requirement. Numerous studies have quantified the contribution of occupant-related heat gains to total cooling load, reporting values ranging from approximately one-third to nearly one-half under peak occupancy conditions. Despite this strong dependence, most conventional bus air-conditioning systems continue to be designed for worst-case passenger loads and operate at constant capacity. This design philosophy results in significant overcooling and energy wastage during off-peak operation, while simultaneously struggling to maintain comfort during sudden increases in passenger density. In response to these inefficiencies, recent research has increasingly focused on adaptive, predictive, and occupancy aware HVAC control strategies. Model predictive control has emerged as a particularly promising approach, enabling real time adjustment of cooling capacity and airflow based on predicted passenger occupancy, ambient conditions, and route schedules. Simulation studies conducted on conventional, hybrid, and electric buses indicate that occupancy-aware HVAC operation can significantly reduce air-conditioning energy consumption while maintaining acceptable thermal comfort levels. To further improve robustness under real-world uncertainty, stochastic and chance-constrained optimization techniques have been proposed to explicitly account for variability in passenger arrival patterns and operational conditions. While these control-oriented studies demonstrate substantial energy-saving potential, many rely on simplified lumped thermal models and do not present the detailed engineering calculations required for practical system design. Parallel to advancements in control methodologies, significant research attention has been devoted to airflow distribution and duct design within bus cabins. Computational fluid dynamics (CFD) studies have demonstrated that non-uniform airflow distribution can result in localized thermal discomfort even when average cabin temperatures satisfy design criteria. Regions near doors, windows, and aisle spaces are particularly susceptible to thermal stratification and uneven air movement. These studies emphasize the critical role of diffuser placement, duct geometry, airflow direction, and velocity control in achieving uniform thermal conditions across the passenger zone. Both numerical and experimental investigations consistently show that optimized duct layouts with controlled airflow velocities can enhance thermal comfort while simultaneously reducing fan power requirements. Thermal comfort assessment in bus environments has also evolved beyond simple temperature-based metrics. Numerous studies apply standardized comfort indices such as Predicted Mean Vote and Predicted Percentage of Dissatisfied, while others adopt adaptive comfort models more suitable for transient environments. More recent research leverages data-driven and machine-learning-based approaches to classify passenger comfort states using multi-variable inputs, including temperature, humidity, air velocity, and occupancy density. These studies consistently highlight the importance of humidity control and airflow characteristics in perceived comfort, reinforcing the need for integrated cooling load estimation and airflow design rather than capacity-based sizing alone. Energy efficiency and environmental impact constitute another major theme in the literature, particularly with the growing adoption of electric and hybrid buses. HVAC systems are frequently identified as one of the largest auxiliary energy consumers, with a direct impact on battery range, operating cost, and lifecycle emissions. Studies focusing on electric buses report that HVAC operation can account for a substantial fraction of total auxiliary energy consumption under extreme climatic conditions. Consequently, adaptive HVAC operation based on real-time thermal demand and passenger occupancy is widely recognized as one of the most effective strategies for improving overall vehicle energy efficiency without compromising passenger comfort. In summary, existing research clearly establishes that accurate thermal load estimation, passenger-adaptive operation, and optimized airflow distribution are critical to efficient bus HVAC performance. However, a detailed review of the literature reveals that many published works emphasize control algorithms, optimization techniques, or high-level system performance metrics without presenting comprehensive engineering design calculations for cooling load breakdown, airflow sizing, duct velocity limits, and pressure loss estimation. Moreover, relatively few studies offer an integrated analytical framework that explicitly links passenger-dependent cooling load estimation with practical duct design and electrical power evaluation. These gaps motivate the present work, which adopts a calculation-driven approach to the design of a passenger-adaptive bus air-conditioning system grounded in fundamental heat transfer and fluid mechanics principles.

3. Methodology

3.1 Proposed Work

The proposed system architecture is based on a centralized air-conditioning unit supplying conditioned air to the bus cabin through a structured duct and diffuser network, with cooling demand linked to passenger occupancy. The core components of the system include the refrigeration unit (compressor, condenser, and evaporator), an air handling section comprising the cooling coil and fan, and a dual-side plenum duct arrangement for air distribution. The system is designed to maintain a specified indoor setpoint temperature and humidity while operating efficiently across varying passenger loads. Air is drawn through filters and passed over the evaporator coil, where both sensible and latent heat removal occur to achieve the desired supply air temperature. The conditioned air is then delivered to a main supply duct, which splits into two longitudinal side plenums running along the length of the bus. Each plenum feeds multiple branch ducts connected to diffusers positioned above passenger seating zones. This configuration ensures uniform airflow distribution, minimizes temperature gradients along the cabin, and maintains acceptable air velocities to avoid drafts and noise. The adaptive aspect of the architecture is enabled through a conceptual passenger-count sensing and control layer. Passenger occupancy data, obtained through suitable sensors, is used to estimate real-time cooling demand by adjusting compressor capacity and fan airflow rate accordingly. Temperature and humidity sensors provide feedback on cabin conditions, allowing the system to modulate cooling output while maintaining comfort. Although the present work focuses on analytical design rather than hardware implementation, the proposed architecture establishes a scalable and practical framework for integrating occupancy-based control into bus air-conditioning systems. Bus Geometry and Cabin Dimensions are; Bus internal dimensions (L × W × H): 8.0 m × 3.0 m × 2.0 m, Total cabin volume: 48.0 m^3, Total glazing area: 10 m^2. The internal dimensions define the enclosed air volume that must be conditioned and directly influence both sensible and latent load calculations. Cabin volume governs the ventilation and infiltration air mass flow, while the glazing area plays a dominant role in solar heat gain. The relatively high glazing to-volume ratio typical of buses makes solar radiation a significant contributor to peak cooling demand, especially under urban operating conditions.

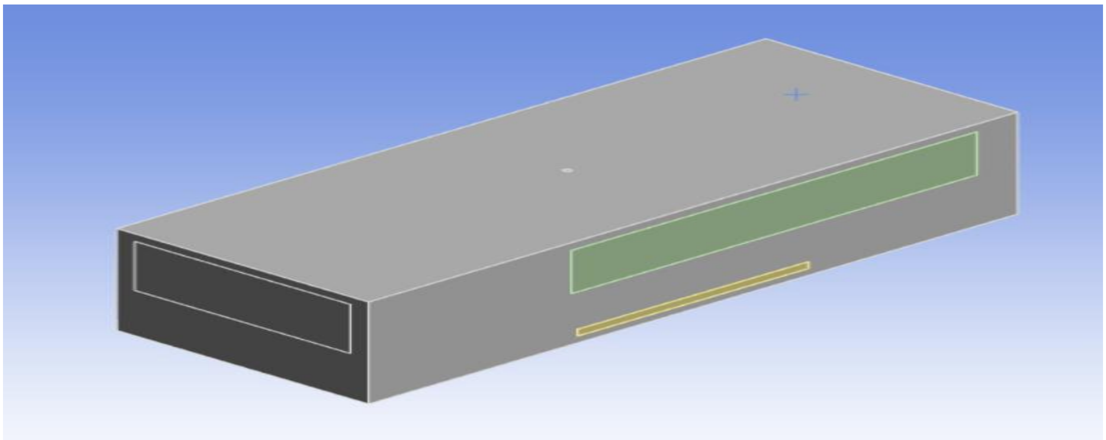


Fig. 1: Three-dimensional CAD model of the bus cabin with glazing and envelope representation

The figure 1 depicts the simplified solid model of the bus cabin geometry used for thermal and airflow analysis. The model represents the cabin envelope, glazing surfaces, and air volume while excluding unnecessary structural details to reduce computational complexity. Such geometric simplification allows efficient evaluation of heat transfer and airflow behavior without compromising result accuracy. The model dimensions are based on actual bus interior specifications. Temperature and Comfort Design Conditions • Indoor design setpoint temperature: 25 ◦C • Indoor relative humidity (assumed): 50% • Outdoor design condition: 40 ◦C, 40% RH • Supply air temperature (SAT): 12 ◦C These temperature and humidity conditions are selected to ensure acceptable thermal comfort for seated and standing passengers under peak summer operation. The large temperature difference between outdoor air and the indoor setpoint increases conduction and ventilation loads. A low supply air temperature is required to handle both sensible and latent loads effectively, particularly under high occupancy conditions. Envelope Thermal Parameters • Roof U-value: 1.8 W/m2・K • Sidewall U-value: 1.5 W/m2・K • Glazing U-value: 5.7 W/m2・K • Floor U-value: 1.0 W/m2・K • Solar Heat Gain Coefficient (SHGC) of glazing: 0.55 • Solar irradiance (design peak): 800 W/m2 These parameters characterize heat transfer through the bus envelope. The relatively high glazing U-value and SHGC indicate significant conductive and radiative heat ingress through windows. Solar irradiance under worst-case conditions contributes substantially to peak sensible load, reinforcing the need for accurate envelope modeling and appropriate airflow distribution to mitigate localized overheating. Occupancy, Internal Gains, and Ventilation Inputs • Maximum occupancy: 25 persons • Sensible heat per person: 55 W/person • Latent heat per person: 45 W/person • Ventilation rate: 4.5 L/s per person (112.5 L/s total) • Door exchange: 15% of cabin volume at 40 stops/h • Infiltration rate: 1 ACH • Lighting load: 60 W • Phone charging load: 75 W • Assumed engine heat gain: 500 W Occupants represent a major source of both sensible and latent heat within the bus cabin, with their contribution varying directly with passenger count. Ventilation and door opening events introduce large quantities of hot and humid outdoor air, significantly increasing the cooling requirement. Auxiliary loads such as lighting, electronic devices, and engine heat further elevate internal heat gains and must be included to avoid underestimation of peak load.

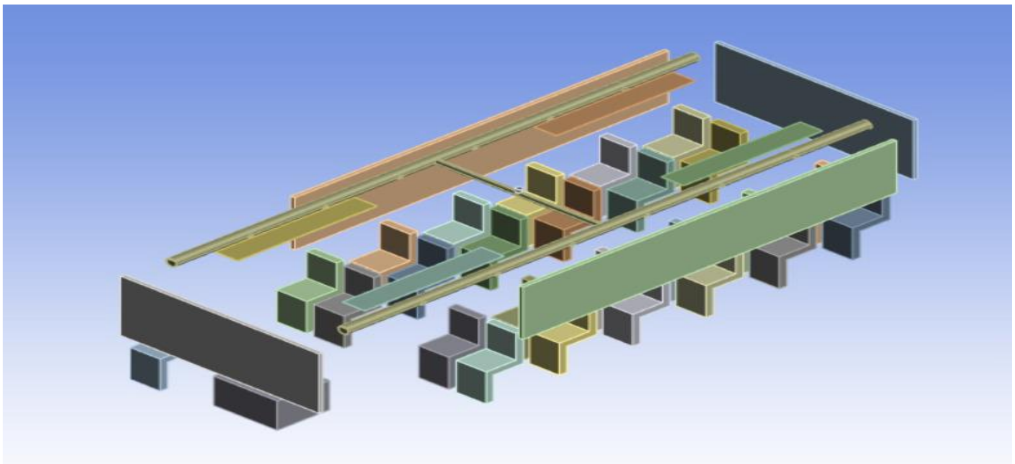


Fig. 2: Exploded view of the bus showing seating and duct placement

The figure 2 presents an exploded three-dimensional CAD representation of the bus cabin along with the proposed air distribution system. The layout illustrates the main supply duct, dual side plenums, branch ducts, and diffuser locations relative to the passenger seating arrangement. The exploded view clearly highlights the airflow path from the central supply duct to individual diffusers. This configuration was adopted to ensure uniform air distribution and effective cooling across the entire passenger compartment. Duct and Air Distribution Design Inputs are-

- Total supply volumetric flow rate, Vtot: 0.7030 m3/s
- Plenum configuration: Two side plenums (each carrying half flow)
- Flow per plenum, Vplenum: 0.3515 m3/s
- Number of diffusers per plenum: 6
- Flow per diffuser, Vbranch: 0.05858 m3/s
- Branch duct diameter: 120 mm
- Branch duct length: 0.40 m
- Target branch velocity: computed (≈5.18 m/s)
  Plenum target velocity: 2.0 m/s
- Main duct target velocity: 6.0 m/s
- Friction factor (sheet metal): 0.03
- Air density: 1.2 kg/m3

The air distribution system is designed to deliver the required cooling uniformly across the passenger cabin. The dualplenum configuration ensures balanced airflow distribution on both sides of the bus. Velocity limits are selected to minimize noise and draft discomfort while maintaining compact duct dimensions suitable for space-constrained vehicle interiors.

Pressure Loss and Fan Performance Parameters

- Coil pressure drop: 300 Pa
- Filter pressure drop: 70 Pa
- Diffuser pressure drop (used): 14 Pa
- Fittings allowance: 30% of line friction losses
- Fan mechanical and motor efficiency: 0.55

These parameters are used to estimate the total static pressure that the fan must overcome. Coil and filter losses dominate the pressure budget, while duct and fitting losses are minimized through careful sizing and velocity control. Fan efficiency directly affects electrical power consumption and plays a critical role in overall HVAC energy performance. The above inputs collectively define the physical, thermal, and operational framework for the proposed passenger adaptive bus air conditioning system. By clearly specifying cabin geometry, environmental conditions, envelope thermal properties, internal heat gains, ventilation requirements, and airflow distribution parameters, the system boundaries and assumptions are unambiguously established. This structured definition ensures that all subsequent analyses are grounded in realistic operating conditions representative of an urban bus subjected to peak summer loads and varying passenger occupancy. Organizing the methodology around these well-defined parameters enables the mathematical modeling and performance evaluation to be carried out in a consistent, transparent, and traceable manner. The explicit linkage between load inputs, airflow design variables, and pressure loss characteristics ensures coherence between cooling load estimation, duct sizing, and electrical power calculations. As a result, the analytical framework developed in this study provides a reliable basis for assessing the effectiveness of passenger-adaptive HVAC operation and for identifying opportunities to improve energy efficiency while maintaining thermal comfort.

3.2 Mathematical modeling

By applying fundamental principles of heat transfer, thermodynamics, and fluid mechanics, the model translates physical and operational inputs into measurable performance parameters such as cooling load, airflow rate, pressure loss, and electrical power consumption. This approach ensures that the HVAC system design is grounded in first-principles analysis rather than empirical sizing alone. The modeling structure explicitly separates sensible and latent heat components and accounts for both fixed and occupancy-dependent heat gains within the bus cabin. By formulating cooling demand as a function of passenger count, the framework enables dynamic adjustment of cooling capacity and airflow. This mathematical representation serves as the analytical backbone for evaluating system performance, energy efficiency, and adaptability under varying occupancy conditions

Total Cooling Load Estimation: The total cooling load of the bus cabin is expressed as the sum of sensible and latent heat gains:

$Qtotal = Qsensible + Qlatent$ (1)

a) Sensible Heat Load: The total sensible heat load is obtained by summing contributions from envelope conduction, solar heat gain, occupants, ventilation, infiltration, door opening events, and internal equipment:

$Qsensible = Qcond+Qsolar+Qocc,s+Qvent,s+Qinf,s+Qdoor+Qint$ (2)

Each term is evaluated as follows. Envelope conduction $Qcond = X\ (UiAi\Delta T)$ (3)

Solar heat gain through glazing $Qsolar = I\ Aglass\ SHGC$ (4)

Occupant sensible heat $Qocc,s = N\ qsensible, person$ (5)

Ventilation sensible load $Qvent,s = \dot{m}\ vent\ cp\ (Tout - Tin)$ (6)

b) Latent Heat Load: The latent cooling load arises primarily from occupants and ventilation air and is calculated as: $Qlatent = Qocc,l + Qvent,l$ (7)

Occupant latent heat $Qocc,l = N\ qlatent, person$ (8)

Ventilation latent load

$Qvent,l = \dot{m}\ vent\ hfg\ (\omega out - \omega in)$ (9)

where ω represents the humidity ratio and hfg is the latent heat of vaporization.

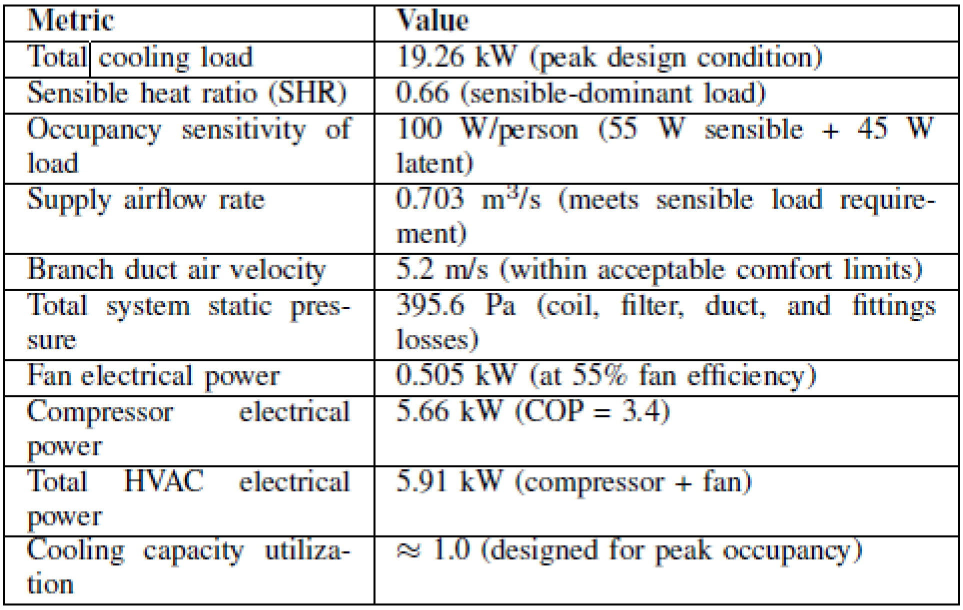
c) Supply Airflow Requirement: The required supply airflow rate is determined from the sensible heat balance between the cabin air and the supplied conditioned air: $Qsensible = \dot{m}\ air\ cp\ (Tin - TSA)$ (10)

d) Significance of Model and Design: The proposed analytical model and HVAC system design provide a structured and physically grounded approach to addressing the dynamic thermal behavior of bus passenger cabins. By explicitly accounting for all major sources of sensible and latent heat—including passenger occupancy, ventilation, infiltration, solar radiation, and envelope heat transfer—the model offers a realistic representation of actual operating conditions. This level of detail ensures that system sizing and performance evaluation are based on accurate thermal demand rather than conservative assumptions alone. A key significance of the model lies in its ability to link cooling load directly with passenger occupancy. Unlike conventional fixed-capacity designs, the proposed framework treats occupancy as a variable input, enabling proportional adjustment of cooling capacity and airflow. This passenger dependent formulation forms a strong foundation for adaptive HVAC operation, allowing energy consumption to be minimized during low-occupancy periods while maintaining thermal comfort during peak usage. As a result, the model supports energy-efficient operation without compromising passenger satisfaction. The air distribution design further enhances the significance of the proposed system by translating thermal requirements into practical engineering solutions. The dual-side plenum configuration, controlled airflow velocities, and detailed pressure loss evaluation ensure uniform air distribution, reduced thermal stratification, and efficient fan operation within the spatial constraints of a bus. This integration of airflow design with thermal modeling distinguishes the work from studies that focus solely on control strategies or lumped thermal analysis. Overall, the significance of the model and design lies in their combined analytical rigor and practical applicability. The framework bridges the gap between theoretical thermal modelling and real-world HVAC system design by providing detailed cooling load breakdowns, duct sizing, and power estimation. This makes the proposed approach highly relevant for the development of intelligent, passenger-adaptive air conditioning systems in modern public transportation, supporting energy efficiency, sustainability, and improved passenger comfort.

4. Results

The result analysis tabled in Table I evaluates the performance of the proposed passenger-adaptive air conditioning system by interpreting the calculated cooling loads, airflow distribution characteristics, and electrical power consumption. The objective of this chapter is to assess whether the designed system meets thermal comfort requirements while maintaining energy-efficient operation under peak passenger occupancy, and to examine how the results support adaptive HVAC operation in a bus environment. The analysis is organized around four key performance aspects: cooling load composition, airflow and air distribution effectiveness, pressure and fan power performance, and overall energy efficiency. Each aspect is discussed based on the numerical outputs derived in Chapter 5, with emphasis on the implications of passenger-dependent loads and system scalability.

TABLE I: Evaluation Metrics with Computed Values

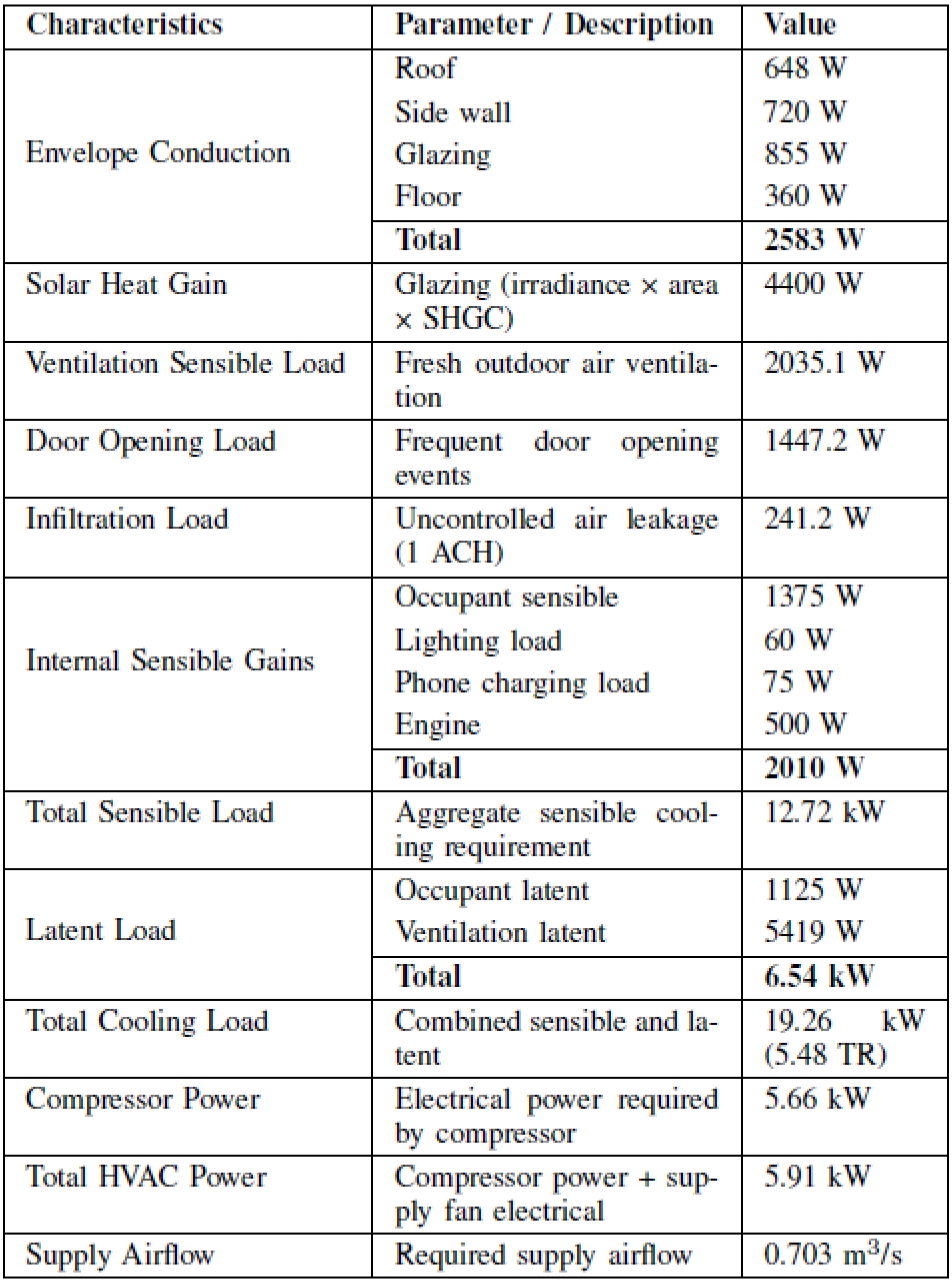


Metric	Value
Total cooling load	19.26 kW (peak design condition)
Sensible heat ratio (SHR)	0.66 (sensible-dominant load)
Occupancy sensitivity of load	100 W/person (55 W sensible + 45 W latent)
Supply airflow rate	0.703 m^3/s (meets sensible load requirement)
Branch duct air velocity	5.2 m/s (within acceptable comfort limits)
Total system static pressure	395.6 Pa (coil, filter, duct, and fittings losses)
Fan electrical power	0.505 kW (at 55% fan efficiency)
Compressor electrical power	5.66 kW (COP = 3.4)
Total HVAC electrical power	5.91 kW (compressor + fan)
Cooling capacity utilization	≈ 1.0 (designed for peak occupancy)

The implementation of the proposed passenger-adaptive air conditioning system is carried out at the analytical and design level, translating the developed mathematical model and system architecture into a practical HVAC configuration for a bus application. The implementation focuses on integrating cooling load estimation, airflow delivery, and electrical power evaluation into a coherent system that can respond to variations in passenger occupancy. The design is based on peak operating conditions to ensure robustness, while retaining flexibility for adaptive operation at partial loads. The air conditioning unit is implemented as a centralized system consisting of a compressor–condenser–evaporator assembly sized to meet the calculated peak cooling demand of 19.26 kW. The evaporator coil is designed to deliver a supply air temperature of 12 °C, enabling effective removal of both sensible and latent heat from the cabin air. Air filtration is incorporated upstream of the coil to maintain indoor air quality and protect system components. A blower is selected to supply the required total airflow rate of 0.703 m3/s while overcoming the calculated system static pressure, ensuring stable and efficient air delivery. Passenger adaptivity is conceptually implemented through the integration of passenger-count sensing and control logic. Occupancy data is used to estimate real-time cooling demand by adjusting compressor capacity and fan airflow rate in proportion to passenger heat gains and ventilation requirements. While physical sensors and control hardware are not implemented in this study, the analytical framework demonstrates how passenger-dependent inputs can be directly linked to HVAC operation. This implementation approach establishes a scalable pathway for future integration of real-time control and experimental validation.

4.1 Model Integration: Model integration in this study is achieved through a unified analytical framework that couples cooling load estimation, air distribution design, and electrical power evaluation for a passenger-adaptive bus air-conditioning system. Cooling load calculations establish the required sensible and latent capacity based on bus geometry, envelope thermal properties, operating conditions, and passenger occupancy, thereby defining the fundamental thermal demand. The outputs of the load model are used to determine supply air temperature and mass flow rate requirements, which govern duct sizing, airflow velocities, and pressure loss estimation within the air distribution network. These airflow parameters are further linked with component level characteristics, including coil, filter, and diffuser pressure drops, to evaluate total system resistance and fan power requirements, ensuring consistency between thermal demand, airflow delivery, and energy consumption. As passenger occupancy varies, its influence propagates coherently through the integrated model, affecting cooling load, airflow requirements, and electrical power demand. This integrated approach provides a robust and scalable basis for evaluating passenger adaptive HVAC performance and supports future implementation of occupancy-based control and optimization strategies in bus air-conditioning systems.

TABLE II: Step-by-Step Cooling Load Estimation Summary

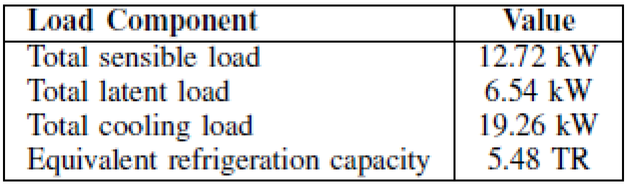


Characteristics	Parameter / Description	Value
Envelope Conduction	Roof	648 W
	Side wall	720 W
	Glazing	855 W
	Floor	360 W
	Total	**2583 W**
Solar Heat Gain	Glazing (irradiance × area × SHGC)	4400 W
Ventilation Sensible Load	Fresh outdoor air ventilation	2035.1 W
Door Opening Load	Frequent door opening events	1447.2 W
Infiltration Load	Uncontrolled air leakage (1 ACH)	241.2 W
Internal Sensible Gains	Occupant sensible	1375 W
	Lighting load	60 W
	Phone charging load	75 W
	Engine	500 W
	Total	**2010 W**
Total Sensible Load	Aggregate sensible cooling requirement	12.72 kW
Latent Load	Occupant latent	1125 W
	Ventilation latent	5419 W
	Total	**6.54 kW**
Total Cooling Load	Combined sensible and latent	19.26 kW (5.48 TR)
Compressor Power	Electrical power required by compressor	5.66 kW
Total HVAC Power	Compressor power + supply fan electrical	5.91 kW
Supply Airflow	Required supply airflow	0.703 m^3/s

B. Key observation norms: The numerical model provides key performance outputs under peak design conditions, which serve as reference values for evaluating system behavior and scalability under varying passenger occupancy. 1) Thermal Output (Cooling Load): a) Key observations: • Latent load constitutes a significant fraction of the total cooling demand. • Passenger occupancy, ventilation air, and infiltration are the dominant contributors to latent and sensible loads. • Adequate moisture removal capability is therefore essential for maintaining thermal comfort. 2) Airflow and Distribution Output: a) Key observations: • Airflow is uniformly distributed across the passenger cabin. • The per-diffuser airflow supports even temperature distribution. • The design minimizes localized overheating and passenger discomfort.3) Duct Velocity and Pressure Performance: a) Key observations: • All duct velocities remain within recommended HVAC design limits. • Pressure losses are dominated by coil and filter components. • Proper duct sizing effectively limits fan energy consumption. 4) Electrical Power Output: a) Key observations: • The compressor accounts for the majority of the HVAC power demand. • Fan power remains relatively low due to optimized airflow and duct design. • The results confirm the feasibility of the proposed HVAC system under peak load operating conditions.

C. Experimental Results

TABLE III: Summary of Cooling Load Components



Load Component	Value
Total sensible load	12.72 kW
Total latent load	6.54 kW
Total cooling load	19.26 kW
Equivalent refrigeration capacity	5.48 TR

1) Cooling Load Analysis: The results indicate that the total cooling requirement of the bus cabin under peak conditions is 19.26 kW, with the sensible load accounting for approximately 66% of the total load and the latent load contributing the remaining 34%. This significant latent fraction highlights the strong influence of passenger occupancy, ventilation air, and infiltration on overall cooling demand. Such a load distribution justifies the selection of a low supply air temperature to ensure adequate dehumidification alongside sensible cooling. The figures in 3, 4, 5 presents the three-dimensional airflow pattern within the passenger cabin, visualized using velocity streamlines. Conditioned air supplied from the overhead diffusers propagates downward into the occupied zone before recirculating toward the return region. The flow structure demonstrates effective mixing of supply air with cabin air, ensuring uniform thermal distribution. No large stagnant regions are observed, indicating satisfactory air circulation throughout the cabin.

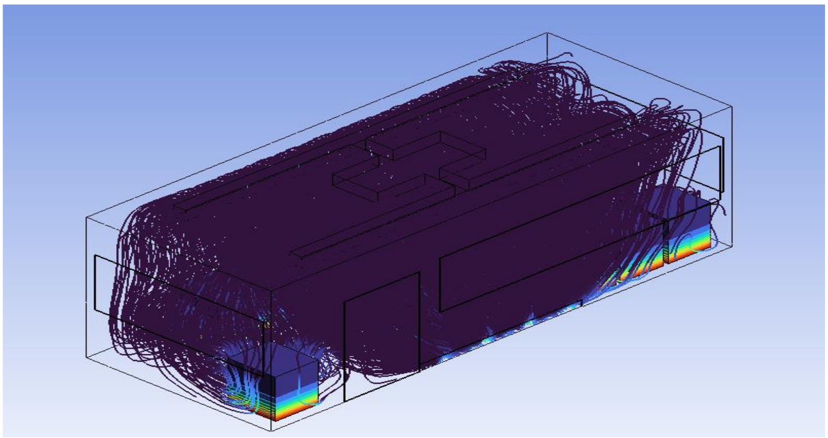


Fig. 3: Isometric view of airflow streamlines

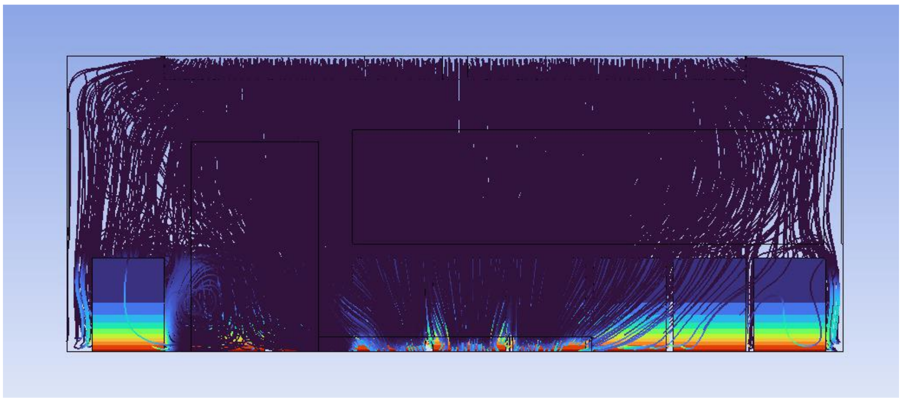


Fig. 4: Side view streamlines and temperature contours

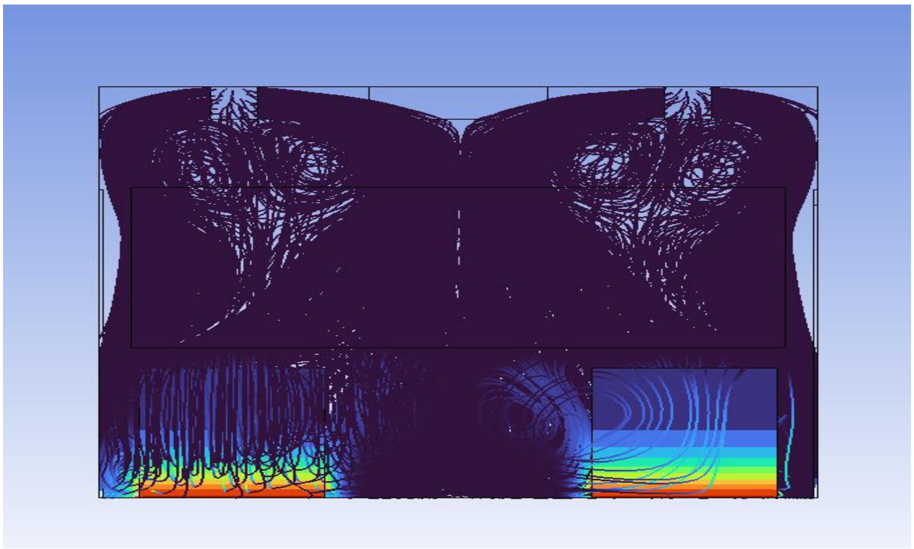


Fig. 5: Front cross-sectional airflow and temperature distribution

Occupant-related heat gains and ventilation loads form a major portion of the total cooling requirement, confirming that passenger count is a dominant driver of HVAC demand in buses. This observation validates the core premise of the project—that fixed-capacity systems are inherently inefficient for bus applications where occupancy varies widely. By explicitly linking cooling capacity to passenger-dependent loads, the proposed system enables proportional adjustment of cooling output, reducing energy wastage during low-occupancy operation. 2) Airflow and Distribution Performance Analysis: The airflow results demonstrate that the calculated supply airflow rate is sufficient to meet the sensible cooling demand while maintaining acceptable temperature gradients across the cabin. Dividing the total airflow equally between two side plenums ensures balanced air delivery along the length of the bus. The per-diffuser airflow rate supports uniform cooling of seated and standing passenger zones, reducing the likelihood of localized hot spots.

TABLE IV: Airflow and Distribution Performance Parameters

Parameter	Value
Total supply airflow	0.703 m^3/s
Airflow per plenum	0.3515 m^3/s
Airflow per diffuser	58.6 L/s

These figures in 6, 7, 8 illustrate the velocity streamlines inside the main supply duct, branch unction, and dual side plenums. The flow visualization confirms smooth air division from the main duct into the two plenums with no significant flow separation or stagnation zones. Velocity distribution remains consistent along the plenum length, supporting uniform diffuser supply. The results validate the duct sizing and velocity targets adopted during the analytical design stage.

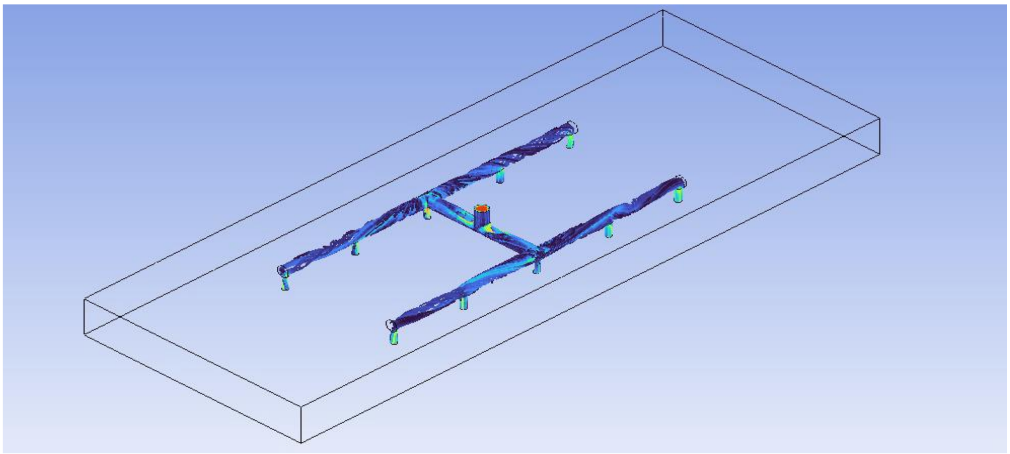


Fig. 6: Isometric view of airflow velocity streamlines inside the ducts

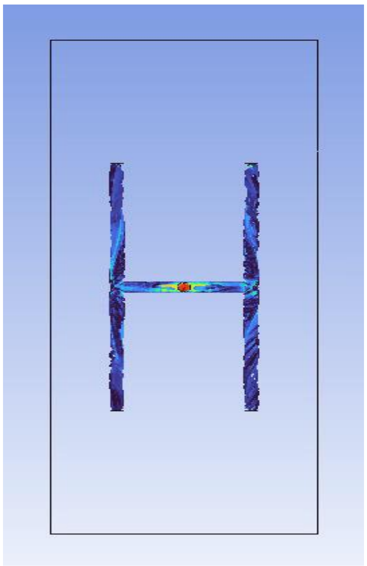


Fig. 7: Top view streamlines of velocity inside ducts

Maintaining controlled airflow velocities in the main duct, plenums, and branch ducts ensures effective mixing of supply air with cabin air without causing draft discomfort or excessive noise. These results indicate that the selected duct configuration and sizing strategy successfully balances thermal performance and passenger comfort.

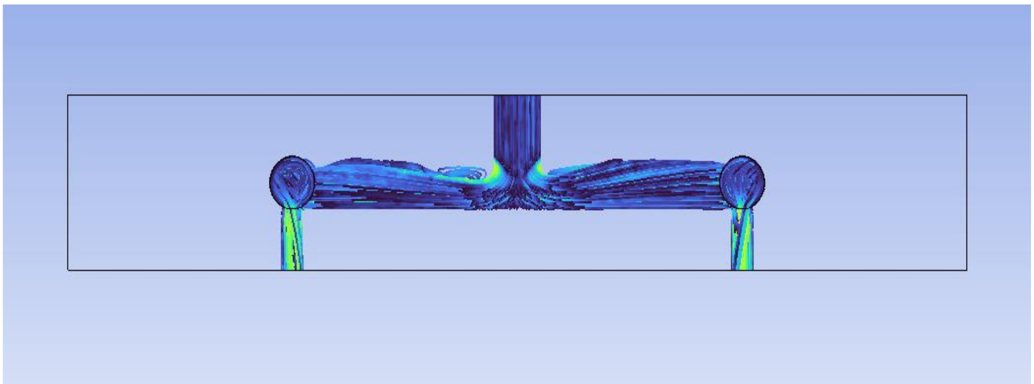


Fig. 8: Front cross-sectional airflow and velocity distribution inside the ducts

D. Output 1) Cooling Unit Capacity Comparison and Performance

Summary:

a) 15 kW Nominal Cooling Capacity: • Sensible Heat Ratio (SHR) varied between 0.60 and

0.679. • Peak cooling coil delivery: 15.00 kW (unit operated at maximum capacity continuously). • Saturation duration: 60 minutes (coil remained fully saturated, indicating insufficient capacity). • Peak electrical power draw (HVAC): approximately 5.35 kW. • Total electrical energy consumption over 1 hour: approximately

4.70 kWh.• Total reheat energy over 1 hour: approximately 0.04 kWh (minimal due to continuous saturation). b) 22 kW Nominal Cooling Capacity: • Sensible Heat Ratio (SHR) range remained unchanged (0.60 to 0.679). • Peak cooling coil delivery: approximately 20.40 kW (coil did not reach the nominal 22 kW limit). • Saturation duration: 0 minutes (unit did not hit capacity limit). • Peak electrical power draw (HVAC): approximately 7.39 kW. • Total electrical energy consumption over 1 hour: approximately 6.90 kWh. • Total reheat energy over 1 hour: approximately 1.13 kWh. c) 26 kW Nominal Cooling Capacity: • Performance results were identical to the 22 kW case. • The cooling coil did not utilize additional capacity beyond approximately 20.40 kW. • No further reduction in saturation, energy consumption, or thermal imbalance was observed. • Increasing nominal capacity beyond 22 kW provided no operational benefit under the evaluated conditions. The total peak cooling load for the bus cabin is 19.26 kW (5.48 TR), comprising 12.72 kW of sensible load and 6.54 kW of latent load, indicating a significant contribution of moisture related loads due to passenger occupancy and ventilation

CONCLUSION

This project investigated the design and analysis of a passenger-adaptive air conditioning system for a bus, addressing the inherent inefficiencies of conventional fixed-capacity HVAC operation. By recognizing passenger occupancy as a dominant and dynamic contributor to cabin heat gain, the study established a framework in which cooling demand is directly linked to real-time usage conditions. The approach emphasizes the importance of aligning thermal supply with actual demand to enhance both passenger comfort and energy efficiency. A comprehensive methodology was adopted that integrated detailed cooling load estimation with airflow distribution and electrical performance evaluation. By accounting for all major sources of sensible and latent heat within the bus cabin, the analysis ensured a realistic representation of operating conditions. The air distribution system was designed to deliver conditioned air uniformly across the passenger zone while maintaining acceptable airflow characteristics, highlighting the role of duct configuration and velocity control in achieving effective thermal management. The results demonstrate that passenger-dependent heat gains and ventilation requirements significantly influence overall cooling demand. This finding validates the central premise that fixed-capacity systems are inherently mismatched to the dynamic nature of bus operation. The proposed passenger adaptive framework provides a technically sound alternative that allows cooling capacity and airflow to be scaled in response to occupancy, thereby reducing unnecessary energy usage during low-demand periods while preserving comfort during peak usage. Further research could involve transient and computational fluid dynamics (CFD) simulations to analyze detailed airflow patterns, temperature gradients, and comfort levels throughout the bus cabin. Such studies would provide deeper insight into local thermal comfort and help refine diffuser placement and duct geometry for improved performance under real operating scenarios, including frequent door openings and partial occupancy.

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