

# **VENTILATION STUDIES ON OPEN WINDOW BUS**

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# **VENTILATION STUDIES ON OPEN WINDOW BUS**

by

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# CERTIFICATE

The thesis entitled “**Ventilation studies on open window bus**” being submitted by **Mr. Pawan Kumar Pant** to the Indian Institute of Technology Delhi for award of the degree of **Doctor of Philosophy**, is a record of original bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirement for the submission of the thesis, which has attained the standard required for a Ph.D. degree of this institute.

The results represented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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# ABSTRACT

Motorized road transport is a significant contributor to poor air quality as well as to the carbon footprint which can be alleviated by a well-designed public transport system. Passenger thermal comfort, especially in warm/hot and humid climates, and safety related to virus transmission, affect the attractiveness of public transport. Thermal comfort can be augmented by air-conditioning which is energy intensive and increases the carbon footprint. Most buses in low/middle income countries where such climates are common not air-conditioned, have open windows, and are crowded. Open windows improve airflow inside the bus and augments thermal comfort. The airflow in these buses with passengers has been studied minimally and an understanding of this airflow can give insights into thermal comfort and airborne virus transmission.

Experimental and numerical investigations have been performed on a naturally ventilated open window bus to understand: (i) the effect of ground condition (moving vs stationary) on flow pattern around a bus, (ii) flow pattern in an around closed and open window bus with passengers, (iii) air borne virus dispersion inside an open window bus, and (iv) change in flow pattern and thermal comfort in an open window bus with ventilation interventions (slots and deflector).

The two simulations with stationary or moving ground for a closed window bus show that the ground boundary conditions weakly affects the flow pattern on the top and sides with minor changes below the floor and in the wake. For this reason, the ground condition is not likely to influence the cabin airflow when windows are open.

The time-averaged flow structures on the top and bottom, and in the wake are almost similar for closed and open window buses. The time-averaged flows at the sides are very different when windows are open as against when they are closed. With open windows, the flow enters the cabin from the rear windows and exits from the front windows and interacts with the oncoming freestream flow and alters the flow structure significantly by forming multiple vortices. Mean velocities inside the cabin are less than 1 m/s. The instantaneous flow around the bus is highly unsteady and three-dimensional. At the top, bottom and sides, multiple sub-vortices are formed in separation bubbles for both Cases. The wake region for both is characterized by multiple sub-vortices and these are affected by window openings. The interior flow structures are affected by

the seated passengers which results in formation of recirculation zones in the vicinity of passengers and in the aisle.

The dispersion of sub-micron particles, representative of virus emanating from the face mask, was studied. Passengers at the window seats in the last rows are safe as they experience outside airflow on their faces. However, if these passengers are infected, they can spread the virus to passengers seated ahead of them. At other seats, an infected passenger could transmit the virus to adjacent passengers. Hence, leaving alternate seats vacant is desirable.

The introduction of one front slot and two rear slots substantially increases flow velocities inside the bus. The number and extent of the separation bubbles at the bus sides decreases. The extent of top and bottom separation bubbles and the wake region are smaller. The drag coefficient decreases by 8 % compared to the open window bus without these slots. Introduction of a deflector along with front and rear slots, and closing of front windows improves air velocities at passenger faces. The drag coefficient is unaffected. These interventions substantially improve flow over passenger face that enhances thermal comfort in hot and humid climates.

Keywords: Open window bus, ground condition, numerical simulation, wind tunnel, air borne virus dispersion, ventilation interventions.

## सार

मोटर चालित सड़क परिवहन खराब वायु गुणवत्ता के साथ-साथ कार्बन फुटप्रिंट में एक महत्वपूर्ण योगदानकर्ता है जिसे एक अच्छी तरह से डिज़ाइन की गई सार्वजनिक परिवहन प्रणाली द्वारा कम किया जा सकता है। यात्री थर्मल आराम, विशेष रूप से गर्म/गर्म और आर्द्र जलवायु में, और वायरस संचरण से संबंधित सुरक्षा, सार्वजनिक परिवहन के आकर्षण को प्रभावित करते हैं। थर्मल आराम को एयर कंडीशनिंग द्वारा बढ़ाया जा सकता है जो ऊर्जा गहन है और कार्बन पदचिह्न को बढ़ाता है। निम्न/मध्यम आय वाले देशों में अधिकांश बसें जहां ऐसी जलवायु आम है, वातानुकूलित नहीं हैं, खुली खिड़कियां हैं, और भीड़भाड़ है। खुली खिड़कियां बस के अंदर वायु प्रवाह में सुधार करती हैं और थर्मल आराम को बढ़ाती हैं। यात्रियों के साथ इन बसों में वायु प्रवाह का न्यूनतम अध्ययन किया गया है और इस वायु प्रवाह की समझ थर्मल आराम और हवाई वायरस संचरण में अंतर्दृष्टि प्रदान कर सकती है।

यह समझने के लिए एक स्वाभाविक रूप से हवादार खुली खिड़की बस पर प्रायोगिक और संख्यात्मक जांच की गई है: (i) बस के चारों ओर प्रवाह पैटर्न पर जमीन की स्थिति (चलती बनाम स्थिर) का प्रभाव, (ii) एक बंद और खुली खिड़की बस में प्रवाह पैटर्न यात्रियों के साथ, (iii) एक खुली खिड़की वाली बस के अंदर हवा से फैलने वाले वायरस, और (iv) वेंटिलेशन इंटरवेंशन (स्लॉट और डिफ्लेक्टर) के साथ एक खुली खिड़की वाली बस में प्रवाह पैटर्न और थर्मल आराम में बदलाव।

एक बंद खिड़की बस के लिए स्थिर या चलती जमीन के साथ दो सिमुलेशन दिखाते हैं कि जमीन की सीमा की स्थिति फर्श के नीचे और जागने में मामूली बदलाव के साथ शीर्ष और किनारों पर प्रवाह पैटर्न को कमजोर रूप से प्रभावित करती है। इस कारण से, जब खिड़कियां खुली होती हैं, तो जमीन की स्थिति केबिन एयरफ्लो को प्रभावित करने की संभावना नहीं होती है।

ऊपर और नीचे समय-औसत प्रवाह संरचनाएं, और वेक में बंद और खुली खिड़की वाली बसों के लिए लगभग समान हैं। जब खिड़कियां खुली होती हैं तो किनारों पर समय-औसत प्रवाह बहुत अलग होते हैं, जब वे बंद होते हैं। खुली खिड़कियों के साथ, प्रवाह पिछली खिड़कियों से केबिन में प्रवेश करता है और सामने की खिड़कियों से बाहर निकलता है और आने वाले फ्रीस्ट्रीम प्रवाह के साथ बातचीत करता है और कई भंवर बनाकर प्रवाह संरचना को महत्वपूर्ण रूप से बदल देता है। केबिन के अंदर औसत वेग 1 मी/से से कम है।

बस के चारों ओर तात्कालिक प्रवाह अत्यधिक अस्थिर और त्रि-आयामी है। ऊपर, नीचे और किनारों पर, दोनों मामलों के लिए अलग-अलग बुलबुले में कई उप-भंवर बनते हैं। दोनों के लिए वेक क्षेत्र कई उप-भंवरों की विशेषता है और ये खिड़की के खुलने से प्रभावित होते हैं। आंतरिक प्रवाह संरचनाएं बैठे यात्रियों से प्रभावित होती हैं जिसके परिणामस्वरूप यात्रियों के आस-पास और गलियारे में पुनरावर्तन क्षेत्र बनते हैं।

फेस मास्क से निकलने वाले वायरस के प्रतिनिधि उप-माइक्रोन कणों के फैलाव का अध्ययन किया गया। अंतिम पंक्तियों में खिड़की की सीटों पर यात्री सुरक्षित हैं क्योंकि वे अपने चेहरे पर बाहरी वायु प्रवाह का अनुभव करते हैं। हालांकि, अगर ये यात्री संक्रमित होते हैं, तो वे अपने आगे बैठे यात्रियों में वायरस फैला सकते हैं। अन्य सीटों पर, एक संक्रमित यात्री आसन्न यात्रियों को वायरस संचारित कर सकता है। इसलिए, वैकल्पिक सीटों को खाली छोड़ना वांछनीय है।

एक फ्रंट स्लॉट और दो रियर स्लॉट की शुरूआत से बस के अंदर प्रवाह वेग में काफी वृद्धि हुई है। बस के किनारों पर जुदाई के बुलबुले की संख्या और सीमा घट जाती है। ऊपर और नीचे के पृथक्करण बुलबुले और वेक क्षेत्र की सीमा छोटी होती है। इन स्लॉट के बिना खुली खिड़की बस की तुलना में ड्रैग गुणांक 8% कम हो जाता है। आगे और पीछे के स्लॉट के साथ एक डिफ्लेक्टर का परिचय, और सामने की खिड़कियों को बंद करने से यात्री के चेहरों पर हवा के वेग में सुधार होता है। ड्रैग गुणांक अप्रभावित है। इन हस्तक्षेपों से यात्री के चेहरे पर प्रवाह में काफी सुधार होता है जो गर्म और आर्द्र जलवायु में थर्मल आराम को बढ़ाता है।

कीवर्ड: ओपन विंडो बस, ग्राउंड कंडीशन, न्यूमेरिकल सिमुलेशन, विंड टनल, एयर बोर्न वायरस फैलाव, वेंटिलेशन इंटरवेंशन।

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# NOMENCLATURE

$\rho$	Density
$\mu$	Viscosity
$c/t$	Chord to thickness ratio
$Re$	Reynolds number
$\tilde{d}$	Distance between wall and first cell
$\Delta$	Largest of three-direction spacing
$C_{DES}$	Detached eddy simulation constant
$f_d$	Shielding function
$r_d$	Ratio of model length scale and wall distance
$\nu_t$	eddy viscosity
$\nu$	Kinematic viscosity
$\kappa$	Karman constant
$u$	Streamwise velocity
$v$	Transverse velocity
$w$	Spanwise velocity
$U$	Free stream velocity
$L$	Length of the bus
$H$	Height of the bus
$W$	Width of the bus
$C_d$	Drag coefficient