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Improving Thermal Comfort and Ventilation in Commercial Buses in Nigeria in Covid-19 Era

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Abstract: *Studies abound on thermal comfort assessment of passenger cabin of various types of cars. Not many are known for commuter buses especially the types common in African cities with hot and humid weather. Also, concerns have been raised on the spread of the corona virus among passengers of these often-overcrowded buses. This study therefore investigates experimentally the level of heat build-up within the passenger segments of Volkswagen minibus, small and big Mercedes Benz 911 commuter buses in Lagos, Nigeria under varying conditions with the aim of suggesting ventilation methods that can mitigate the challenges. Using a sensitive digital thermometer, air temperature in the passenger segment is measured at strategic locations within the bus for varying number of passengers when loading, when in motion and when held-up in traffic. The results show that, when loading, the number of passengers in the vehicle correlates with the rate of metabolic heat generated. While in motion, air temperature drops steadily as the bus speed increases due to cool outdoor air inflow. However, when in traffic, the heat level becomes very high with the temperature up to 41 ºC in some cases. Air convection within such environment encourages the spread of the corona virus. To mitigate the challenges, two cost-effective and efficient ventilation methods are proposed. It is believed that enforcing the implementation of the ventilation methods will not only greatly improve the comfort of the passengers in the buses but also minimize number of passengers getting infected with the corona virus while commuting.*

Keywords: *thermal performance, commuter vehicles, heat build-up, passenger segment, virus infection.*

1. INTRODUCTION

Transportation has always held an essential role in the economic, social and cultural development of any city [1]. Public transportation especially is utilized on a daily basis. Most people spend a significant period of daily life in moving to and from secular places of employment or business. It is therefore necessary that the passenger segment of commuter vehicles be conducive enough to ensure human comfort always. Human thermal comfort is expressed as that state of mind which expresses satisfaction with the thermal environment. It is affected by environmental factors such as air temperature, air speed and relative humidity and personal factors like body metabolic heat and clothing insulation [2]. Thermal comfort consideration is vital in the design of passenger compartment of vehicles due to its significance to human life. In particular, for a commercial vehicle passenger environment, a relatively comfortable temperature and constant fresh air is required as it brings good physical conditions to the occupants. Depending on their activities, people release certain amount of metabolic heat to the surrounding. With good ventilation, the internal human body temperature is maintained at about 37 ºC for a healthy body. ASHRAE Standard 55 [2] recommends that the temperature of a comfortable human environment should be between 22 ºC and 26 ºC. However, if the environmental conditions go beyond the body's temperature regulation ability, the body tries to maintain constant inner temperature by pumping more blood to the skin and open its pores to sweat. A rise in the body temperature occurs which may lead to complex physiological problems [3]. Therefore, to ensure thermal comfort, a number of researchers have employed different models and approaches to assess heat flow patterns within different parts of vehicles [4-8].

In many African cities, the bulk of commuter vehicles used for transportation are from the Western countries and they were not originally designed for such purpose. Unfortunately, most are being used with little or no structural adjustment to meet the new purpose and climate, thereby making the passenger segment poorly ventilated. As a result, there is heat build-up constantly within the segment both due to metabolic heat from the passengers and heat from the vehicle engine (which, in some cases, is within the passenger cabin). Also, it is common for buses to be at standstill on the highway for many hours during traffic jam. Under this condition, if the vehicle is overloaded, the temperature and humidity in the segment could be very high; leading to near suffocation especially if the entrance and exit doors are blocked as in Figure 1. That could put little children and elderly passengers with sensitive heart conditions at health risk. It is worthy of note however that providing a generally comfortable condition inside a bus cabin is difficult due to the unsteady nature of the service, vis-a-vis variation

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with the average journey time per passenger, interval between bus stops, the passenger volume per time, the bus glazed window area varies while outside conditions are highly erratic.

In this Covid-19 era, air circulation within the passenger cabin encourages the spread of the virus infection. According to Public Health Ontario [9], scientists are unclear on how the corona virus spread in passenger compartments. Some said it spreads through the particles in the air, through contaminated sources or by being near an infected person. In order to minimize the risk of COVID-19 infection, some of the measures suggested in [9] include: constant use of face masks by passengers, minimizing crowding of passengers at boarding and off-boarding areas and physical distancing of passengers within the bus through reduction in loading capacity. Others are compliance with entrance and exit areas to prevent passengers' contacts and employing proper ventilation in the vehicles. However, in Lagos, Nigeria, the number of commuter buses at peak periods is not commensurate with the number of commuters. Therefore, crowd control becomes difficult as passengers often rushed the vehicles. Covid-19 protocol becomes impossible to enforce.

Figure 1: Overloaded small 911 bus; with blocked entrance. Courtesy [1]

In the light of this widespread apathy of passengers to comply with the guidelines for covid virus spread prevention, it is therefore imperative that a special technique be developed to vent the passenger segment in buses and make it thermally comfortable for the passengers while controlling the spread of the covid virus. This study therefore aims to develop effective methods to improve the ventilation and minimising the spread of the covid virus within the passenger compartment of large commuter buses using Lagos State as a case study.

2. METHODOLOGY

Three commonly used commuter vehicles in Lagos metropolis, Nigeria were employed in this study. The vehicles are the Volkswagen minibus, the small and big models of the Mercedes 911 buses. The Volkswagen minibus, usually called "Danfo" in Lagos, Nigeria, comes in different models. There are some that have their engines just behind the backseat and there are some that have their engines under the driver's seat. Figure 2 shows the LT 35 model. This vehicle has its engine under the driver's seat with part of it projecting into the passenger segment. Normally, it is for 18 people; 4 passengers per seat of 4 rows with 2 beside the driver. But during rush hour, there could be up to 22 people with 5 people per row. This poses further discomfort to the passengers. The window area of the vehicle is not large enough to allow enough fresh air inflow. Normal human comfort is hardly achieved in these buses especially during hot weather.

The Mercedes 911 bus, fabricated on Mercedes Benz model 911 chassis, is fashioned after the formerly-used American-style school bus. There are two sizes: the small size and the big size. Both have their engines in the bonnet. The small bus, Figure 1, has a capacity for about 60 passengers. The dimensions of the passenger segment are 4.5 m x 2.0 m x 2.5 m resulting in a volume of about 22.5 m^3. The big bus, Figure 2(b), has a capacity for about 80 passengers.

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(a) Volkswagen minibus (b) Mercedes Benz model 911

Figure 2: Common commuter buses in Lagos, Nigeria. Courtesy [10]

2.1 *Experimental Measurements*

The heat exchange interactions in a bus leading to temperature change in the passenger segment are complex. The largely inhomogeneous air temperature distribution within the segment creates an atmosphere that varies significantly with time. According to ANSI/ASHRAE Standard 55 [2], under normal condition, the temperature difference between the floor and the roof should not be greater than 3 °C; else it may lead to thermal discomfort.

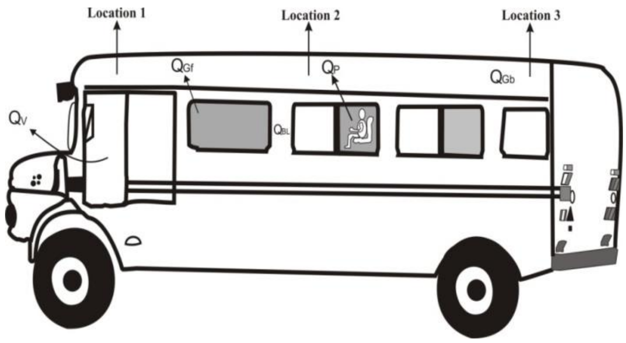

Figure 3: The heat components and the experimental locations

The sources of heat build-up within the passenger segment are: heat through the body of the vehicle Q_B; heat through the window glasses, Q_G; heat from the seats, Q_S; heat from the luggage, Q_{LC}; heat from ventilated air through the windows and doors, Q_V; heat from the passengers, $Q_{P;}$ The heat from the seats, Q_S (because they are upholstered or made of wood) and the heat from the luggage, Q_{LC} (contains mostly non-heat-generating items) are relatively small compared to others and as such are often neglected in analysis. Hence, it could be concluded that heat build-up in the cabin is mainly due to the heat from the passengers, Q_P, heat through the body of the vehicle Q_B and heat from ventilated air through the windows and doors, Q_V.

Ventilation of the passenger segment of the buses depends mainly on air flows through the doors and the sliding windows (which is normally half-opened). The average window area for the Volkswagen mini bus is 0.45 m^2 while the one for 911 bus is 0.73 m^2. Expectedly, the more the number of windows and the higher the vehicle speed, the higher the rate of air flow into the segment to cool it. However, the effect of vehicle speed on air within the segment is limited to air volume near the window and door openings due to passenger congestion.

Thermal comfort within the passenger compartment requires measuring parameters such as air temperature, air velocity and relative humidity. However, measuring each parameter requires a lot of instrumentation and it is difficult to measure all the parameters at the same location simultaneously. Using a digital thermometer having time, date and temperature displays, as shown in Figure 4, the temperature of air in the passenger segment is measured at three different designated locations, indicated in Figure 3, where stagnant hot air is most likely to be within the vehicle. Also, in order to monitor the effect of the interior of the vehicles on the heating of the air within the segment, a multimeter, with a type-K thermocouple, was used to measure the temperatures of the structural parts of the buses. The readings were taken at time intervals till it becomes fairly steady.

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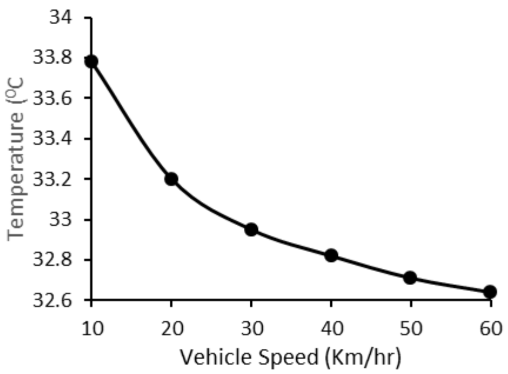
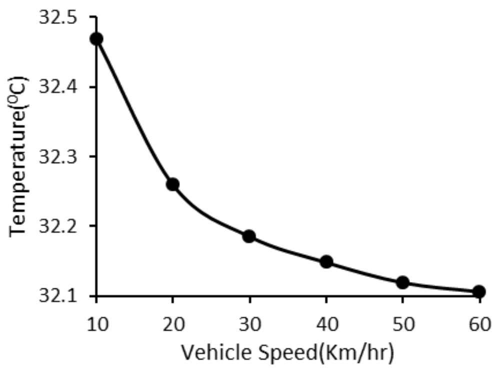
Figure 4: Multimeter and digital thermometer used for temperature measurements

3. RESULTS AND DISCUSSION

The air temperature in the passenger segment of the small and big buses at locations indicated in Figure 3 is measured for different routes and for varying number of passengers. Figures 5-10 show the temperature changes at these locations under different bus loading conditions. It is worthy of note that special compensatory arrangements made with the bus drivers made the measurements under those conditions possible. Therefore, being a real-life experiment that depends on a number of constraints which include the disruption of the bus operations, cost of driver's compensation, constant change in weather conditions and consideration of different scenarios, the measurements per scenario had to be taken while going through three different routes.



(a)



(b)

Figure 5: Cabin temperature against vehicle speed for VCB (a) with the engine under the driver's seat and (b) with the engine at the back

Temperature change at the location behind the driver when the Volkswagen bus with the engine under the driver's seat is in motion is shown in Figure 5(a). The plot shows that, as the vehicle accelerates, there is a quick drop in temperature as cooler air rushes in through the windows to diffuse the heat accumulating within the cabin. As the vehicle speed approaches 60 km/hr, the cabin appears to have been well ventilated. For VCB with the engine at the back, the air temperature is measured at the back passenger seat. As indicated in Figure 5(b), the segment is cooler; most of the heat from the engine is ejected under the bus. The temperature drops faster to that of the outside air when the bus was about 60 km/hr. It can be deduced from the results that ventilation through the windows of the VCB is sufficient to make the passengers thermally comfortable. However, with no COVID-19 protocol observed by the passengers, the continual spread of the virus is inevitable.

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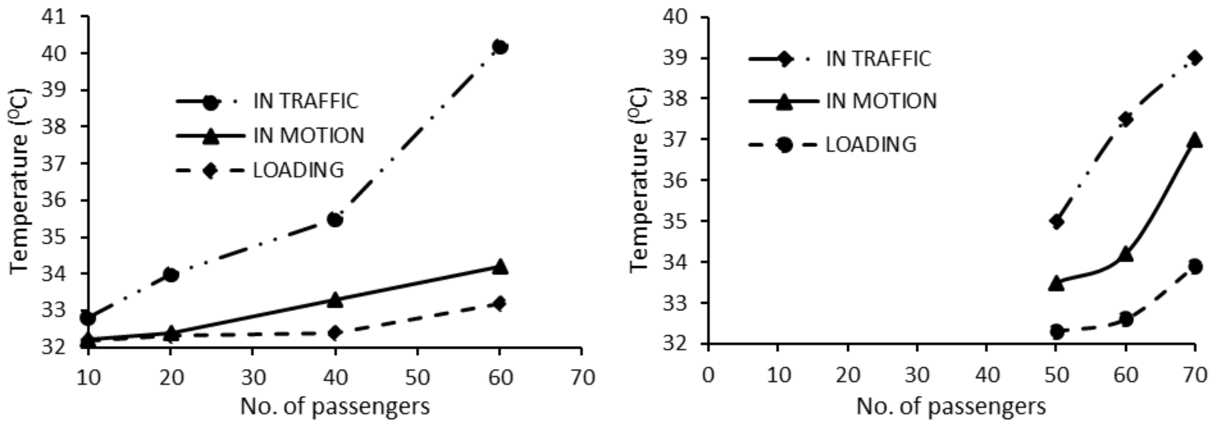

(a) (b)

Figure 6: Air temperature at Location 2 with number of passengers in the (a) small 911 bus and (b) big 911 bus under different bus conditions

Figure 6 shows the air temperature at Location 2 for different number of passengers under three different bus conditions. Figure 6(a) shows when the small 911 bus was loading passengers, when in motion and when held-up in traffic on a day that the ambient average temperature was 32 ºC. It is observed that, under the three conditions, temperature increases with the number of passengers. While loading, the slight increase in air temperature in the passenger segment was mainly due to the metabolic heat from the passengers. Since most of the sliding windows are usually half-opened, heat exchange with the outside air would be limited. As the bus moves, outside air rushes in. This air inflow rate increases with the bus speed. Thus, average temperature within the segment remains relatively low at about 1. 5ºC higher than ambient at full load. When the bus hit the traffic, ventilation reduced drastically. At full load, air temperature shuts up to 40 ºC. This is mainly due to increasing metabolic heat dissipation by the passengers. Under this condition, the tightly-packed passengers usually perspire profusely. At times, the condition could be suffocating; especially when the vehicle is at the middle of the road where passengers could not disembark for fresh air. Studies have shown that this rapid rise in passenger segment temperature is not dependent on outside environmental condition. Rugh *et al.* [11] observed a temperature of 43 ºC in an integrated vehicle when the ambient temperature was 22.3 ºC. Saboora & Man-Hoe [12] put the initial passenger cabin temperature at 46 ºC while cooling a vehicle in South Korea.

In Figure 6(b), the heat build-up trend for the big 911 bus is similar to that observed for the small bus. But, air temperature at location 2 increases at a higher rate in the big bus than in the small bus with the same number of passengers. During loading, with only 50 passengers, the temperature rise is relatively insignificant; indicating that the metabolic heat generated by the paasengers was effectively neutralized by the normal air exchange through the window openings. Therefore, the passengers are comfortable. As the number of passengers increases though, the temperature increases steadily; getting to 34ºC at full load of 70 passengers. Immediately, the vehicle moves. While in motion, at the same full load, the air temperature is observed to have increased by 3ºC. This is because the outside air rushing in is limited to the window areas. When the bus hit a traffic, the temperature rose up to 39ºC. It is pertinent to note that during the rush hours, the number of passengers could be as high as 80. The level of discomfort under this situation is better imagined than experienced. In many African countries, the situation is not too different. Commuters boarding these types of vehicles from time to time expose themselves to a lot of heat which may affect their health thereafter.

To study the thermal evolution within the vehicle with varying number of passengers, air temperature is measured at Location 2, mid-section of the bus, while the small bus is in motion and plotted as shown in Figure 7. For less than 20 passengers, there was no noticeable change in air temperature because the air breeze through the windows and doors effectively neutralized the passenger metabolic heat alongside other possible heat sources. But with more passengers, the metabolic heat increases. But due to cooler air inflow, it could only increase cabin temperature by 2 ºC for 60 passengers. It is worthy of note that in all bus in motion conditions, heat from the metallic body of the vehicle flows into the cabin also on hot days. Despite being in Poland, in the temperate region of the world with outside air temperature of 22 ºC, Gajewski [13] observed a rise of 12 ºC above ambient in a 31-person bus with just 24 passengers.

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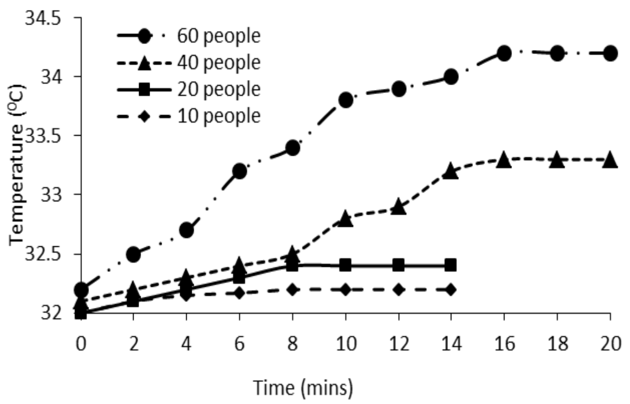

Figure 7: Air temperature variation with time for different number of passengers, at Location 2, when the small bus is in motion

During morning and evening rush hours, heavy traffic is common along most routes. The thermal condition of the cabin at such periods in the afternoon of some selected days was observed. Figure 8 shows the temperature changes with time at Location 2 for different number of passengers while the small 911 bus was in traffic. From the plot, when the number of passengers was only 10, the metabolic heat released was low. The air temperature increase was just marginal above that of the outside air. That implies that there was effective heat exchange between the segment and the bus surrounding. With 20 passengers, the temperature rise doubled. That of 40 passengers was also slightly higher. But, at full load of 60, there was a rapid temperature rise which became steady at about 41ºC. That implies that Location 2 is a hotspot within the cabin. Any covid infected cough or sneeze spread faster through air flow system.

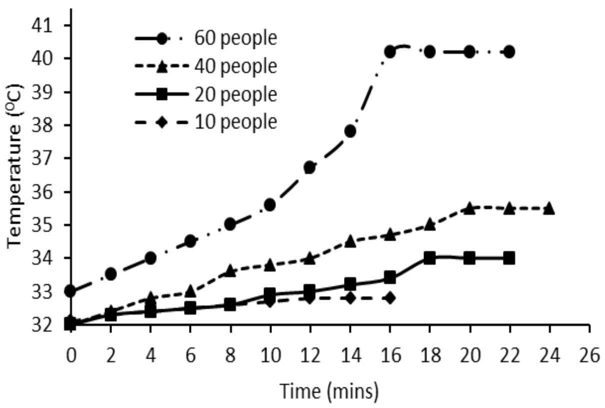

Figure 8: Air temperature changes at Location 2 when the small bus was in traffic

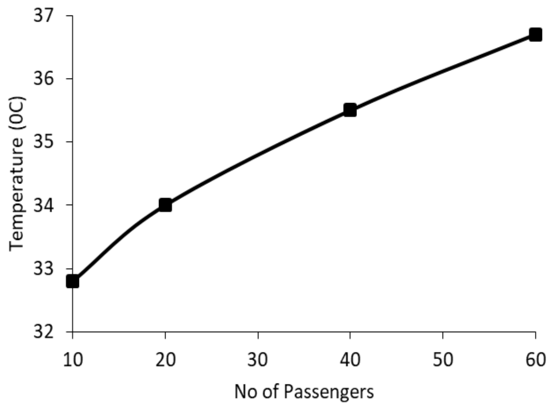

Figure 9: Air temperature at Location 1 when the small bus was in traffic

In traffic, it was observed that air temperature across the segment was not uniformly very high. As shown in Figure 9, air temperature measurements taken at Location 1, near the front door of the small bus, was found to be about 4 ºC less than that at Location 2, the midsection. This is because the entrance door and the door beside the driver create cross ventilation that encourages rapid dissipation of heat around the location. Hence, the breeze would make the passengers sitting within the area to be comfortable when the weather is warm and somehow uncomfortable in cold weather.

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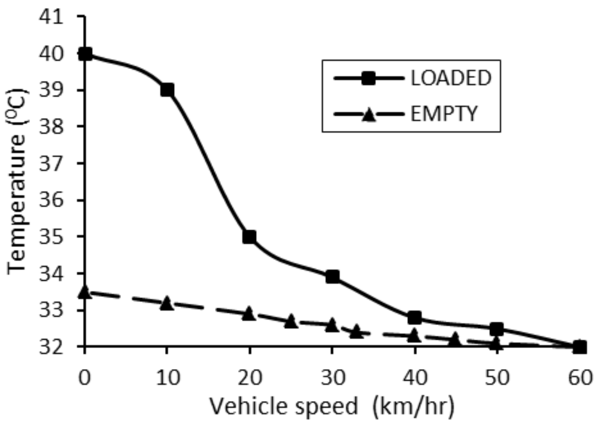

Figure 10: Air temperature with vehicle speed at Location 3 in the big 911 bus when empty and when fully-loaded

To investigate the thermal condition at the back of the passenger cabin, air temperature measurements were taken at Location 3, near the back door, in the big 911 bus. Figure 10 illustrates the temperature of air against bus speed at the location soon after the bus, with full passenger load, came out of traffic. The steady drop in air temperature as the speed increases was due to the increasing rate of cool outdoor air inflow into the passenger compartment through the back door and nearby window openings. Same measurements were taken at the same location with the bus empty. The temperature was just 1 ºC higher than ambient when stationary. With low speed, the cabin space quickly became well-ventilated. Figure 10 then shows that much of the heat at that location when the bus had passengers was mainly metabolic heat.

3.1 *Human Reaction to Hot Environment*

Naturally, a healthy human body maintains internal temperature at about 37 ºC. A change of body temperature exceeding 1 ºC occurs when surrounding condition surpass the body's temperature regulation ability. As the environment warms-up, the body tends to warm-up as well [14]. A rise in the body temperature may result in heat illnesses. In a hotter environment, more complex physiological problems may occur. Iwase *et al.* [3] indicated that the heat stress disorders reportedly suffered by passengers regularly boarding these vehicles may include heat rashes, dehydration and heat exhaustion. It is therefore imperative to have a ventilation system that can maintain comfortable temperature range recommended by ASHRAE [2] within the passenger segment.

3.2 *Recommended Designs*

To maintain a healthy environment that is thermally comfortable for passengers and to minimize the spread of the covid virus within a bus cabin, good ventilation is imperative. In most commuter buses in Nigeria, the natural ventilation relied on is often inadequate. The current steady increase in environmental temperature due to global warming and the current covid 19 pandemic make the situation to get worse. It becomes more germane to improve the indoor air quality of the passenger segments. This paper therefore suggests two methods of ventilation design, namely, (i) displacement ventilation, and (ii) personalized ventilation techniques.

3.2.1 *Displacement Ventilation Technique*

Displacement ventilation system applies buoyancy-driven air convection principle to regulate the thermal condition in an occupied space. With displacement ventilation, the flow of air is maintained by buoyancy forces, which also have effect on the transport of pollutants rising from the floor to ceiling. Rees et al. [15] indicate that there is less likelihood of complaints due to draughts using displacement ventilation and the air is likely to be cleaner as contaminants are removed from the occupied zone. In a bus cabin, stale, hot and contaminated air rises to the bus ceiling to give room for cool fresh air through the window and door openings. This poor-quality indoor air could be extracted out of the vehicle by air-driven ventilators installed on the top of the roof at regular intervals as shown in Figure 11(a). ANSI/ASHRAE Standard 62.1 [16] recommends that effective ventilation rate per passenger should be somewhat higher than 5 litre/s; though depends on the type of vehicle, length of ride, door and window openings, and average passenger occupancy. The installed ventilator us expected to meet this requirement.

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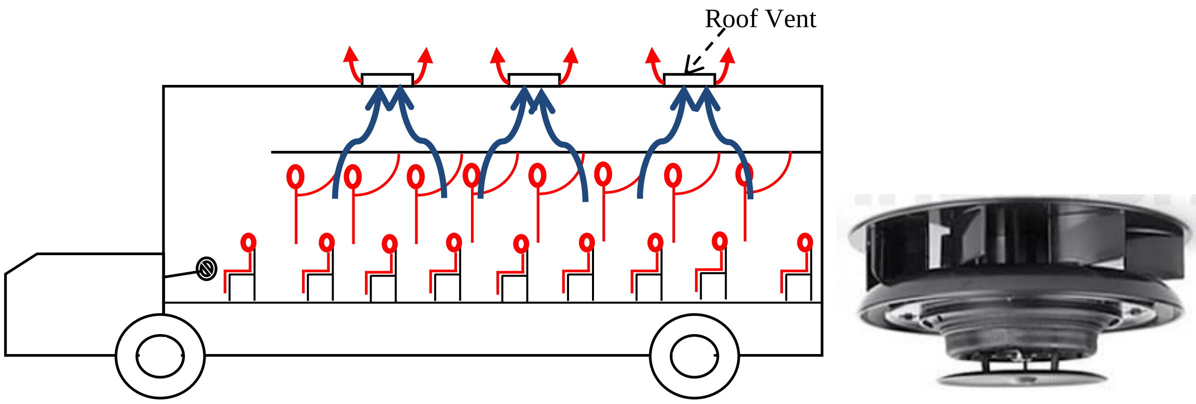
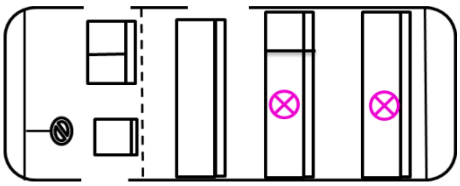


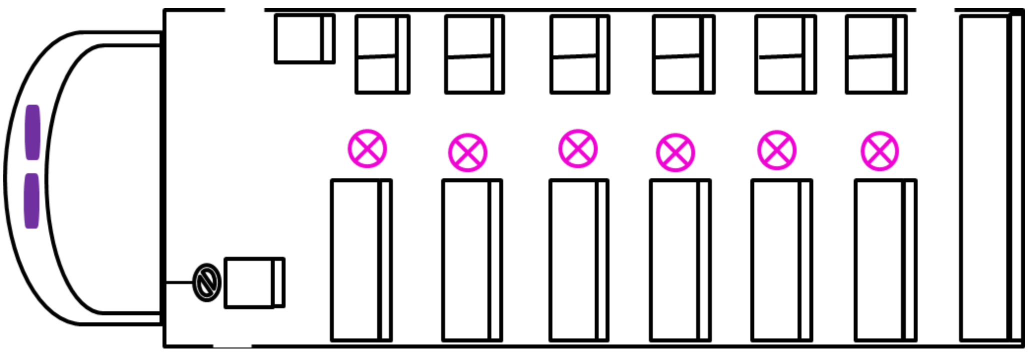
(a) (b)

Figure 11: (a) Passenger segment displacement ventilation design using (b) air-driven ventilator

An air-driven ventilator is available commercially with various blade designs, sizes and materials. It usually rotates in its vertical axis to create updraft inside the casing which extracts air and, in the absence of wind, still ventilate the bus using stack effect. It is installed on top of vehicle roof due to higher wind speeds available there. A typical example is shown in Figure 11(b); a portable, rotary, air-driven ventilator suitable for large commercial vehicles that require air movement within the passenger cabin [17]. It features a push/pull interior trim for opening and closing. It rotates freely while the vehicle is in motion; drawing out stale air. At a wind speed of 40 km/h, air extraction rate (AER) of the ventilator is 1.48 m^3/min. This meets the requirement in [16]. Since AER depends on wind speed and most buses moves between 40 km/h and 80 km/h, AER within this speed range will be 1.5 m^3/min and 3.0 m^3/min. With the space volume of the Volkswagen minibus to be about 8 m^3, it implies 3 ventilators will be required. But due to the multiple openings towards the front side of the bus, 2 ventilators, as arranged in Figure 12(a), are recommended. For the big 911 bus, with passenger segment volume of 22.5 m^3, about 8 ventilators will be required. However, with two entrance doors at the front and one at the back creating effective cross ventilation within the areas, six ventilators are recommended to be installed as shown in Figure 12(b), in order to meet the requirement.



(a)

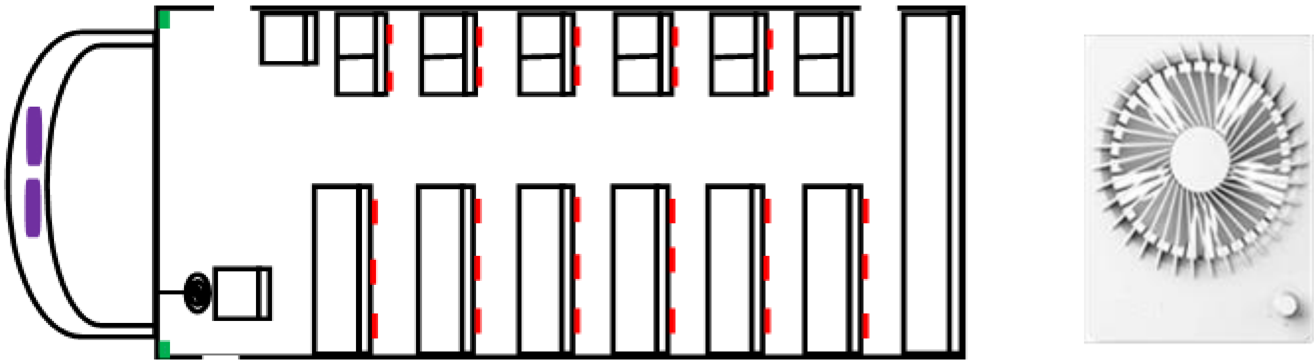


(b)

Figure 12: Recommended arrangement of ventilators in (a) Volkswagen minibus, and (b) big Mercedes Benz 911 bus

3.2.2 *Personalized Ventilation Techniques*

Naturally in most cases, when a bus is mechanically cooled, different locations in the bus are not equally cooled thereby causing discomfort that leads to loss of interest in the usage of such buses for transportation. Melikov *et al.* [18] observed that about half of passengers were dissatisfied with the indoor air quality in some commercial buses even when displacement ventilation system was employed. One method often adopted to improve thermal comfort or indoor air quality in the breathing zone of individuals is the personalized ventilation (PV) technique. PV is a promising air distribution approach that delivers clean air directly to occupants' breathing zone, improving inhaled air quality and reducing contaminant exposure risk [19]. Research has shown that, in a hot and humid climate like Lagos, the use of personalized ventilation systems aimed for improvement of inhaled air quality and thermal comfort has high ventilation effectiveness that is able to provide almost 100% clean air for breathing [20, 21]. With appropriate PV system, passengers can control their environment through control of the air temperature, air velocity, noise level and air quality. With appropriate direct fan speed, PV delivers fresh air directly to the breathing zone with enough momentum to prevent intrusion of harmful contaminants.



(a) (b)

Figure 13: (a) Personalised ventilation design using (b) portable personal fan

Following the arrangement shown in Figure 13 (a), portable, variable-speed, personal fans (indicated in red), such as shown in Figure 13 (b), can be installed at the back of the seats of a bus. The 175 mm x 145 mm, 260 g portable fan with brushless motor runs quietly and steadily without disturbing. When with highest speed of 2500 rpm, it gives out sound of less than 30 dB which is below that audible to human ear [22].

4. CONCLUSION

Heat build-up and the spread of the corona virus within the passenger segment of Volkswagen minibus, small and big sizes of the Mercedes Benz 911 model of commercial buses in Lagos, Nigeria have been investigated experimentally with the aim of developing effective methods to improve ventilation and minimising the spread of the covid virus within the passenger compartment. The following conclusions are made from the results:

(i) When a stationary bus is loading, the number of passengers in the vehicle correlates with the rate of metabolic heat generated; the more the number of passengers, the more the heat generated.
(ii) When the bus is in motion, the heat generated during loading is dissipated steadily as the bus speed increases due to the increasing rate of cool outdoor air inflow.
(iii) When the bus is in traffic and fully loaded, the heat level becomes very high. The back of the minibus and the middle of the 911 buses are found to be hotspots. Human discomfort that encourages actions such as sneezing and splashing of sweat that could spread the covid virus become common.
(iv) To mitigate the challenges, two methods are proposed, namely, displacement ventilation and personalized ventilation techniques. The latter improves on the effectiveness of the former.

Though, some commercial buses in Lagos, Nigeria are used as case studies, the situation is not too different from those in many African countries. It is expected that adopting the ventilation methods recommended and enforcing their installation in all commuter buses without mechanical cooling will go a long way to improve the comfort of commuters and reduce the spread of the corona virus in Africa.

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