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Ventilation Challenges in Costa Rican Urban Public Transport: Implications for Health and Sustainable Mobility

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Abstract

Public transport is essential for achieving net-zero emissions and sustainable urban growth. Yet, the health implications of indoor air quality (IAQ) in these vehicles are often overlooked, especially as passengers may spend hours in these enclosed spaces each day. We assessed IAQ in air-conditioned buses and trains in the metropolitan region of San Jose, Costa Rica. The tropical climate of San Jose means that high temperatures and humidity drive energy-intensive cooling on buses and trains, which rely on fossil fuels. To conserve energy, vehicle windows remain sealed, and air is mostly recirculated, undermining ventilation requirements. Our measurements revealed CO_2 concentrations reaching up to 5000 ppm during a 45 min bus ride. This far exceeds recommended thresholds and highlights significant ventilation deficits. These elevated CO_2 levels are indicative of potential health risks, particularly during prolonged travel. Our findings emphasize the urgent need to redesign air circulation strategies in urban public transport, especially in air-conditioned vehicles, to safeguard public health without undermining sustainability goals. Future research should focus on innovative ventilation solutions that reconcile energy efficiency with occupant well-being, supporting the transition to truly sustainable, net-zero urban mobility.

Keywords: urban air quality; public transport systems; ventilation efficiency; low-carbon mobility; sustainable urban development; rebreathed air volume; airborne transmission; SDG 11

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1. Introduction

The use of heating, ventilation, and air conditioning (HVAC) systems in buses and trains is becoming standard nowadays to ensure passenger comfort [1]. These systems ensure comfortable thermal conditions and protect passengers from traffic noise and pollution. To improve HVAC system performance, passenger cabins have moved from openable windows to sealed windows that passengers cannot operate. Hence, the indoor environmental conditions inside buses and trains become dependent on HVAC systems and how these systems are operated. Achieving adequate air quality in these situations depends on ventilation using outside air.

In tropical regions of the world (classified as "A" in the Köppen–Geiger climate system), such as most of Costa Rica, the outside air is warm and humid. [2]. Before it can be introduced inside the vehicles, the air needs to be conditioned, at the expense of

substantial energy, to get closer to the desired thermal comfort conditions for passengers. The greater the differential in temperature and humidity, and the greater the exchanged volume of air, the greater the energy used by the HVAC system. In a moving vehicle, this means greater fuel consumption and reduced mileage. Thus, ventilating public transport can have an impact on the operating costs of the transportation companies [3–5]. These operating considerations and the upfront costs often mean that ventilation on the vehicle using outside air is neglected and air is mostly recirculated, as illustrated in Figure 1.

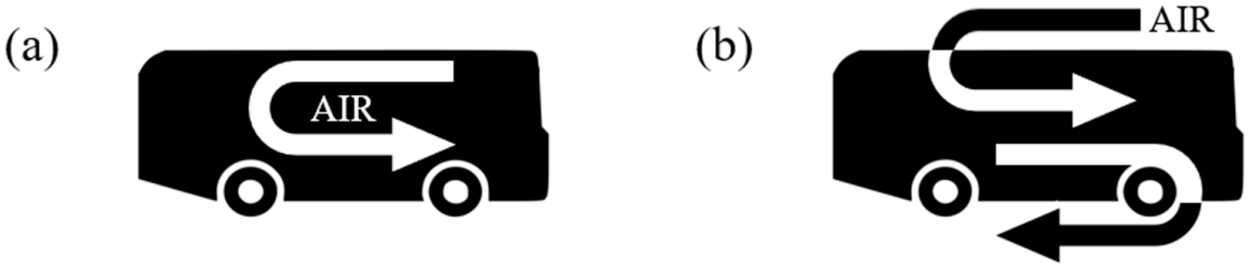


Figure 1. Ventilation modes in public transport. (**a**) Air is recirculated within the vehicle cabin with minimal to no fresh air intake. (**b**) Outdoor air is taken inside, continuously, and conditioned in terms of temperature and humidity for rider comfort.

In Latin America, a significant share of passenger travel—approximately 68%—takes place on public transit or shared systems, and 42% of daily commutes are made by collective transport, based on 29 metropolitan areas, with fleets composed mainly of buses, along with some trains and shared taxis [6]. Although the supply of high-quality public transport has not kept pace with the growth in transport demand [7], buses and trains equipped with HVAC systems are gradually being introduced in Latin America to improve service quality and enhance passenger comfort (e.g., Metro de Panama; EMTU, São Paulo, Brazil; La Rolita, Colombia; and Red Metropolitana, Santiago, Chile).

Unfortunately, the cabin air quality of these vehicles is rarely investigated, meaning little is known about the suitability of air quality for passengers [8]. There are generally no binding regulations governing air quality or thermal comfort inside public transport vehicles in most countries, except some instances [9], including Costa Rica. As a result, the design and operation of HVAC systems are typically at the discretion of operating companies.

The bus sector in Latin America underwent widespread deregulation and privatization in the 1980s and 1990s, resulting in predominantly private ownership in many urban areas [7], with operations largely motivated by profit maximization [10]. As mentioned, public transportation (buses and trains) remains the primary mode of travel for a significant portion of the low- and middle-income population. For instance, the Regulatory Authority for Public Services of Costa Rica (ARESEP) estimates that over 900,000 Costa Ricans use the public bus system daily, nearly 60% of whom have not completed high school [11,12].

While there are ambient air quality standards in many jurisdictions, these do not apply to the air onboard a bus or a train. There are very few jurisdictions, like Hong Kong [9], which have established official guidelines specifying CO_2 concentration limits and thermal comfort ranges for air-conditioned buses and trains.

Recent systematic reviews of indoor environmental quality (IEQ) in passenger transport vehicles reveal a stark geographic and climatic research gap [8]. While multiple detailed CO_2-oriented audits exist for temperate, developed contexts including Tokyo, Hong Kong, and U.S. bus systems, peer-reviewed work from tropical developing regions remains sparse. A comprehensive review of tropical and sub-tropical passenger vehicle IEQ studies confirms this disparity, showing that most research originates from East Asia's

wealthy jurisdictions, with "very limited representation" from Latin America, Sub-Saharan Africa, and South Asia.

This geographic bias is particularly problematic, since, as pointed out earlier in the section, in Latin America public transport systems account for approximately 68% of passenger traffic. The region's unique tropical climate conditions create distinct challenges for public transport ventilation systems. High ambient temperatures and humidity necessitate energy-intensive cooling systems that typically operate in recirculation mode to conserve energy, fundamentally altering indoor air quality dynamics compared to temperate regions.

The few existing tropical studies have predominantly focused on particulate matter pollution, with only eight studies from Malaysia, Nigeria, Brazil, and China addressing broader indoor air quality parameters [8]. Notably absent are comprehensive CO_2 assessments that account for the specific operational constraints of tropical public transport systems, where sealed windows and recirculated air (Figure 1a) become a necessity rather than a choice due to climatic demands.

Within this context, our study aimed to: (i) assess indoor air quality in buses and trains equipped with HVAC systems; (ii) determine whether measured air quality parameters comply with international health and comfort standards; and (iii) estimate potential disease transmission risks using CO_2 concentrations as an indicator of ventilation adequacy. In the absence of specific health-based indoor air quality guidelines for public transport, measured values were compared against international recommendations established for the built environment.

The findings will provide transportation authorities and public health regulators with robust empirical evidence on air quality conditions in HVAC-equipped buses and trains. This evidence can guide the development of data-driven ventilation guidelines and operational strategies that balance energy efficiency, passenger comfort, and health. The results may also motivate public and private operators to adopt targeted measures that reduce passenger exposure to poorly ventilated environments and mitigate the risk of airborne disease transmission.

2. Materials and Methods

2.1. Case Study

The Ciudad Universitaria Rodrigo Facio is the main campus of the University of Costa Rica (UCR). The campus occupies approximately 75 ha. and is located in San Pedro de Montes de Oca, about 3 km from the capital, San José. Total enrollment is around 30,000 students, of which more than 60% use public transport to access the university [13]. In addition to regular bus routes, the Rodrigo Facio campus is served by two train routes and sixteen exclusive staff and student routes that connect the campus with different parts of the Costa Rican Great Metropolitan Area (GMA). The most used means are the regular routes with 32% of the users, followed by the exclusive routes with 26% [13]. No data is available on the number of students traveling by train.

A total of four collective transport routes were selected for this research based on the following eligibility criteria. The primary criterion was that the routes operated at least one bus or train equipped with an HVAC system and a sealed passenger cabin without the possibility of opening windows. Another key factor was that these buses and trains operated during peak hours to allow for air quality assessment under worst-case scenarios. Finally, the selected routes had multiple trips per day, ensuring they carried a significant volume of passengers to the university.

According to the above criteria, the selected bus routes were Alajuela–UCR and Heredia–UCR, and the train routes were Cartago–UCR and Alajuela–Heredia–San Jose–UCR (see Figure 2). Alajuela, Cartago, and Heredia are, with San Jose, the most populated

cities of the GMA. To the best of our knowledge, this is the first study to systematically compare bus vs. train CO_2 levels under identical tropical climatic constraints.

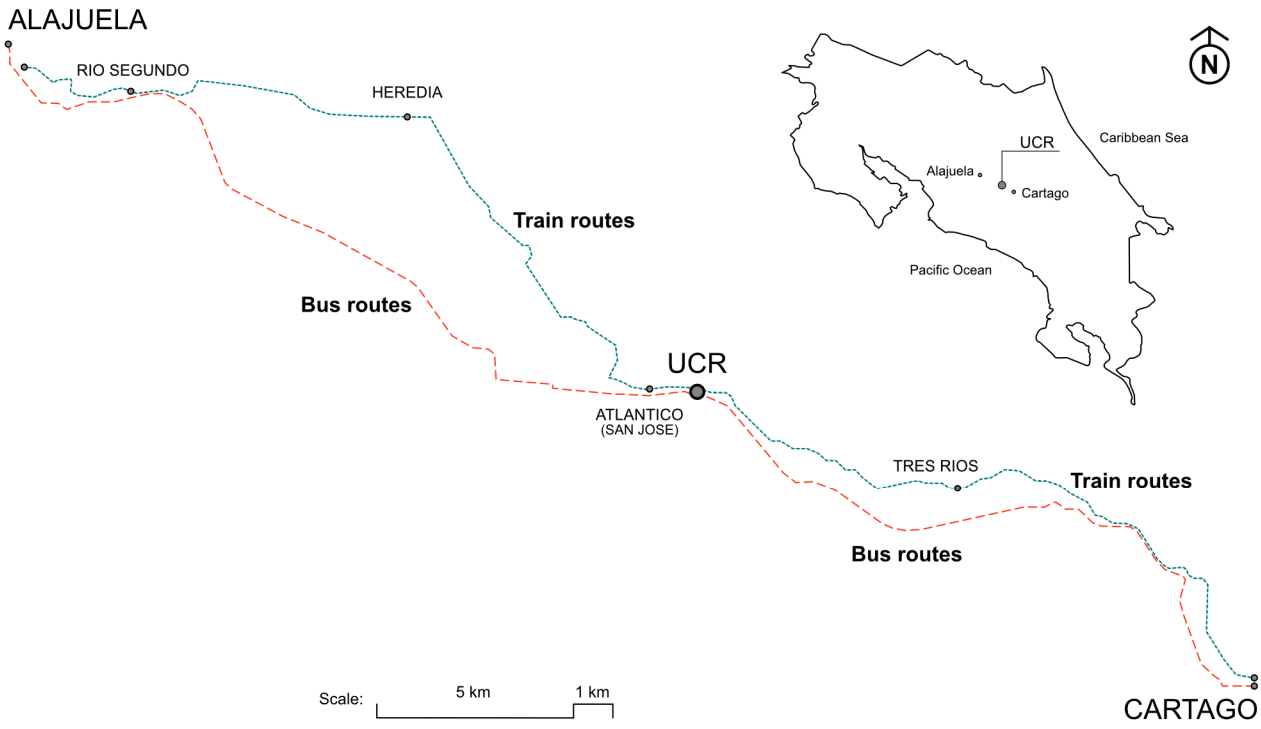


Figure 2. The map shows the location of the cities and the selected bus routes (large, dashed line) and train routes (small, dashed line) in the central region of Costa Rica. The names of the other major train stops on the route are also shown on the map.

2.2. Collective Transport Routes

Buses in Costa Rica are owned by private companies [10]; thus, coach type, size, and conditions vary depending on the company. A single company can run several types of buses on the same route. Therefore, during the measuring period, research assistants traveled in both AC and non-AC buses, from which we selected only those journeys carried out in AC buses.

On both the Alajuela and Heredia routes, bus models consist of double seats on each side, separated by an aisle. The coach's capacity is around 50 seated passengers, and a certain number of standing passengers are allowed. Buses are loaded using the front door 15 to 20 min before departure, and passengers pay the fare as they board. Seating is unassigned, allowing passengers to choose their seats upon entry, except for designated seats reserved for individuals with disabilities.

To prevent routes that provide exclusive service to the University of Costa Rica from competing with regular routes, the Public Transportation Council—the entity responsible for regulating public transport in Costa Rica—allows the UCR-exclusive routes to make only a limited number of stops on the route when the bus is headed to or from the university. Therefore, for most of the journey, the bus does not stop, and the doors remain closed. Once the bus arrives at the last stop, all passengers exit, and the bus starts a new journey.

The investigated trains in Costa Rica consist of two Diesel Multiple Units (DMU) built by the Chinese company CRRC Qingdao Sifang Co. (Qingdao, China) Each unit is 30 m long and has four entrances on each side. The total capacity is 188 passengers per car, with 74 seated on side-placed seats and 114 standing.

The journey between Alajuela and UCR is 23 km and includes ten stops: four between Alajuela and Heredia, and six between Heredia and UCR. These stops are mandatory. There

are two travel options: the first is to take the train to Heredia and transfer to another train to UCR. The second option is to travel from Alajuela to San José (Atlántico Station) and then either take the train one more stop toward Cartago to reach UCR or take a taxi directly from the Atlantico Station.

Between Cartago station and San Jose, the distance is 18.6 km and there are five stops. This route can be completed on a single train line.

Except for the journey between Tres Rios and Cartago stations, which lasts 24 min, travel times between other stations range from 4 to 9 min (median = 5 min). Trains stop at all stations, open all doors on one side, and wait about 30 s for passengers to board or alight. Passengers pay the fare once they are inside the train.

2.3. On-Site Measurements

Between September and November 2022, we collected CO_2 measurements with the help of an experimenter and three research assistants who volunteered to carry the measurement equipment during their regular journeys on selected train and bus routes. As regular users of these routes, the volunteers maintained their typical travel schedules to ensure the data reflected normal conditions.

We securely attached dataloggers with CO_2 sensors (specifications of the equipment are provided in Section 2.4) to their backpacks (see Figure 3f). While standing, the volunteers wore the backpacks on their backs, and when seated, they placed them as far as possible from their nose and mouth—as well as from other passengers—to prevent artificially elevated CO_2 readings.



Figure 3. Pictures a to c present the exterior (**a**) and interior cabins (**b**,**c**) of the Diesel Multiple Unit (DMU) trains. Pictures (**d**,**e**) show the exterior and interior of the buses, respectively. Picture (**f**) displays the CO_2 measurement equipment and illustrates how the sensors were securely attached to the backpack.

Most journeys the one experimenter and three research assistants made covered nearly the entire route, with trips typically beginning at or near the starting stop and continuing to the end or close to it. Seating positions varied between trips to capture a range of conditions.

To ensure that operating conditions remained typical, we did not inform the bus and train companies, or the drivers, that measures were being taken.

2.4. Measurement Equipment

The equipment we used for environmental measurements consisted of HOBO model MX-1102 (Onset, Bourne, MA, USA) mobile data loggers, which primarily measured CO_2. Temperature and relative humidity were also recorded. We assigned one device to each route, and all devices were calibrated beforehand according to the supplier's manual. The logging frequency was set to three minutes. We used the HOBOware (Onset, Bourne, MA, USA) monitoring software (Version 3.7.23) to program, launch, and read data from the loggers [14]. We first performed a manual calibration with outdoor air as reference, following the procedures recommended by the manufacturer. After that, we checked the measurements of all four devices and selected the three that showed the closest agreement for this study. Prior to each usage, the monitor was calibrated against outdoor air as reference, again, following manufacturer's recommendations.

The equipment remained switched on throughout the entire measurement period. Measurements taken during transport were subset from the complete dataset using the drop-in and drop-off information reported by the volunteers, along with time schedules. The subset included data from 10 min before and after each journey.

2.5. Carbon Dioxide Concentrations as an Indicator of Ventilation Levels and Infection Risks

Carbon dioxide has served as a reliable ventilation indicator for over a century due to its direct relationship with human occupancy and exhaled breath [15]. Elevated CO_2 levels are linked to mucous membrane irritation, headaches, fatigue, and increased risks of respiratory infections [16].

Carbon dioxide concentrations can be used to estimate the rebreathed air fraction—the proportion of exhaled air inhaled by others. Rebreathed air fraction is a key determinant of airborne transmission risks, as illustrated by the Rudnick–Milton model [17].

While CO_2 monitoring is a useful tool, it should not be treated as an "end all" means for risk evaluation. There is no universal CO_2 threshold that accurately reflects risk, as factors like occupant activity, masking, community spread, and time spent indoors all play a role. Individual differences and other CO_2 sources (e.g., vehicles, cooking) further complicate interpretation. Air cleaners reduce aerosols but not CO_2, requiring adjusted risk estimates. Point-in-time CO_2 readings offer only momentary insight, while continuous monitoring is needed for ventilation assessment, which itself varies with outdoor conditions. Despite these limitations, low-cost CO_2 monitors remain valuable for large-scale risk indication.

2.6. Analysis

We conducted the data curation and analysis using R Core Team software, version 4.4.1 [18]. Our analysis process began by importing CSV files containing continuous measurements collected with the HOBO devices over the three-month measurement period. Since the HOBOs measured continuously throughout the entire experimental phase—not just during the trips—we downloaded the data using the HOBO Ware program whenever a device's memory reached its storage capacity. We then exported the data to CSV format before relaunching the device for ongoing data collection.

We uploaded and combined the CSV data files for each route separately. Once we obtained a complete measurement file for each route, we subset the journeys based on the drop-in and drop-off information, along with the time schedules reported by the volunteers.

Each journey was labeled with the route name, date, entry time, and exit time, which allowed us to estimate travel times.

We also verified that the drop-in and drop-off information aligned with the CO_2 measurements. Since the volunteers walked to and from the bus and train stops, it was essential for the entry and exit times of the transport to align with significant changes in CO_2 levels, marking the transition from outdoors to inside a vehicle.

Finally, for each journey, we estimated the median and 95th percentile CO_2 values, as well as the percentage of time that CO_2 levels exceeded 800 ppm. This threshold of 800 ppm corresponds to a rebreathed air fraction of 1%. Increased median CO_2 levels have been shown to be associated with increased risks of disease transmission [19].

2.6.1. Estimation of the Rebreathed Air Fraction

Based on the median CO_2 values measured during the journeys, we estimated the rebreathed fraction (f), which represents the proportion of indoor air that consists of previously exhaled breath. In other words, it quantifies the amount of air a person inhales that has already been exhaled by others. Rudnick and Milton [17] proposed that the rebreathed fraction can be calculated using CO_2 measurements, as shown in Equation (1):

$$f = \frac{V_e}{V} = \frac{C - C_o}{C_a} \quad (1)$$

where Ve is the equivalent volume of exhaled breath contained in indoor air, V is the volume of the shared air space, C is the volume fraction of CO_2 in indoor air, and C_o is the volume fraction of CO_2 in outdoor air. C_a is the volume fraction of CO_2 added to exhaled breath during breathing. At low levels of oxygen consumption, such as office work, sitting at a desk, or sitting inside a vehicle, the CO_2 production rate and breathing rate are approximately 0.30 L/min and 8.0 L/min, respectively, giving a C_a of 0.038.

2.6.2. Estimation of Rebreathed Air Volume

For each time point where the CO_2 level was logged, i.e., every 3 min, the CO_2 concentration average was taken for the time point and the subsequent time point. Using this averaged CO_2 level, a rebreathed air fraction was calculated for this 3 min duration. Assuming, for seated people, a breathing frequency of 16 breaths per minute—which is an average of the 12 to 20 breaths per minute that is normal for healthy adults [20]—and a breath volume of 0.5 L [21], we used the rebreathed air fraction to calculate an estimate of rebreathed air volume during each trip.

Since exhaled air can contain aerosols carrying potentially infectious particles, the risk of airborne transmission of infectious diseases increases with greater volume of rebreathed air.

3. Results

We present here the results derived from the dataset of CO_2 concentrations measured inside the train and bus cabins during regular schedule trips to and from the main campus of the University of Costa Rica (UCR) across the Costa Rican Great Metropolitan Area (GMA).

3.1. Trip Descriptions

The dataset comprised 37 monitored journeys across several routes, including UCR–Cartago, Cartago–UCR, Río Segundo–Heredia, Heredia–Atlántico, Atlántico–Heredia, Heredia–Río Segundo, and UCR–Heredia (see Figure 2). Trip durations varied depending on the route and time of day (mean = 40.1 min, SD = 14.7); however, all shorter trips occurred on the Río Segundo–Heredia and Heredia–Río Segundo routes. Morning trips

lasted between 14 and 51 min, while afternoon and evening trips ranged from 19 to 78 min. On one train trip and five bus trips, CO_2 concentrations reached or exceeded 5000 ppm—the upper limit of our measuring device.

3.2. Summary Statistics

As an initial step, a descriptive statistical analysis was conducted to summarize the key features of the dataset. This has been summarized in the form of an epidemiology style Table 1. As CO_2 concentration was our primary concern, for the 37 trips, the data was classified into tertiles based on median CO_2 concentrations during each trip: Low (N = 13), Medium (N = 12), and High (N = 12) tertiles.

Table 1. Summary statistics of the trips: an "epidemiology style Table 1". Data summarized as median [5th, 95th] percentiles.

	Low (N = 13)	**Medium (N = 12)**	**High (N = 12)**	**Total (N = 37)**
Median CO_2 during trip (ppm)	1456 [859, 1965]	2364 [2113, 2818]	4210 [3123, 5000]	2354 [908, 5000]
Median temperature during trip (°C)	22.0 [19.0, 24.4]	22.0 [20.6, 25.9]	23.0 [19.6, 26.4]	22.0 [19.0, 26.2]
Median relative humidity during trip (%)	74 [56, 89]	58 [46, 77]	58 [46, 77]	63 [46, 85]
95th percentile of CO_2 during trip (ppm)	1702 [1181, 2276]	2935 [2474, 3378]	4930 [3536, 5000]	2820 [1225, 5000]
Trip length (minutes)	22.0 [14.6, 54.6]	40.5 [34.1, 49.3]	49.5 [43.7, 71.4]	42.0 [15.8, 61.2]
Fraction of time over 800 ppm CO_2 (%)	94.0 [63.6, 100.0]	94.0 [87.0, 100.0]	94.0 [93.0, 100.0]	94.0 [72.0, 100.0]
Rebreathed air fraction (%)	2.7 [1.2, 4.1]	5.2 [4.5, 6.3]	10.0 [7.2, 12.1]	5.1 [1.3, 12.1]
Rebreathed air volume (L)	5.4 [1.4, 14.7]	15.2 [12.2, 22.8]	35.5 [24.8, 66.2]	15.7 [1.8, 45.3]
Route of the trip				
Alajuela–UCR	0 (0%)	0 (0%)	1 (8.3%)	1 (2.7%)
Atlantico–Heredia	4 (30.8%)	0 (0%)	0 (0%)	4 (10.8%)
Cartago–UCR	2 (15.4%)	7 (58.3%)	4 (33.3%)	13 (35.1%)
Heredia–Rio Segundo	6 (46.2%)	0 (0%)	0 (0%)	6 (16.2%)
Heredia–UCR	1 (7.7%)	5 (41.7%)	7 (58.3%)	13 (35.1%)
Mode of public transport				
Bus	1 (7.7%)	0 (0%)	8 (66.7%)	9 (24.3%)
Train	12 (92.3%)	12 (100%)	4 (33.3%)	28 (75.7%)

The table provides trip duration, median temperature and humidity during the trips (a reflection of thermal comfort during the trips), 95th percentile of CO_2 concentrations (representative of ventilation on board the vehicles), fraction of trip time over 800 ppm CO_2 concentration, rebreathed air fraction, and rebreathed air volume (all representative of infection transmission risks), as well as the mode of transport and the route. As the CO_2 levels exceeded the instrument limit of 5000 ppm on six trips (as described in Section 3.1), we could not calculate precise values for these trips.

3.2.1. Ventilation Metrics and Infection Risk Indicators

The median CO_2 concentrations were 1456 ppm for the Low tertile, 2364 ppm for the Medium tertile, and 4210 ppm for the High tertile. Correspondingly, the 95th percentile CO_2 values increased across tertiles: 1702 ppm, 2935 ppm, and 4930 ppm. The fraction of trip time spent above 800 ppm CO_2 remained consistently high across all tertiles at 94.0%, though the interquartile ranges varied: [63.6, 100.0%] for Low, [87.0, 100.0%] for Medium, and [93.0, 100.0%] for High tertiles.

Rebreathed air fraction, as expected, also showed a clear progressive increase across CO_2 tertiles: 2.7% [1.2, 4.1] in the Low tertile, 5.2% [4.5, 6.3] in the Medium tertile, and 10.0% [7.2, 12.1] in the High tertile. Similarly, rebreathed air volume increased substantially from Low to High tertiles: 5.4 L [1.4, 14.7], 15.2 L [12.2, 22.8], and 35.5 L [24.8, 66.2].

3.2.2. Trip Characteristics, Transport Modes, and Routes

Trip duration demonstrated a positive association with CO_2 tertiles, with median durations of 22.0 min [14.6, 54.6] for Low, 40.5 min [34.1, 49.3] for Medium, and 49.5 min

[43.7, 71.4] for High tertiles. This indicates that longer trips lead to greater possibilities of being exposed to higher CO_2 levels.

Median temperature showed a slight increase across tertiles: 22.0 °C [19.0, 24.4], 22.0 °C [20.6, 25.9], and 23.0 °C [19.6, 26.4] for Low, Medium, and High tertiles, respectively. Median relative humidity did not follow a consistent pattern, being highest in the Low tertile at 74% and similar in Medium and High tertiles at 58% for both. While the temperature data indicated that it was mostly within thermal comfort ranges, humidity levels often exceeded 50%.

Train trips predominantly occupied the lower CO_2 tertiles, comprising 92.3% of Low tertile trips and 100% of Medium tertile trips, but only 33.3% of High tertile trips. Conversely, bus trips were heavily concentrated in the High tertile, representing 66.7% of these trips, with minimal representation in Low (7.7%) and no representation in Medium tertiles. Route-specific patterns emerged, with the Heredia–UCR and Cartago–UCR routes showing the most diverse distribution across tertiles, while the Heredia–Rio Segundo and Atlantico–Heredia routes were exclusively represented in the Low tertile.

The highest recorded 95th percentile values—reaching 5000 ppm—were observed on trips along the Heredia–UCR bus routes. Some Cartago–UCR trips also reached values over 4900 ppm. Intermediate values were observed on the Heredia–Atlántico and Atlántico–Heredia routes.

Overall, the data in Table 1 suggest substantial CO_2 accumulation inside both train and bus cabins, particularly during longer trips. These findings point to the need for targeted interventions to improve in-cabin air quality, although even shorter routes showed persistent ventilation challenges.

3.3. Trip Duration and Infection Transmission Risk Relations

The scatter plot analysis (Figure 4) revealed distinct patterns in the relationship between trip duration and CO_2 concentrations across transport modes. For the 95th percentile CO_2 measurements, train trips (represented by green dots) consistently demonstrated lower CO_2 concentrations across all trip durations, with values generally ranging from approximately 1000 to 3000 ppm regardless of trip length. In contrast, bus trips (orange dots) showed considerably higher 95th percentile CO_2 concentrations, with values extending up to 5000–6000 ppm, particularly for longer duration trips.

The median CO_2 concentrations followed a similar pattern, but with less pronounced differences between transport modes. Train trips maintained relatively stable median CO_2 levels between 1000 and 2500 ppm across varying trip durations, while bus trips exhibited greater variability and generally higher concentrations, with several trips exceeding 3000–4000 ppm median CO_2 levels. Both transport modes showed some degree of positive correlation between trip duration and CO_2 concentrations, though this relationship was more pronounced for bus trips.

The relationship between trip duration and rebreathed air fraction demonstrated clear modal differences. Train trips consistently maintained lower rebreathed air fractions, typically ranging from 0.01 to 0.08 (1–8%) across all trip durations. Bus trips exhibited substantially higher rebreathed air fractions, with values extending up to 0.12–0.15 (12–15%). Most bus trips with durations exceeding 40 min showed rebreathed air fractions above 0.06 (6%).

Rebreathed air volume showed the most pronounced differences between transport modes. Train trips generally maintained rebreathed air volumes below 20–30 L even for longer journeys, with most trips showing volumes under 15 L. Bus trips demonstrated substantially higher rebreathed air volumes, with several trips exceeding 50–70 L, particu-

larly for journeys longer than 40 min. The longest bus trips showed rebreathed air volumes approaching 80 L, representing a four-fold increase compared to typical train trip values.

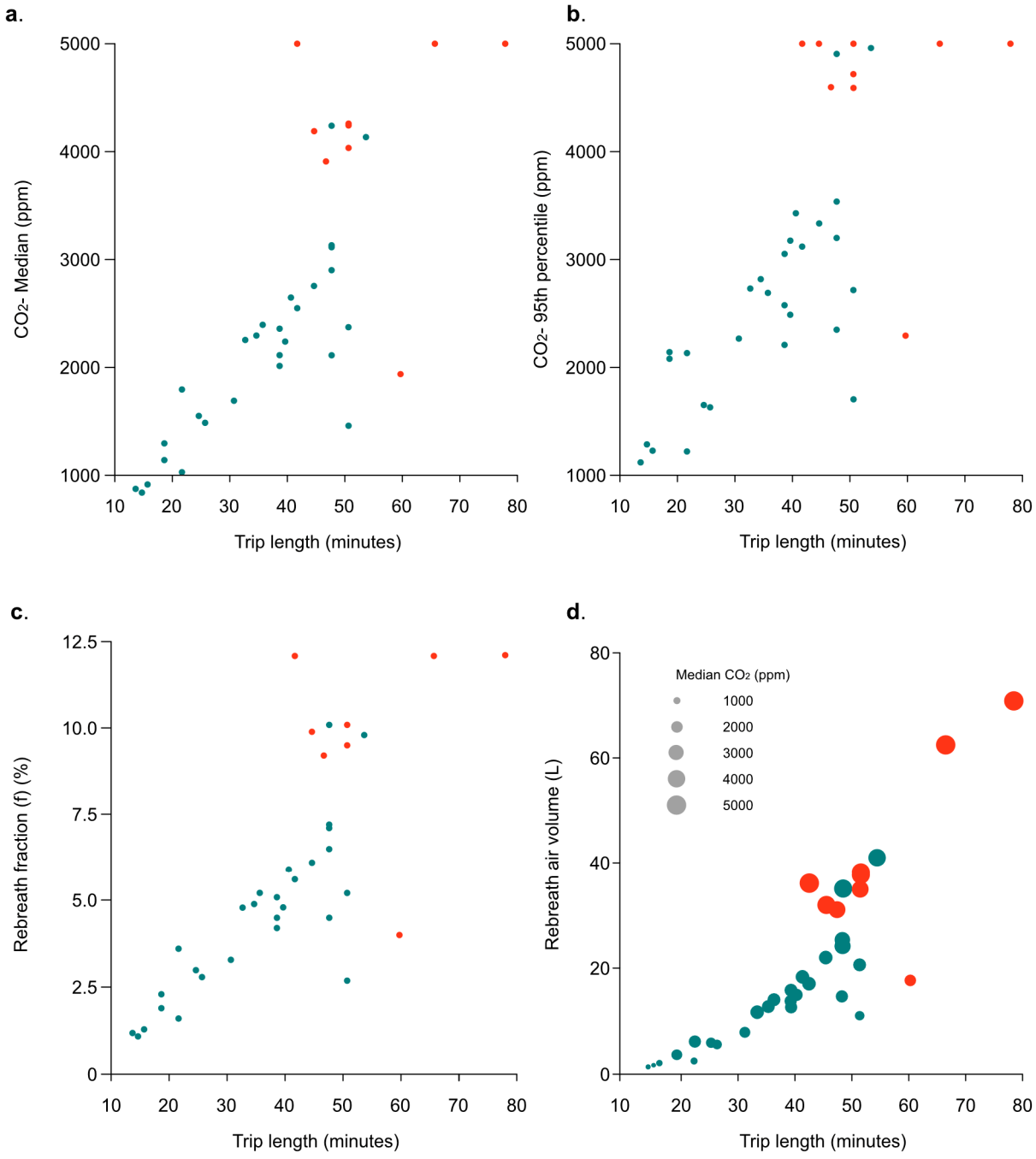


Figure 4. Scatter plot showing the relation between the train and bus trip duration and CO_2 measurements ((**a**) median, (**b**) 95th percentile), rebreathed air fraction (f) (**c**) as the proportion of air composed of previously exhaled breath, and rebreathed air volume (**d**). Teal and red dots correspond to train and bus trips, respectively.

The scatter plots revealed clear clustering patterns by transport mode across all measured ventilation and infection risk parameters. Train trips formed a distinct cluster in the lower ranges of all metrics (CO_2 concentrations, rebreathed air fraction, and rebreathed air volume), while bus trips showed a greater dispersion and consistently higher values. This clustering was most pronounced for rebreathed air volume, where the separation

between train and bus trips was nearly complete, with minimal overlap between the two transport modes.

4. Discussion

Overall, the results highlight widespread challenges in maintaining good indoor air quality across public transportation modes in the GMA, with more severe issues observed in buses than in trains, a finding that compares well with the relevant literature [8,22]. Future investigations should consider real-time measurements of occupancy, door opening events, outdoor weather conditions, and ventilation rates to better understand the dynamics of CO_2 buildup inside moving vehicles.

Our quantification of rebreathed air volumes (ranging from 1.8 to 66.2 L per trip) establishes the first baseline measurements for health risk assessment in tropical developing region public transport. These data enable evidence-based policy development for the estimated 200 million daily public transport users across Latin America [7], filling a critical gap that has hindered region-specific health protection standards.

4.1. Transport Mode Differences and Ventilation Performance

The striking disparity in CO_2 concentrations between train and bus trips reflects fundamental differences in ventilation design and passenger density management. Trains demonstrated superior ventilation performance, with most trips falling within the Low and Medium CO_2 tertiles, suggesting better air exchange rates and a lower air recirculation fraction. Trains had the advantage of more frequent stops where the doors open, allowing for air exchange with the outside (see Figure A1 in the Appendix A). It may also be noted that the passenger cabin of a train has an effective volume several times larger than a bus. This is because each train comprises two interconnected coaches where each coach is similar to or larger than the size of a bus. As these coaches are interconnected, the effective volume of the passenger cabin is larger for the trains than the buses, which slows the rate of increase in CO_2 concentration in the trains.

Such differences in CO_2 accumulation and rebreathed air between the transportation modes have also been noted in studies performed in South Africa, examining transmission of tuberculosis on board public transport [23]. Similar studies have shown higher risks of transmission aboard public transport, as compared to other congregate public settings [24]. This implies that the public transportation system can also present a suitable target for interventions to reduce airborne transmission in community settings.

Our findings of CO_2 concentrations reaching 5000 ppm during bus travel represent the first quantitative documentation of such extreme ventilation deficits in Central American public transport. These values exceed by nearly 100% the highest concentrations reported in previous tropical studies, where maximum levels typically ranged from 2000 to 3000 ppm in similar air-conditioned vehicles [8]. The stark difference likely reflects the unique operational constraints of the Costa Rican tropical climate, where energy conservation pressures lead to more aggressive recirculation strategies.

The concentration of bus trips in the High CO_2 tertile (66.7%) indicates significant ventilation challenges in the urban bus fleet studied. The maximum levels reached 5000 ppm, which goes beyond the 1000 ppm to 3000 ppm levels recorded for buses in several prior studies [8,25–27]. This pattern may reflect several factors, including higher passenger density relative to vehicle volume, more frequent door openings that disrupt air circulation patterns, and potentially different operational practices regarding mechanical ventilation use.

The clustering of train trips in the lower ranges of all ventilation metrics (in Figure 4) suggests that rail transport infrastructure provides more consistent and effective air quality

management. However, the results could be an artefact of the larger effective volume in rail transport and the more frequent stops.

4.2. Route-Specific Ventilation Patterns and Operational Factors

The route-specific distribution of CO_2 levels reveals important operational and infrastructure-related factors. The Heredia–UCR route's predominance in the High tertile (58.3% of High tertile trips) suggests that this route puts the highest exposure risks on the passengers. This could be attributed to longer trip segments without adequate air exchange, higher passenger loading factors, or the use of older/less well-maintained vehicles on this route. Conversely, routes like Heredia–Rio Segundo and Atlantico–Heredia showed exclusively Low tertile CO_2 concentrations, indicating consistently better ventilation performance. The Cartago–UCR route showed the most balanced distribution across all tertiles, suggesting heterogeneous conditions or mixed vehicle types serving this route.

4.3. Trip Duration and CO_2 Accumulation Dynamics

The clear positive association between trip duration and CO_2 tertile classification demonstrates the time-dependent nature of CO_2 accumulation in enclosed transport environments. Longer trips provide more opportunity for CO_2 buildup, particularly in vehicles with inadequate ventilation rates relative to passenger loads.

The rebreathed air metrics show a particularly concerning escalation across tertiles, with the High tertile showing nearly four-fold higher rebreathed air fractions (10.0% vs. 2.7%) and more than six-fold higher rebreathed air volumes (35.5 L vs. 5.4 L) compared to the Low tertile. These substantial differences underscore the potential for significantly elevated infection transmission risks in poorly ventilated vehicles, especially during longer journeys. In high-density occupancy like public transport where the air may not necessarily be homogeneous and an infectious co-passenger may be physically close to susceptible passengers, there are added risks from close range transmission [28]. So, the rebreathed air fraction may be treated as a conservative expression of the overall risks.

The relation between trip duration and air quality degradation was particularly evident in bus trips. For bus trips, the steeper slopes in the duration–ventilation relationships suggest the current ventilation systems' inadequacy for the longer journeys.

The rebreathed air volume metric showed the most dramatic duration-dependent increases, particularly for bus trips, where values could exceed 70–80 L for longer journeys. This substantial accumulation of rebreathed air represents a significant infection transmission risk, as passengers are increasingly exposed to potentially contaminated air from other occupants.

4.4. Environmental Conditions and Thermal Comfort Considerations

The absence of a clear humidity trend across CO_2 tertiles, with the Low tertile showing the highest median humidity (74%), suggests that humidity levels are not directly correlated with ventilation performance in this dataset. This counterintuitive finding may indicate that vehicles with poorer ventilation (higher CO_2) operate with different climate control strategies, potentially prioritizing dehumidification (using cooling) over fresh air exchange.

The slight increase in temperature across CO_2 tertiles (22.0 °C to 23.0 °C median values) may reflect the higher heat load associated with higher passenger densities or reduced cooling efficiency in poorly ventilated vehicles. However, the modest temperature differences suggest that thermal comfort considerations may be the primary driver of the vehicle's AC system operation. This potentially led to inadequate fresh air provision despite acceptable temperature conditions, while minimizing fuel usage for AC.

4.5. Operational and Policy Implications: Modal Risk Stratification

While conducted in Costa Rica, these findings have broad implications for the billions using public transport in tropical, developing countries. The energy–ventilation trade-off, leading to suboptimal vehicle cabin air quality documented here, represents a systematic challenge. This requires innovative solutions and policy that balance sustainability goals with health protection.

The substantial variation in infection risk indicators across transport modes and routes demonstrates the need for targeted interventions rather than uniform policies. The consistently high fraction of time above 800 ppm CO_2 (94% across all tertiles) indicates that the public transportation vehicles have very low levels of outdoor air ventilation. This raises questions regarding the adequacy of such air quality for preventing airborne transmission during peak occupancy periods.

Routes with longer trip times may require enhanced ventilation protocols, such as mandatory fresh air exchanges during intermediate stops, reduced passenger capacity limits, or the deployment of vehicles with superior ventilation systems. The clear performance differences also support the implementation of mode-specific ventilation standards, thresholds for CO_2 monitoring, monitoring protocols, and targeted infrastructure investments in bus fleet ventilation systems.

The clustering patterns observed in the data indicate that simple CO_2 monitoring could effectively distinguish between acceptable and concerning ventilation performance in real-time operations. This approach could enable targeted interventions and resource allocation to address the highest-risk scenarios while maintaining practical operational flexibility.

The data also suggests that train travel may represent a lower-risk option for public transport, particularly during periods of high community transmission of respiratory pathogens. The pronounced difference between bus and train CO_2 levels in our study (median 4210 ppm vs. 2364 ppm for high-occupancy scenarios) provides novel empirical evidence for modal-specific ventilation performance in tropical conditions. This finding has immediate policy implications for Latin American cities investing in Bus Rapid Transit (BRT) versus rail infrastructure [7]. Ventilation adequacy should factor into these critical infrastructure decisions alongside traditional metrics of capacity and cost-effectiveness.

4.6. Study Limitations

A key limitation of the present study lies in its exclusive reliance on CO_2 measurements as a proxy for air quality, which restricts the comprehensiveness of the environmental assessment. This approach does not account for other critical pollutants, such as particulate matter or volatile organic compounds.

Moreover, using a single parameter might overlook spatial and functional variability within transport vehicles. The seating place during the data collection was not controlled. However, differences between driver cabins and passenger areas may exhibit distinct air quality conditions. This had been pointed out in a previous study reporting that CO_2 concentrations were higher towards the back of the bus than close to the driver position (Chiu et al., 2015) [25].

Relying solely on CO_2 data also limits the capacity to assess long-term exposure risks for transport workers and frequent commuters, whose cumulative exposure to suboptimal environments may have significant health implications. In addition, the study did not address the energy demands associated with air conditioning systems in public transportation.

It was also beyond the scope of this research to evaluate the required minimum fresh air intake rates necessary for air quality improvements with alternative air-conditioning operation modes, nor did it consider the potential confounding effects of poor outdoor air quality in high-traffic urban environments.

Notwithstanding these limitations, our study suggests that CO_2 monitoring remains a valuable indicator for assessing ventilation effectiveness and potential exposure to re-breathed air in mass transit environments and argues for a reevaluation of current ventilation practices in public transportation.

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Appendix A

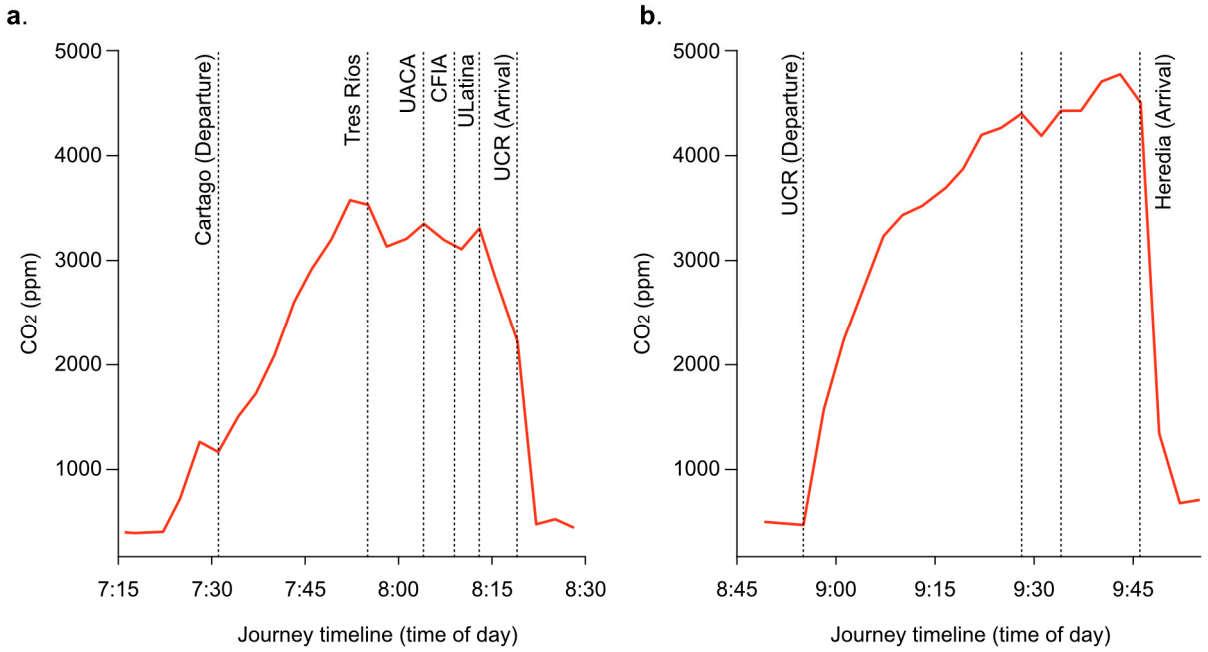


Figure A1. Representative CO_2 concentration profiles from (**a**) Cartago–UCR and (**b**) UCR–Heredia monitored train and bus journeys respectively. Vertical dashed lines indicate station stops along each route. The continuous red line shows carbon dioxide concentration levels. The figures illustrate how CO_2 levels drop during station stops due to the opening of bus and train doors.

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