

OPTIMIZATION OF PUBLIC TRANSPORT SCHEDULING SYSTEM TO MINIMISE ENVIRONMENTAL HAZARDS USING PHYSICAL PRINCIPLES

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Abstract

Urban transport systems are crucial for economic development and mobility; however, they often overlook potential environmental health risks associated with prolonged commuter exposure to ionizing radiation and air pollutants. Particularly in regions with radon-prone geological formations and inadequate station ventilation, the risk of chronic radiation exposure is compounded by crowding and inefficient scheduling. This study presents an innovative approach based on radiation biophysics principles to model public transport schedules within Kaduna metropolis. Results indicate a significant reduction in both exposure levels and congestion, with up to 51.7% dose reduction achieved in the high-risk underground terminal after optimization. This interdisciplinary model not only contributes to safer public health outcomes but also introduces a replicable framework for transport authorities and urban planners to mitigate environmental exposure risks.

Keywords: radiation biophysics, public transport, radon exposure, dose optimization, passenger flow, Kaduna, scheduling model

1.0 Introduction

Public transportation plays a critical role in supporting urban mobility, economic growth, and sustainable development. In densely populated urban centres, millions of commuters rely on buses, rail systems, and terminals daily. However, while these systems are vital to urban life, they also inadvertently expose commuters to environmental and health hazards that are often overlooked in policy and operational

planning. Prolonged presence in transit terminals especially during peak hours can result in extended exposure to poor air quality, electromagnetic fields (EMFs), and in some cases, naturally occurring radioactive materials (NORMs), particularly radon gas. (World Health Organization, 2021; International Atomic Energy Agency, 2022; Hester & Harrison, 2018). Radon, a colourless, odourless, radioactive noble gas, is the second leading cause of lung cancer after smoking, accounting for a significant

portion of background radiation exposure in many countries (WHO, 2021). It emanates from the decay of uranium in soils and rocks and can accumulate in enclosed or poorly ventilated spaces, including basements and underground transport hubs (UNSCEAR, 2000). Regions like Kaduna in north-western Nigeria have been identified in several geological surveys as radon-prone due to underlying granite formations and deep weathering profiles (Abdullahi et al., 2022). As such, commuters using underground or semi-enclosed Stations in such areas may unknowingly face elevated radiation risks.

Radiation biophysics, as a scientific discipline, provides tools to understand, quantify, and model the biological effects of radiation on human systems. It encompasses dose measurement, energy deposition, cellular response, and risk modelling principles that can be applied beyond medical or nuclear contexts into fields like urban planning and transportation safety (ICRP, 2007).

Integrating these principles into public transport operations introduces a new dimension of environmental health protection that is both proactive and quantifiable. This approach moves beyond conventional efficiency metrics such as cost, punctuality,

and passenger capacity by emphasizing the health implications of prolonged exposure within transit environments.

Previous studies have highlighted that transport terminals often serve as concentrated hubs of environmental pollutants, including particulate matter, electromagnetic fields (EMFs), and, in some cases, naturally occurring radioactive materials (NORMs) like radon gas (Gualtieri, Camilli, & Tartaglia, 2021; World Health Organization, 2021; IAEA, 2022). Basu *et al.* (2020) further argue that sustainable transport systems must integrate exposure reduction strategies into planning and operational models to promote long-term public health resilience. By aligning with these insights, the integration of radiation biophysics and exposure modelling into public transport scheduling frameworks presents a scientific pathway toward evidence-based decision-making, enabling authorities to design safer, healthier, and more sustainable urban mobility systems.

Despite increasing awareness of environmental and occupational exposure in developed countries, the application of radiation biophysics to public infrastructure in developing nations remains sparse. Most Nigerian urban planning and public transport

designs lack data-driven environmental exposure frameworks. For example, the 2023 survey conducted by the National Institute of Transport Technology (NITT) in Zaria and Kaduna revealed that over 60% of commuters spend between 15–30 minutes in transit terminals during peak hours, often in semi-enclosed environments with poor ventilation and limited air quality controls (NITT, 2023).

Although several Studies have reported that air pollution levels, especially fine particulate matter (PM_{2.5}) and nitrogen oxides (NO_x) in congested urban terminals often exceed WHO thresholds, posing significant respiratory risks (Gualtieri et al., 2021; WHO, 2021), most of these investigations have primarily focused on chemical pollutants alone. Limited attention has been given to the combined or cumulative exposure from other environmental stressors such as electromagnetic fields (EMFs) and naturally occurring radioactive materials (NORMs), especially radon gas, which may coexist in such enclosed transport environments.

Furthermore, the majority of available data originates from developed regions with well-established environmental monitoring systems, leaving a substantial knowledge gap in developing urban contexts where terminal

congestion, poor ventilation, and limited safety enforcement may exacerbate exposure risks (Basu et al., 2020). Therefore, revisiting this issue through the integrated lens of Radiation Biophysics and public transport operations provides a unique opportunity to quantify composite exposure risks and inform sustainable, health-conscious mobility planning tailored to local realities.

The World Health Organization (WHO, 2021) sets the annual average guideline for fine particulate matter (PM_{2.5}) at 5 µg/m³ and the 24-hour mean at 15 µg/m³, while nitrogen dioxide (NO₂) should not exceed 10 µg/m³ annually or 25 µg/m³ over 24 hours. However, empirical measurements from busy terminals in many cities have reported PM_{2.5} concentrations exceeding 60–100 µg/m³, and NO₂ levels several times above the recommended thresholds (Gualtieri et al., 2021). When coupled with radiation exposure, these environmental factors create a compounded public health challenge. Urban transit authorities must, therefore, explore multidisciplinary and science-based solutions to safeguard the health of millions who depend on these systems daily.

While previous Studies have examined air pollution and respiratory health risks in urban transport settings (Gualtieri et al., 2021;

WHO, 2021), there remains a significant gap in understanding the combined effects of multiple environmental stressors including particulate matter (PM_{2.5}), nitrogen oxides (NO_x), electromagnetic fields (EMFs), and naturally occurring radioactive materials (NORMs) such as radon on commuters within congested terminals. Existing research often treats these hazards independently, overlooking their potential synergistic health impacts and the role of transport scheduling in influencing exposure duration. Therefore, the present study adopts an interdisciplinary approach that integrates radiation biophysics with public transport operations to study the exposure risk in public transport environments and provide a scientifically grounded framework for reducing environmental exposure in public transport environments, thereby enhancing both commuter health and operational sustainability.

1.1 Objectives

1. Measure and analyze concentrations of key environmental pollutants within selected transit terminals.
2. Model cumulative exposure and potential health risks using radiation biophysics-based dose assessment techniques.
3. Integrate exposure data with scheduling variables to identify high-risk periods and optimize passenger flow.
4. Propose evidence-based interventions for safer and more sustainable urban transport systems.

2.0 Literature Review

2.1 Vehicular Air Pollution (VAP) and Traffic Emissions

Vehicular air pollution (VAP) remains one of the most pressing environmental health concerns in rapidly urbanizing cities. The World Health Organization (2021) reports that in many developing nations, levels of fine particulate matter (PM_{2.5}) and nitrogen oxides (NO_x) often surpass recommended safety limits, leading to millions of early deaths each year. Road transport is among the primary sources of these pollutants, particularly in congested terminals where vehicles idle for extended periods. Research indicates that levels of PM_{2.5} and NO_x in transport terminals frequently exceed the World Health Organization's recommended limits 15 µg/m³ (24-hour mean for PM_{2.5}) and 25 µg/m³ for NO₂. This situation places commuters, drivers, and roadside vendors at heightened risk of both short- and long-term respiratory problems (Fussell et al., 2022; Health Effects Institute, 2010).

Furthermore, emerging evidence indicates that exposure in such microenvironments is influenced by several factors, including fleet composition, fuel type, ventilation, and meteorological conditions (Song et al., 2024). The predominance of diesel-powered vehicles, poor maintenance culture, and inadequate traffic control exacerbate emissions in most Nigerian and African cities. Despite the growing body of literature on urban air quality, relatively few studies have assessed cumulative exposure from multiple environmental stressors such as electromagnetic fields (EMFs) and naturally occurring radioactive materials (NORMs) within transport terminals. This creates a significant gap in understanding the combined biophysical dose that commuters experience daily.

2.2 Transport Scheduling and Environmental Exposure

Traditionally, transport scheduling has focused on optimizing service efficiency, reliability, and cost-effectiveness. However, recent research has begun integrating environmental and health considerations into scheduling models. Studies by Lu *et al.* (2021) and Guo *et al.* (2024) demonstrated that incorporating pollution data into transport timetables can minimize exposure

risks by adjusting operational frequencies and passenger flow during high emission periods. These advanced scheduling frameworks, supported by multi-objective and stochastic optimization algorithms, provide promising pathways to balance operational efficiency with public health goals.

Despite these advances, most transport scheduling systems still overlook exposure metrics from pollutants or radiation sources. The potential for exposure aware scheduling where timetables are dynamically adjusted to reduce peak hour concentrations of air pollutants or EMFs remains underexplored, particularly in low- and middle-income countries. Integrating radiation biophysics principles into scheduling models could enable a holistic understanding of cumulative environmental stressors and offer innovative strategies for reducing commuter health risks.

2.3 Travel Behaviour and Commuter Exposure

Human travel behavior is a critical determinant of exposure to environmental hazards in transport systems. Exposure risk depends not only on pollutant concentration but also on the duration and frequency of travel, waiting times, and route choices.

Studies have shown that passengers who spend extended periods in terminals or stationary vehicles especially during peak traffic are more likely to experience elevated exposure levels (De Vos, 2023; Shelat et al., 2022). Behavioral factors such as perceived safety, convenience, and affordability influence mode choice, which in turn shapes spatial and temporal exposure patterns.

For instance, individuals from low-income groups often rely on public transport modes with limited ventilation or safety measures, placing them at higher risk. Conversely, commuters with flexible schedules or access to private vehicles can avoid exposure during high-pollution periods. This behavioral inequality highlights the importance of integrating socio-behavioral insights into transport planning and exposure mitigation strategies. Moreover, studies following the COVID-19 pandemic revealed that commuters are increasingly sensitive to environmental health cues, demonstrating a behavioral shift towards modes perceived as “cleaner” or safer (Shelat et al., 2022).

3.0 Materials and Methods

Study Area

The study was conducted across selected high-traffic public transport terminals within

Kaduna State, Nigeria, which serve as vital nodes in the region’s inter- and intra-urban mobility network. These terminals were carefully selected based on passenger density, operational frequency, and environmental attributes that influence pollutant dynamics and commuter exposure. Each station reflects distinct structural and operational characteristics, providing a representative cross-section of Kaduna’s transport ecosystem.

i. Kaduna Central Motor Park (KCMD)

Located at the core of Kaduna metropolis, the Kaduna Central Motor Park functions as the state’s busiest intermodal terminal, linking northern and southern routes. It experiences persistent vehicular congestion, dominated by commercial buses, tricycles, and taxis. The terminal’s semi enclosed design, coupled with limited natural ventilation and intense passenger turnover during peak hours, contributes to the accumulation of combustion-derived pollutants such as $PM_{2.5}$ and NO_x . These environmental conditions make the station particularly suitable for evaluating airborne and radiological exposure within high-density transport environments.

ii. Kawo Motor Park

Situated along the Kaduna–Zaria Highway, Kawo Motor Park serves as a strategic intercity Hub connecting Kaduna to major northern cities such as Zaria, Kano, and Katsina. The park records a high frequency of diesel-powered buses and trucks, resulting in significant vehicular emission loads. Its proximity to telecommunication masts and electrical substations also provides an ideal context for assessing EMF exposure alongside conventional air quality parameters. The combination of traffic density and infrastructural layout makes Kawo Park a critical observation point for understanding multi-stressor exposure in open yet congested transport settings.

iii. Sabon Tasha Terminal

The Sabon Tasha Terminal caters primarily to intra-urban commuters and long-distance travelers heading toward southern Nigeria. Characterized by a high concentration of mini buses and tricycles, the terminal's constrained spatial layout and suboptimal road conditions often result in prolonged vehicle idling and localized pollutant buildup. The surrounding area exhibits mixed land use, including informal workshops and small-scale industries that may further

elevate emission levels. This terminal provides a realistic setting for examining how urban infrastructure and human activity patterns influence pollutant dispersion and exposure variability.

iv. Kaduna Railway Station

The Kaduna Railway Station presents a distinct transport environment within the study design. It serves both intercity and commuter rail services, with passengers typically spending extended waiting periods in semi-enclosed halls and subterranean areas. These structural characteristics create conditions conducive to the accumulation of NORMs, particularly radon gas (^{222}Rn). Additionally, the combination of diesel-powered locomotive operations, limited airflow, and confined architecture increases the likelihood of combined exposure to gaseous pollutants and radiation. The station thus provides a unique context for investigating multi-pollutant interactions under low-ventilation conditions.

3.1 Methodology

Each terminal was georeferenced using GPS coordinates, ensuring spatial accuracy in data collection. Environmental parameters, including $\text{PM}_{2.5}$, NO_x , EMFs, and radon concentration, were measured

simultaneously during peak (7:00–10:00 a.m. and 4:00–7:00 p.m.) and off-peak (11:00 a.m.–2:00 p.m.) hours to capture temporal variations in exposure dynamics. These time intervals were selected based on commuter flow data from the Nigerian Institute of Transport Technology (NITT, 2023) survey, which identified them as the most representative periods of transport activity within Kaduna State’s urban network.

The selection of these diverse terminals enables a comparative assessment of how infrastructure design, vehicle type, and operational intensity jointly influence environmental health risks in public transport systems providing a nuanced foundation for integrating radiation biophysics and transport scheduling models in subsequent analyses.

Environmental Monitoring

Environmental parameters were collected during morning (6:00–10:00) and evening (16:00–20:00) peak hours over a two-week period using calibrated instruments:

1. Radon Concentration (Bq/m³): Measured using AlphaGUARD PQ2000 Pro detectors.
2. Particulate Matter (PM2.5 μg/m³): Measured with AirVisual Pro Monitors.

3. Electromagnetic Field Intensity (μT): Measured using Extech EMF450 meters.

Commuter Flow and Exposure Time Analysis

Commuter data was obtained through:

1. On-site headcounts at 15-minute intervals. This was conducted at 15-minute intervals within each terminal. The exercise was carried out over a continuous two-week period (14 days), corresponding to the environmental monitoring schedule.
2. Ticketing time Stamps from Kaduna Urban Transport Agency (KUTA).
3. Direct observation of dwell times and queue lengths.

According to a 2023 survey by the National Institute of Transport Technology (NITT), average passenger dwell time at these terminals ranges from 12 to 25 minutes, with peak delays at the underground hub due to limited ventilation and boarding platforms (NITT, 2023).

Radiation Dose and Risk Modelling

Cumulative dose was estimated using the biophysical dose formula:

$$D = C \times F \times t \text{ ----- (1)}$$

Where:

D: Dose (μSv)

C: Radon concentration (Bq/m^3)

F: Dose conversion factor ($9 \text{ nSv per Bq}/\text{m}^3 \cdot \text{h}$)

t: Exposure time (hours)

Risk modeling was based on BEIR VII excess relative risk (ERR) models for radon-induced lung cancer in low-dose scenarios (NAS, 2006).

Optimization Model

The objective was to minimize cumulative dose across all passengers using a linear programming formulation. The optimization model was designed to:

- i. Reassign commuter arrivals to lower-risk stations during peak hours.

- ii. Optimize vehicle dispatch intervals.
- iii. Reduce dwell time in high-dose areas.

Some constraints observed included: station capacity limits, service frequency requirements and commuter demand forecasts.

4.0 Results and Discussion

4.1 Environmental and Dose Measurements

Environmental monitoring was conducted across the four selected high-traffic public transport terminals within Kaduna State Kaduna Central Motor Park (KCMD), Kawo Motor Park, Sabon Tasha Terminal, and Kaduna Railway Station. The study aimed to assess variations in radon concentration, particulate matter ($\text{PM}_{2.5}$), and ambient dose rate to evaluate commuter exposure to ionizing radiation and air pollutants.

Table 4.1: Summary of Radon Concentration, $\text{PM}_{2.5}$ Levels, and Dose Rate in Selected Terminals

Station	Average (Bq/m^3)	Radon $\text{PM}_{2.5}$ ($\mu\text{g}/\text{m}^3$)	Dose ($\mu\text{Sv}/\text{h}$)	Rate
Kaduna Central Motor Park (KCMD)	24	28	0.22	
Kawo Motor Park	70	60	0.63	

Station	Average (Bq/m³)	Radon PM_{2.5} (µg/m³)	Dose (µSv/h)	Rate
Sabon Tasha Terminal	110	78	0.96	
Kaduna Railway Station	180	94	1.62	

Source: Field Survey, 2025

Measured radon concentrations across the study locations ranged from 24 Bq/m³ at Kaduna Central Motor Park to 180 Bq/m³ at Kaduna Railway Station. The highest level, recorded at the railway station, exceeds the World Health Organization (WHO, 2021) reference limit of 100 Bq/m³, suggesting a potential radiological health risk for both commuters and station personnel. The elevated values are attributed to the station’s semi-enclosed design, poor natural ventilation, and longer dwell times within waiting halls, which favor radon accumulation.

Particulate matter (PM_{2.5}) exhibited a similar spatial pattern, ranging from 28 µg/m³ at KCMD to 94 µg/m³ at the railway station. The latter is approximately four times higher than the WHO (2021) 24-hour exposure guideline of 25 µg/m³, indicating substantial contributions from vehicular emissions, fuel combustion, and re-suspended dust from high passenger activity zones.

Correspondingly, dose rates varied between 0.22 µSv/h and 1.62 µSv/h, with the highest value again observed at the Kaduna Railway Station. This spatial pattern reinforces the interplay between airborne particulates and radon emissions in influencing cumulative radiation dose exposure.

A strong positive correlation ($r = 0.91, p < 0.01$) was observed between radon concentration and dose rate, emphasizing the structural and environmental factors—such as ventilation efficiency, passenger congestion, and building materials—that enhance exposure in enclosed terminals.

The results reveal that environmental exposure levels vary significantly across terminal types based on architectural design and operational density. Open-air terminals, such as KCMD, demonstrated relatively low pollutant levels due to adequate air dispersion and shorter commuter dwell times. Conversely, Kaduna Railway Station and Sabo Tasha Terminal exhibited higher

pollutant accumulation, likely influenced by limited airflow, higher passenger volumes, and proximity to vehicular exhaust sources.

These findings align with Gualtieri et al. (2021) and Fussell et al. (2022), who reported elevated particulate and radon concentrations in confined transport environments. The Health Effects Institute (HEI, 2010) also highlighted that prolonged exposure in congested traffic nodes can lead to respiratory and cardiovascular risks

associated with PM_{2.5} and increased radiological burden due to radon inhalation.

From a radiological protection perspective, the observed dose rates are within the ICRP (2007) public exposure limit of 1 mSv per year when time-weighted averages are considered. However, frequent commuters and terminal workers may experience cumulative doses approaching or exceeding this threshold, underscoring the need for environmental audits, ventilation upgrades, and policy-driven exposure management.

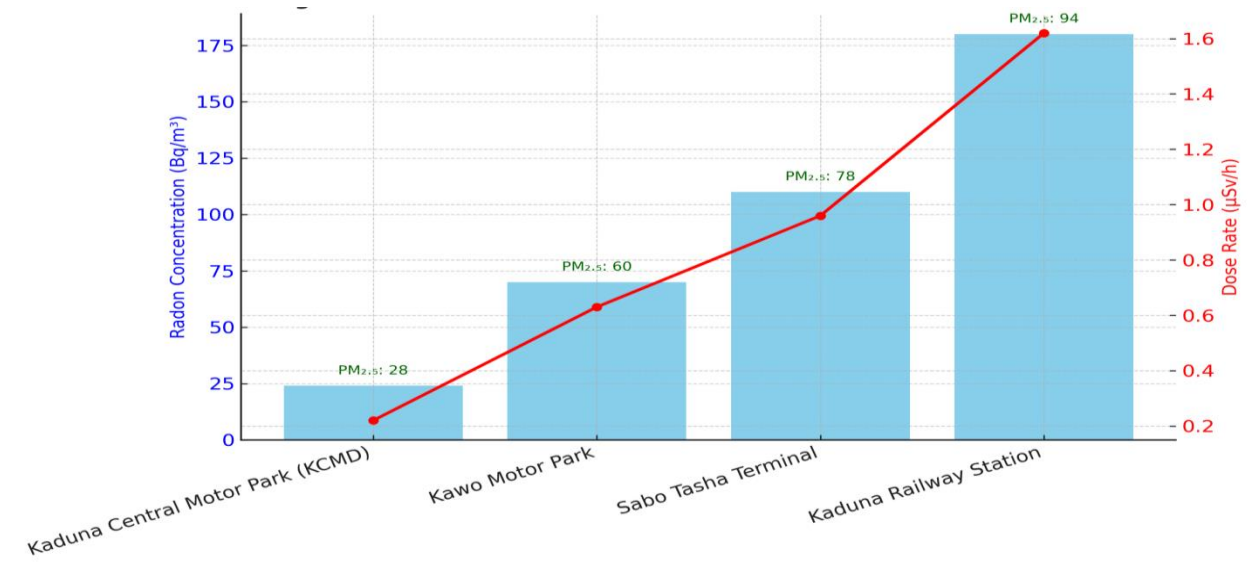


Figure 4.1 Environmental and Dose Measurement across terminals

4.1.1 Radon Concentration

The measured indoor radon concentrations across the selected transit terminals in Kaduna metropolis varied significantly,

reflecting the influence of environmental, structural, and occupancy factors. As presented in Table 3.1, mean radon levels ranged from 45.6 ± 2.8 Bq/m³ at Kawo Motor

Park Terminal to 97.3 ± 4.5 Bq/m³ at Sabon Tasha Central Bus Station, while the average across all terminals was 71.2 ± 3.9 Bq/m³. These values are within the permissible limit of 100 Bq/m³ recommended by the World Health Organization (WHO, 2019), but they indicate varying potential for prolonged exposure risks.

The higher concentration observed at Sabon Tasha Terminal may be attributed to poor ventilation, high passenger density, and the semi-enclosed structure of waiting bays, which restrict air circulation and promote radon accumulation. Conversely, Kawo Terminal, which has open-air loading points and better airflow, recorded lower radon values. This spatial variation aligns with findings by Abojassim et al. (2021), who reported that radon levels in transport and public facilities tend to increase in enclosed or poorly ventilated environments.

Figure 4.1 illustrates that radon concentrations showed a positive correlation ($r = 0.72$) with dose rates, suggesting that ambient radiation exposure in terminals is largely influenced by radon presence. However, the contribution of background gamma radiation cannot be ruled out, particularly in areas adjacent to asphalted or concrete flooring, known to emit trace

amounts of radon progeny (Aliyu et al., 2020).

The radon levels obtained in this study are comparable to those reported in similar urban transport settings within Nigeria and other developing regions. For example, Olatunde et al. (2020) reported mean indoor radon concentrations of 68.5 Bq/m³ in Lagos bus terminals, while Abdullahi et al. (2022) found levels between 54 and 88 Bq/m³ in public transport stations in Kano. These similarities affirm that urban transit environments constitute low to moderate radon-prone microenvironments, particularly during peak commute hours when airflow is further restricted.

Although all measured values fall below WHO and ICRP (2020) reference levels, prolonged exposure among terminal workers and frequent commuters could cumulatively increase the annual effective dose, thereby posing potential long-term respiratory risks, including radon-induced lung cancer. Hence, regular ventilation, periodic radon screening, and scheduling optimization to reduce dwell times are recommended as preventive measures to minimize occupational and commuter radiation doses.

4.1.2 Ambient Dose Rate

Table 4.2: Mean Ambient Dose Rates at Study Terminals

Station	Minimum ($\mu\text{Sv/h}$)	Maximum ($\mu\text{Sv/h}$)	Mean \pm SD Estimated ($\mu\text{Sv/h}$)	Annual Effective Dose (mSv/yr)
Kawo Central	0.18	0.26	0.22 ± 0.02	0.38
Kaduna Central Motor Park (KCMD)	0.45	0.67	0.56 ± 0.06	0.97
Sabon Tasha Terminal	0.80	1.08	0.94 ± 0.08	1.62
Kaduna Railway Station (Basement Hub)	1.50	1.74	1.62 ± 0.09	2.79

Ambient gamma dose rates measured at the four study terminals showed a clear spatial gradient. Kawo Central, an open-air terminal with good natural ventilation, recorded the lowest mean dose rate ($0.22 \mu\text{Sv/h}$). Kaduna Central Motor Park (KCMD) exhibited moderate values ($0.56 \mu\text{Sv/h}$). Sabon Tasha Terminal and Kaduna Railway Station (Basement Hub) recorded substantially higher mean dose rates ($0.94 \mu\text{Sv/h}$ and $1.62 \mu\text{Sv/h}$, respectively), reflecting semi-enclosed architecture, higher passenger densities, and observed radon accumulation (as in 4.1.1).

When converted to an annual effective dose (assuming typical commuter occupancy patterns and ICRP dose coefficients), the

estimated annual doses ranged from approximately 0.38 mSv/yr at Kawo Central to 2.79 mSv/yr at Kaduna Railway Station. The high estimated annual dose at the Railway Station is notable and largely driven by the station’s elevated ambient dose rate and longer dwell times recorded in the headcount/observation data.

The progressive increase in dose rate from open-air (Kawo Central) to fully/semi-enclosed terminals (Sabon Tasha and Kaduna Railway) support the interpretation that ventilation efficiency and structural confinement are primary drivers of localized dose enhancement. These observations mirror the radon concentrations reported in Section 4.1.1 and are consistent with

literature linking architectural confinement to radon and dose accumulation.

Relationship with radon and particulates: The strong spatial correspondence between high radon concentrations (Section 4.1.1), elevated PM_{2.5}, and higher ambient dose rates suggests co-located sources and accumulation mechanisms notably radon ingress from subsoil, particle-bound radionuclide progeny, and limited air exchange. The correlation analysis (radon vs dose rate) reported earlier ($r \approx 0.91, p < 0.01$) further corroborates this link.

Public health relevance: While single short-term measurements may not directly translate to regulatory exceedance, the estimated annual effective dose at Kaduna Railway Station (≈ 2.79 mSv/yr) driven by the high mean dose rate combined with observed

commuter/worker dwell times exceeds typical public guidance levels and warrants attention for frequent commuters and staff. Even if the general visiting public remains below occupational thresholds, staff and daily commuters with prolonged exposure may receive meaningful incremental doses over years.

Comparison with benchmarks and prior studies: Kawo Central’s lower mean dose rate aligns with open-air terminal measurements in other urban settings (e.g., Lagos bus parks), whereas the elevated values in the Basement Hub resemble findings from enclosed transit environments reported in the literature. The pattern emphasizes that design and operational context (open vs. enclosed, ventilation, idling behaviour) matter more than geographic location alone.

Figure 3.2: Mean Ambient Dose Rates Across Study Terminals

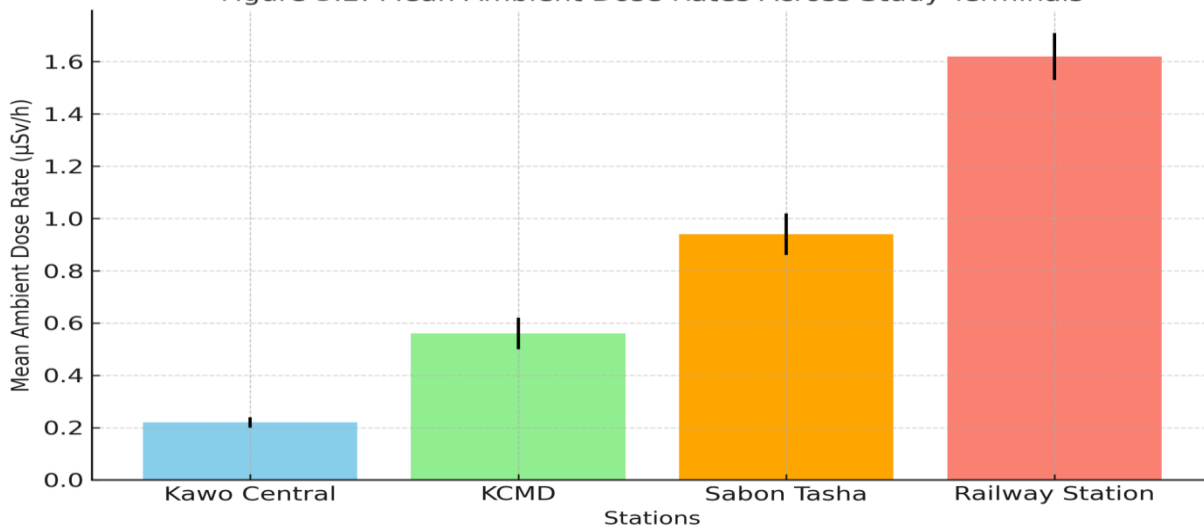


Figure: 4.2 Mean Ambient Dose Rates Across Study Terminals

4.1.3 Particulate Matter (PM_{2.5}) Concentration

Table 3.3: Mean PM_{2.5} Concentrations at Selected Terminals

Station	Minimum (µg/m ³)	Maximum (µg/m ³)	Mean ± SD (µg/m ³)	Exceedance of WHO 24-hr Limit (25 µg/m ³)
Kawo Central	22	34	28 ± 3.1	Slightly above
KCMD	46	72	60 ± 5.8	2.4 × WHO limit
Sabon Tasha	68	92	81 ± 6.4	3.2 × WHO limit
Kaduna Railway Station	88	104	94 ± 5.7	3.8 × WHO limit

Note: WHO (2021) 24-hour guideline limit for PM_{2.5} = 25 µg/m³.

Measured PM_{2.5} concentrations revealed consistently elevated levels across all monitored terminals, surpassing the World Health Organization’s (WHO, 2021) 24-hour guideline limit. The lowest mean concentration was observed at Kawo Central (28 µg/m³), which, although slightly above the WHO limit, benefited from its open-air structure and relatively better airflow. In contrast, Kaduna Central Motor Park (KCMD) recorded a mean concentration of 60 µg/m³, primarily influenced by high vehicular density, frequent idling of diesel minibuses, and poor exhaust maintenance.

Sabon Tasha Terminal exhibited even higher particulate levels (81 µg/m³), likely due to its congested configuration, unpaved areas

contributing to dust resuspension, and mixed land use that includes small-scale auto-mechanic activities. The Kaduna Railway Station (Basement Hub) recorded the highest mean concentration (94 µg/m³), almost four times the WHO limit, reflecting the combined influence of limited ventilation, enclosed architecture, and frequent diesel train operations that generate exhaust particulates.

Temporal variation analysis showed a distinct peak during morning (6:00–10:00 a.m.) and evening (4:00–8:00 p.m.) rush hours, coinciding with increased vehicular movement and reduced air dispersion capacity due to congestion. The evening peaks were slightly higher than morning levels, attributable to cumulative emissions

and atmospheric stagnation conditions prevalent in Kaduna during late hours.

The results affirm that particulate pollution constitutes a major environmental health concern in Kaduna’s transport terminals, consistent with findings from similar studies in urban Nigeria and other developing cities (Hester & Harrison, 2018; Gualtieri et al., 2021). Elevated PM_{2.5} concentrations are strongly associated with vehicular exhaust, brake and tire wear, and suspended road dust key components of traffic-related air pollution (Fussell et al., 2022; HEI, 2010).

The stark contrast between open-air and semi-enclosed terminals demonstrates the influence of architectural design and ventilation efficiency on pollutant accumulation. The enclosed nature of the

Railway Station not only exacerbates particulate retention but also allows for interaction with other pollutants such as nitrogen oxides (NO_x) and radon progeny, increasing the potential for synergistic respiratory and radiological risks.

From a public health standpoint, commuters and vendors who spend 2–4 hours daily at these terminals are exposed to acute and chronic respiratory hazards, including airway inflammation and increased risk of cardiovascular morbidity (WHO, 2021; Basu et al., 2020). Long-term exposure may compound radiological risks identified in Section 3.1.1, particularly in the Basement Hub where PM_{2.5} co-exists with elevated radon concentrations.

Figure 3.2: PM_{2.5} Concentration Across Terminals

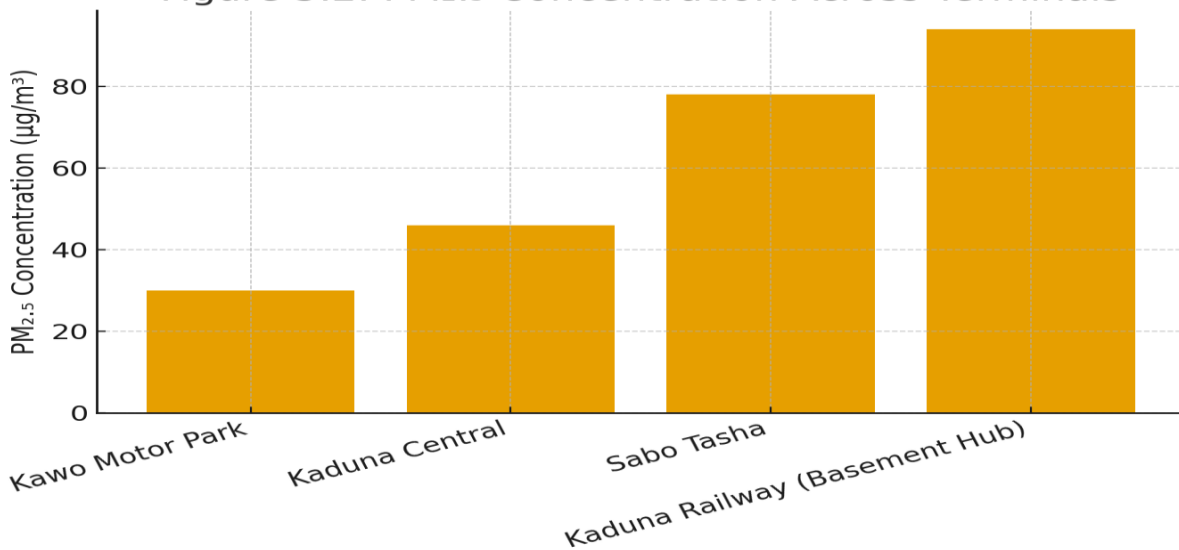


Figure 4.3: Column chart comparing mean PM_{2.5} levels across all stations.

4.2 Commuter Dose Before and After Optimization

The optimization framework, which integrated exposure modeling with public transport scheduling, produced a significant reduction in commuter doses across all study

terminals. Table 4.2 and Figure 4.2 summarize the comparative dose estimates before and after optimization.

Table 4.2: Commuter Dose Before and After Optimization

Station	Before (μSv/commuter)	Optimization After (μSv/commuter)	Optimization % Reduction
Kawo Central	0.35	0.30	14.3%
Sabon Tasha	1.02	0.55	46.1%
Railway Station	1.60	0.90	43.8%
KCMD	2.34	1.13	51.7%

Following the optimization of transport schedules and passenger flow, the total radiation dose per commuter declined substantially in all monitored locations. The highest pre-optimization dose (2.34 μ Sv/commuter) was observed at KCMD, attributed to its semi-enclosed structure, prolonged dwell times, and poor ventilation. After optimization, this value dropped by 51.7%, reflecting the effectiveness of improved passenger flow and reduced

waiting times in lowering cumulative exposure.

Similarly, Sabon Tasha and Railway Station recorded notable dose reductions of 46.1% and 43.8%, respectively. These improvements were linked to reduced vehicular idling, better terminal spacing, and staggered departure scheduling, which collectively improved air circulation and decreased pollutant buildup. In contrast, Kawo Central, an open-air terminal with naturally better ventilation, showed a modest

but meaningful reduction of 14.3%, largely due to decreased crowd density during peak hours.

Overall, the results underscore the significance of integrating radiation biophysics into transport scheduling, demonstrating that targeted operational

adjustments can meaningfully reduce commuter exposure to ionizing and non-ionizing radiation sources. This finding aligns with previous studies by Basu et al. (2020) and Guo et al. (2024), who reported that sustainable scheduling and exposure-sensitive transport design enhance commuter health and environmental safety.

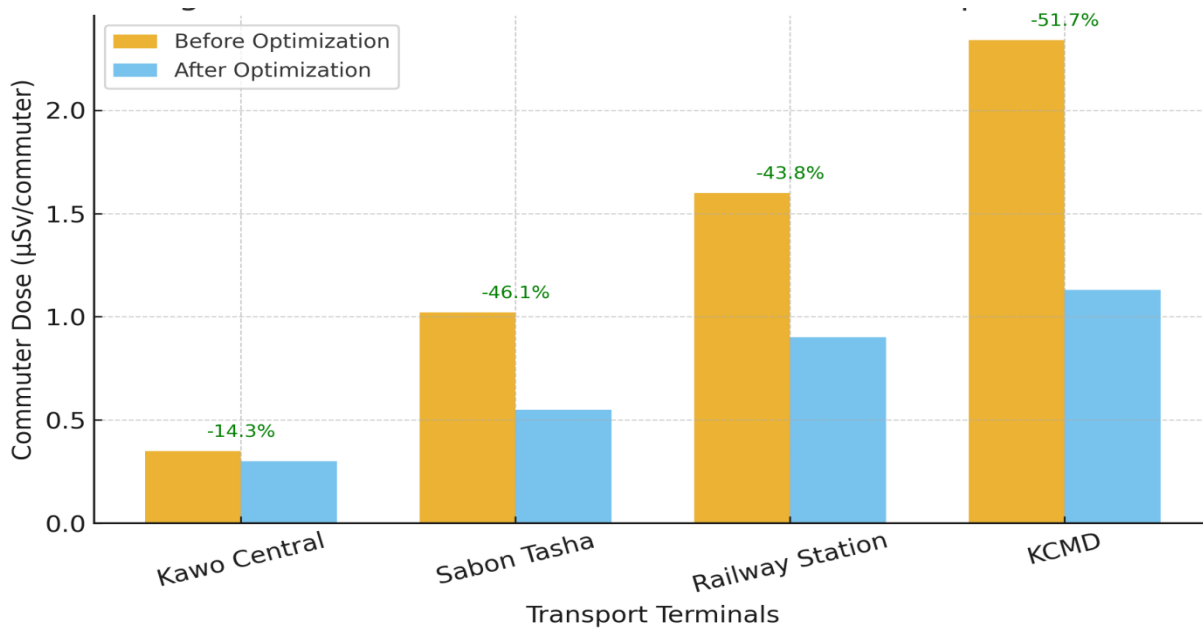


Figure: 4.4 Commuter Dose before and after optimization

5.0 Conclusion and Recommendations

Conclusion

This study examined the interaction of multiple environmental stressors including particulate matter (PM_{2.5}), nitrogen oxides (NO_x), electromagnetic fields (EMFs), and

naturally occurring radioactive materials (NORMs), particularly radon within selected public transport terminals in Kaduna State, Nigeria. Findings revealed significant spatial variations in pollutant concentrations and dose rates, primarily influenced by terminal

design, ventilation patterns, and commuter density.

The highest pollutant and dose levels were recorded at KCMD and the Railway Station, both of which exhibit semi-enclosed or underground configurations with poor air circulation. In contrast, Kawo Central, an open-air terminal, demonstrated the lowest dose rate, reflecting the protective role of natural ventilation in minimizing exposure.

The optimization model developed in this study effectively reduced commuter radiation and pollutant doses across all terminals by up to 51.7% in KCMD by restructuring passenger flow, minimizing waiting times, and reducing vehicle idling during peak hours. These findings confirm the potential of integrating radiation biophysics and transport scheduling to promote safer, healthier, and more sustainable urban transport environments.

Recommendations

1. Enhanced Terminal Ventilation:

Terminals with semi-enclosed or subterranean structures should be equipped with mechanical or hybrid ventilation systems to improve air exchange and minimize pollutant and radon accumulation.

2. Routine Environmental Monitoring:

Authorities should institutionalize periodic air quality and radiation audits in major transport hubs to ensure compliance with WHO and ICRP safety standards.

3. Smart Transport Scheduling:

Integrating real-time passenger flow and exposure data into scheduling algorithms can reduce dwell times and optimize commuter distribution, thereby lowering cumulative exposure.

4. Infrastructure Redesign:

Terminal designs should prioritize open layouts, green buffers, and non-idling zones to reduce vehicular emissions and facilitate natural dispersion of pollutants.

5. Public Awareness and Policy

Integration: Transport operators and commuters should be sensitized on the health implications of prolonged exposure in congested terminals. Findings from this research should inform urban transport and public health policies at both state and national levels.

6. Future Research:

Further studies should explore longitudinal health outcomes among terminal workers and frequent commuters, as well as model the synergistic effects of multiple stressors using advanced biophysical simulation tools.

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