Comparing Diesel and Electric Bus Contributions to Urban Ultrafine Particle Levels in Auckland

1. General Introduction

The adoption of low-emission public transportation systems represents an essential measure to fight climate change while decreasing fossil fuel environmental effects. Electric buses represent a leading sustainable transportation solution which effectively decreases greenhouse gas emissions while enhancing urban air quality and reducing noise pollution. Different electric propulsion system technologies including hybrid and battery electric and fuel cell systems provide unique environmental and operational advantages. The selection of appropriate technology depends on local energy structures and operational environments together with economic factors (Li, 2016; Mahmoud et al., 2016). The city of Auckland will use electric buses as a primary element to establish a sustainable transportation system with reduced environmental impact.

2. Evidence Review — City Cases, Effectiveness, and Transferability to Auckland

Research conducted in various cities demonstrates that electric buses (e-buses) achieve substantial emission reductions and noise reduction and operational success through proper charging and scheduling approaches (Abdelat and Mohamed, 2021). Research indicates that hybrid buses provide only modest greenhouse gas emission reductions but serve as better short-term alternatives until battery electric buses and fuel cell buses can deliver substantial advantages after addressing infrastructure and financial challenges (Borén et al., 2020).

The case study of Shenzhen (China) is the most comprehensive because it features more than 16,000 electric buses running in the city. Success depends on high-power depot charging, strategic en-route opportunity charging, and close coordination between operators, utilities, and manufacturers. These cities have reported significant reductions in nitrogen oxides (NOx), particulate matter (PM) and carbon dioxide (CO₂) along with less operational noise. Challenges include high capital costs and charging station land constraints, mitigated through service-based battery leasing and government subsidies. Success in Stockholm (Sweden) serves as a model for coastal cities and those operating in cold climates. The deployment of charging stations at terminal locations and strategic stopping points enables the optimization of range, grid capacity and service schedule dependability. The combination of opportunity charging with winter heating requirements is necessary to deliver service continuity without overextending battery capacity. This method enables substantial energy and emission reductions with dependable operational performance. Other European deployments (Netherlands, UK, Germany) show that depot-only charging is suitable for shorter, flatter routes, whereas opportunity charging is better suited for high-frequency or hilly lines. The success of energy management strategies depends on aligning route energy requirements with charging opportunities and battery power capabilities (Verbrugge et al., 2021; Mahmoud et al., 2016).

Al-Ogaili et al. (2021) mentioned that local conditions such as topography and site spacing and driving style and HVAC load and temperature significantly affect energy consumption. A single bus will produce different kilowatt-hour per kilometer (kWh/km) readings when operating under various elevation profiles and traffic conditions. Because benchmark data from other cities cannot be directly applied, it is necessary to perform route-specific modeling to predict performance and determine reasonable battery capacity. Some conditions in Auckland match those of these case cities but need specific adjustments. The system integration approach from Shenzhen can be referenced—early utility collaboration, depot electrification, and financing models to mitigate battery replacement risks. The initial phase of phased corridor electrification appears more feasible for Auckland because of its small fleet size and restricted depot capacity. The experience of Stockholm demonstrates to Auckland how opportunity charging technology should be implemented for routes with steep grades or extended distances while evaluating the effects of coastal wind and humidity on auxiliary energy needs (Wang et al., 2017). Most of Auckland's routes can be served by battery-electric buses charged overnight at the depot, provided that the power grid continues its decarbonization efforts. The implementation of quick "opportunity charging" during brief rest periods can support longer and steeper or high-frequency routes. The longest routes with very short charging times may require fuel cell buses as an alternative solution. Auckland can duplicate emission reductions and air quality improvements by conducting detailed energy modeling for each route and building charging infrastructure in stages while working closely with electricity suppliers.

3. Linking Emissions, Concentrations, and Exposure

Research into battery electric buses (BEBs) measures their benefits through the relationship between tailpipe emission reductions and changes in air pollutant concentrations which leads to population exposure analysis. The initial step of emission reduction calculation remains simple because BEBs operate without producing exhaust emissions. The authors of Vilppo and Markkula (2015) measured fuel efficiency and pollution emission reductions for BEBs compared to diesel buses during a 20-kilometer route while using operational energy consumption and fuel emission factors. Rodrigues and Seixas (2022) expanded their analysis by uniting operational data from pilot projects with life-cycle considerations to study both direct and indirect emission reductions. Du et al. (2019) used Chinese fleet data to determine the amount of fuel substitution and the reductions in greenhouse gas emissions while calculating the CO₂, NOₓ, and PM emissions per kilometer that diesel buses would produce instead of BEBs. Multiple international studies show that battery electric buses (BEBs) cut down ultrafine particulate matter (UFP) emissions to much lower levels than conventional diesel buses do. Plassat (2004) investigated diesel bus and BEB emissions through actual field research by measuring particulate matter amounts along with UFP concentrations. BEB operation produces virtually no exhaust emissions which reduces UFP concentrations by about 90% when compared to diesel buses in regular urban driving situations. BEB UFP emissions stay dramatically lower than diesel bus emissions both when operating at higher speeds and when experiencing motor and brake wear-generated particulate matter (Plassat, 2004). The research supports BEBs as effective tools for enhancing air quality across urban transportation routes. The study showed conclusive evidence that diesel buses should be replaced with BEBs to decrease UFP exposure among the public population in densely inhabited urban regions even though it was conducted in a single city during a brief operational period.

The conversion process from emission reductions into environmental pollutant concentration changes proves to be difficult during this phase. Most reviewed studies applied basic dispersion models together with emission inventory methods for their research. The study by Du et al. (2019) made implicit assumptions about tailpipe emission reduction effects on local concentration levels by avoiding detailed atmospheric modeling. Vilppo and Markkula (2015) used their route-level energy consumption and emission calculations to understand avoided tailpipe emissions, but they did not run dispersion simulations to assess how these emissions would affect the local air quality along the corridor. The authors Rodrigues and Seixas (2022) observed that case studies sometimes integrated dispersion models, yet many studies depended on emission-concentration ratios derived from prior urban air quality research which did not properly represent local climate or terrain conditions.

The different research studies allocated different levels of attention to the assessment of population exposure changes. According to Rodrigues and Seixas (2022) the level of population benefits from emission reduction depends on how close the emission reductions are to where people live and work. The replacement of diesel buses in crowded areas produces superior exposure advantages than replacing buses that operate in less busy routes. The exposure reductions in Shenzhen's major transition reached their peak in densely populated regions which had the most active bus network according to Du et al. (2019). The research conducted by Verbo and Markkula (2015) does not provide specific exposure measurements, but their results indicate that diesel bus replacement on busy routes creates the greatest health benefits for the public.

The methods implemented in other cities need adjustments to operate effectively within Auckland. The proportional reduction assumption which assumes emission decreases lead to equivalent concentration reductions does not apply to Auckland's complex coastal environment. The combination of sea breezes and wind direction changes and local temperature inversions generates pollutant dispersion patterns that differ from those found in European or inland Chinese cities. The hilly terrain of Auckland creates multiple street canyon effects and microclimates which produce different path-specific dispersion behaviors according to Papa (2022) and Duke et al. (2009). The seasonal patterns in Auckland differ from Northern Hemisphere cities because the city experiences small temperature variations but strong wind-driven changes in pollutant transport.

The assessment of air quality and exposure benefits from battery-electric buses (BEBs) demands thorough evaluation of these assumptions. The distribution of population throughout Auckland affects the calculated levels of UFP exposure. The majority of main bus routes travel through densely populated suburban areas before reaching the central business district (CBD). The population density of bus routes determines the extent of exposure reduction when diesel buses transition to BEBs because high-density areas will experience greater benefits than low-density areas (Mendoza et al., 2024; Gao et al., 2017). The specific case of Auckland requires a detailed assessment of these assumptions:

* Zero tailpipe emissions — BEBs do not produce tailpipe emissions, so this assumption holds true. The carbon intensity of electricity affects climate benefits and Auckland's electricity has a relatively low carbon intensity.
* Emission reductions through proportional concentration reduction — Studies generally assume that emission reductions will produce equivalent decreases in local pollutant concentrations. The reliability of this assumption is low in Auckland because wind patterns and sea breezes and hilly terrain affect dispersion. Local modeling is required to ensure accuracy.
* Population benefit uniformity — Not all residents benefit equally. The exposure reductions from busy urban routes exceed those from low-demand suburban routes. The population exposure assessment should prioritize high-density corridors.

4. Research Gap and Research Hypotheses

International research has validated the environmental advantages of battery electric buses (BEBs) for air quality and health but there is little research on how these benefits apply to Auckland's particular urban setting. The coastal position of Auckland and its mountainous terrain together with changing wind patterns produce microclimates which prevent direct application of research results from other cities. There is not enough scientific evidence available about how the deployment of BEBs affects ultrafine particulate matter (UFP) concentrations in particular bus routes across Auckland. The current research depends on model emission data and general population exposure assumptions instead of using actual measurements from specific bus routes. The data collected in this research includes UFP measurements from three major bus routes in Auckland. The available data enables researchers to investigate how different BEB deployment strategies affect UFP concentrations in the surrounding environment.

The following research hypotheses were developed to address the identified gaps in the study:

* H1: The replacement of diesel buses with BEBs on busy Auckland routes will decrease the UFP concentrations found along these transportation paths.
* H2: The UFP emissions from routes will decrease when electric buses make up a larger percentage of the total bus fleet compared to diesel or hybrid buses.
* H3: The implementation of BEB systems will produce greater emission reductions when different population exposure conditions are considered.

5. Methodology

The research examined how diesel buses and battery electric buses (BEBs) affect ultrafine particulate matter (UFP) levels throughout three downtown Auckland routes. The current operational conditions of diesel buses are shown through UFP measurement results but BEB emissions were estimated by assuming no exhaust emissions from electric buses. The research team conducted UFP measurements at two times per day to observe the effects of changing traffic patterns and environmental conditions. The p-track instruments received calibration through reference aerosol generators that produced particles of known concentration and underwent testing in clean air environments. The co-location tests used multiple devices at the same site to determine systematic differences and obtain correction factors. The monitoring period included regular calibrations which confirmed that observed emission changes between diesel buses and BEB-dominated routes were genuine rather than instrument-related errors.

The evaluation of ultrafine particulate matter (UFP) concentration changes from diesel bus to battery electric bus (BEB) replacement in Auckland's central business district (CBD) focused on areas with high bus traffic. The researchers divided each route into sections according to UFP measurements and bus traffic statistics to separate busy bus routes from areas with minimal or no bus presence. The researchers determined which bus type (diesel or BEB) operated as the main vehicle in these high-traffic segments. The researchers compared UFP concentrations between diesel-dominated areas and areas with more BEB presence to determine if bus type affects particulate matter levels.

For each route, UFP concentrations associated with buses were weighted according to the proportion of diesel or BEB vehicles:

This calculation estimates the percentage reduction in UFP concentrations on segments dominated by electric buses compared to those dominated by diesel buses.:

The analysis also compared sections of different routes to examine the spatial variability of ultrafine particulate matter (UFP) concentrations. All sampling routes were first divided into sections, with sections with higher bus traffic identified. Based on the proportion of bus types, these sections with higher bus traffic were categorized into two types: sections with a higher proportion of pure electric buses and sections dominated by other types of buses (diesel or hybrid). Subsequently, the UFP concentration differences between the two types of segments were compared within the same period (e.g., morning rush hour or afternoon) to determine whether a higher proportion of pure electric buses is associated with lower UFP emissions. The relative differences between these segments can be calculated using the same formula () described earlier.

Finally, by incorporating measurement data from the morning and midday periods, which reflect changes in traffic flow and pedestrian density, the temporal dimension is included in the analysis. To assess the differences between morning and midday measurement data and estimate reductions in population exposure, the following formula is applied to each segment:

where ​ is the number of pedestrians or residents along different routs. Total route-level exposure reduction is then:

By comparing ​ across different times of day (morning peak vs midday), the analysis evaluates whether BEB replacement provides greater public health benefits during periods of higher traffic and population density.

The research contains several constraints which affect its results. The analysis of UFP concentration levels becomes challenging because different routes experience varying levels of traffic density which might affect the results between electric buses and other traffic factors. The absence of detailed traffic data for all vehicles makes it impossible to separate bus type effects from other traffic-related factors that influence UFP concentrations. Different environmental conditions exist between various routes which create challenges for analysis. The UFP dispersion patterns and background concentrations show variations because some routes pass near coastal areas while others run through urban streets and park spaces. The observed UFP concentration differences between routes become uncertain because environmental or geographical factors might influence the results instead of bus type effects. The uncertainty in UFP concentration estimates increases because weather changes and daily traffic pattern variations affect UFP concentrations (Zhou et al., 2016). The study delivers important findings about how battery electric buses can decrease urban particulate matter exposure despite its limitations.

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