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SCHOOL OF DEVELOPMENT STUDIES CENTER FOR RURAL, LOCAL AND REGIONAL DEVELOPMENT STUDIES

SPATIAL-TEMPORAL VARIATIONS AND INFLUENCING FACTORS OF CARBON MONOXIDE EXPOSURE IN UNDERGROUND PARKING FACILITY: A CASE STUDY OF MESKEL SQUARE, ADDIS ABABA, ETHIOPIA

BY: AZARIA ABEBE

ADVISOR: ENGDAWORK ASSEFA (PhD)

A Thesis Submitted to the Center for Rural, Local and Regional Development Studies, School of Development Studies, Addis Ababa University in Partial Fulfillment for the Requirements of MA Degree in Development Studies (Environment and Sustainable Development)

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DECLARATION

I, Azaria Abebe, confirm that this thesis is the product of an independent study conducted under the auspices of the Center for Rural, Local and Regional Development Studies, School of Development Studies, Addis Ababa University, Ethiopia. This research, titled " Spatial-Temporal Variations and Influencing Factors of Carbon Monoxide Exposure in Underground Parking Facility: A Case Study of Meskel Square, Addis Ababa, Ethiopia. " was undertaken to explore a previously uninvestigated topic, and to the best of my knowledge, it represents wholly original work that has not been submitted elsewhere for any academic credit. All concepts, perspectives, and research findings from other scholars have been duly acknowledged and referenced.

Name of candidate	Signature	Date
Name of advisor	Signature	Date

APPROVAL

This is to declare that the thesis prepared by **Azaria Abebe**, entitled: ‘‘**Spatial-Temporal Variations and Influencing Factors of Carbon Monoxide Exposure in Underground Parking Facility: A Case Study of Meskel Square, Addis Ababa, Ethiopia.** ’’ submitted in partial fulfillment of the requirements for the award of the Degree of Master of Arts (Environment and Sustainable Development) complies with the regulation of the university and meets the accepted standards with respect to originality and quality.

Signed by the Examinee Committee.

Advisor: __________________________Signature: _____________Date:______________

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ABSTRACT

Urban underground parking facilities, while managing surface congestion, pose significant indoor air quality risks from vehicular Carbon Monoxide (CO). This study comprehensively assessed CO spatial-temporal variations, identified influencing factors, and evaluated existing control mechanisms' effectiveness and compliance in the Meskel Square Underground Parking Facility, Addis Ababa. Employing a mixed-methods approach, 432 hourly CO readings from 18 fixed sensors across six zones were integrated with traffic/ventilation logs and qualitative observations from five key informant interviews. Quantitative data were analyzed through descriptive statistics and a Linear Mixed-Effects Model (LMM). The study revealed significant spatial heterogeneity, with Central Parking Zone 1 exhibiting the highest mean CO at 11.92 ppm and entrance/exit zones the lowest (e.g., 5.29 ppm). Temporally, CO progressively increased from morning to evening, peaking at 13.05 ppm during evening hours, with weekend bazaars consistently showing the highest pollution burden (mean 13.07 ppm). CO concentrations frequently exceeded World Health Organization (WHO) and Federal Democratic Republic of Ethiopia Environmental Protection Authority (EPA) permissible limits; Central Parking Zone 1, for instance, reached 31.5 ppm mean CO level or 40 ppm highest individual measurement (1-hour) and 18.3 ppm (8-hour, 103% exceedance of 9 ppm limit) during weekend bazaars. The LMM confirmed that zone, time period, day type, traffic count ($\beta = 0.109$ ppm/vehicle), and ventilation status all significantly influenced CO levels. Qualitative insights revealed critical ventilation management challenges, including manual control, low-speed operation, lack of automation, and maintenance gaps, resulting in poor Air Changes per Hour (ACH) performance below American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 62.1 standards in multiple zones. The study concludes that inconsistent ventilation, institutional inaction, and inadequate protective measures contribute significantly to acute and chronic CO exposure risks for workers and visitors. It recommends automated sensor-based ventilation systems, fan redesign, stricter traffic/idling controls, enhanced occupational safety protocols, and alignment with international health and ventilation standards.

Keywords: Carbon Monoxide (CO); Underground Parking; Indoor Air Quality; Ventilation Compliance; WHO/EPA Standards; Occupational Health; ASHRAE 62.1.

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Last, but certainly not least, I extend my heartfelt thanks to my family for their unconditional love, patience, and understanding. Their moral support and continuous encouragement were a source of strength that helped me stay focused and committed throughout the research process.

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LIST OF ACRONYMS

AMCA - Air Movement and Control Association

ACGIH - American Conference of Governmental Industrial Hygienists

ATPS - African Technology Policy Studies

CAA - Clean Air Act

CDC - Centers for Disease Control and Prevention

CO - Carbon Monoxide

COHb - Carboxyhemoglobin

COPD - Chronic Obstructive Pulmonary Disease

EPA - Environmental Protection Agency

EU - European Union

HAPs - Hazardous Air Pollutants

HEI - Health Effects Institute

IAP - Indoor Air Pollution

NAAQS - National Ambient Air Quality Standards

NCGs - Non-Condensed Gases

NIH - National Institute of Health

NIOSH - National Institute for Occupational Safety and Health

NOx - Nitrogen Oxides

OSHA - Occupational Safety and Health Administration

PEL - Permissible Exposure Limit

PM - Particulate Matter

PPM - Parts Per Million

SOx - Sulfur Oxides

UNEP - United Nations Environment Programme

UNIDO - United Nations Industrial Development Organization

WHO - World Health Organization

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Air pollution, defined as the presence of harmful substances in the atmosphere at concentrations that endanger human health, ecosystems, and materials (EPA, 2024a), remains one of the most pressing environmental and public health challenges globally. According to the State of Global Air Report 2024 by the Health Effects Institute (HEI), air pollution has become the second leading risk factor for premature death, contributing to an estimated 8.1 million fatalities globally each year (HEI, 2024). Major forms of air pollution include fine particulate matter (PM), greenhouse gases (GHGs), and toxic gases such as carbon monoxide (CO), all of which are primarily generated by household energy use, industrial activity, transportation, and agriculture.

Among these pollutants, carbon monoxide (CO) poses a significant health risk, particularly in urban environments where traffic density is high. CO is a colorless, odorless gas produced primarily by the incomplete combustion of fossil fuels, especially from motor vehicles (EPA, 2024b). According to the World Health Organization (WHO), CO readily binds to hemoglobin, forming carboxyhemoglobin and thus impairing the body's ability to deliver oxygen to vital organs. Exposure to elevated CO levels can lead to dizziness, fatigue, headaches, and even death in extreme cases (WHO, 2021). The burden of air pollution, including CO, is not uniformly distributed globally, with cities in developing nations, particularly in Africa, often experiencing higher levels due to factors such as older, less efficient vehicle fleets and less stringent regulatory frameworks (NIH, 2022). Conversely, many developed countries have achieved reductions in CO levels through the implementation of stricter emission standards and the adoption of cleaner technologies (Kerolyn. et al., 2023). Regulatory frameworks have been established globally to address these risks, such as the United States Environmental Protection Agency (EPA) setting National Ambient Air Quality Standards (NAAQS) for CO, limiting exposure to a maximum of 9 ppm over the 8-hour period and 35 ppm over a 1-hour period (EPA, 2024c).

In rapidly urbanizing cities like Addis Ababa, Ethiopia, the rise in vehicle ownership has been dramatic in recent years; a 2020 report by the Ethiopian Ministry of Transport noted approximately 630,440 vehicles registered in Addis Ababa alone. This growth in urban population and vehicle ownership has exacerbated challenges related to traffic congestion and environmental degradation (Gunjo et al., 2024; World Bank, 2021). To address increasing parking demand and alleviate surface congestion, the Addis Ababa City Administration initiated infrastructure mega-projects, including the construction of underground parking facilities. The Meskel Square Underground Parking Facility, completed in June 2021, is one such notable example, designed to accommodate up to 1,400 vehicles simultaneously in a strategically central event zone that frequently hosts large-scale bazaars, festivals, and exhibitions (Office of the Mayor, 2021).

While underground parking offers a practical solution to space constraints in dense urban centers, these enclosed facilities inherently introduce new environmental health risks. They can trap vehicular emissions, causing the concentration of pollutants like CO to rise rapidly, especially during peak hours and special event days when traffic volume is at its highest (Nayef. et al., 2020). Without effective ventilation and control mechanisms, CO accumulation in such confined spaces poses serious health threats to both facility users and employees. Despite Ethiopia having air quality regulations under Environmental Pollution Control Proclamation No. 300/2002 (EPA & UNIDO, 2003), effective enforcement and monitoring remain challenging in rapidly developing urban settings.

This research focuses on the Meskel Square Underground Parking Facility to comprehensively examine carbon monoxide pollution, recognizing that the very design of such facilities creates a unique challenge by concentrating emissions in a confined, low-airflow environment. Specifically, this study aims to assess spatial-temporal CO concentration levels and evaluate the effectiveness of existing technical control mechanisms that are intended to mitigate these concentrations. It investigates how CO levels vary across different facility zones and time periods (e.g., weekdays vs. weekends, bazaar days vs. non-bazaar days, and diurnal cycles), and crucially, how existing ventilation practices perform under such varying conditions in managing the imposed CO concentrations. By rigorously identifying critical gaps and health risks within this specific, high-traffic enclosed urban environment, the research seeks to provide evidence-based recommendations crucial for safer and more sustainable underground parking management in

Addis Ababa and similar urban contexts, where such specific local data is currently scarce and highly needed to safeguard public health.

1.2. Statement of the Problem

Carbon monoxide (CO) accumulation in enclosed parking facilities presents a growing but often overlooked public health concern, particularly in rapidly urbanizing cities like Addis Ababa. Numerous international studies have documented the buildup of vehicular emissions in underground parking structures, identifying inadequate ventilation, high traffic volumes, and engine idling as primary contributors to indoor air pollution (Rahmi et al., 2020; Nayef et al., 2020; Villanueva, 2020). However, much of this research has focused on general average concentrations, with limited attention to the complex spatial-temporal variability of CO within parking zones during different operational conditions (Adeyanju & Manohar, 2017; Al-Waked et al., 2020).

In the context of Addis Ababa, these challenges are further intensified by a fast-growing, aging vehicle fleet that lacks modern emission control technologies (Kebede et al., 2022; Redi, 2024a). Although Ethiopia has recently banned the import of gasoline and diesel vehicles to promote electric mobility (Le Monde, 2024), the existing vehicle stock continues to emit substantial amounts of CO, especially in enclosed spaces where ventilation limitations amplify exposure risks (Nigussie, 2023). These risks are exacerbated during peak operational periods such as weekend bazaars, where the Meskel Square Underground Parking Facility experiences significantly elevated vehicle turnover and occupancy, increasing the likelihood of acute CO concentration spikes.

Previous studies conducted both globally and regionally have typically lacked comprehensive integration of key variables that influence indoor CO concentration. These include zone-specific variations, time-based fluctuations, traffic volume, event-based occupancy changes, and actual ventilation performance indicators such as Air Changes per Hour (ACH) (Ho et al., 2003; Nayef et al., 2020). Many focus on outdoor ambient pollution or use simulation-based modeling rather than real-time measurements. Moreover, few studies have employed continuous monitoring approaches that capture short-term (hourly) diurnal patterns and spatio-temporal differences across different operational scenarios. The absence of such integrated assessments limits the applicability of existing research to dynamic operational realities such as those seen in the Meskel Square Underground Parking Facility.

Additionally, while regulatory bodies such as the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA) have established exposure thresholds (WHO, 2021; EPA, 2024c), and ventilation standards such as ASHRAE 62.1 exist to guide indoor air quality management (ASHRAE, 2019), compliance assessment within Ethiopian parking facilities remains rare. Ethiopia's own Environmental Protection Authority (EPA) has adopted WHO guidelines (EPA & UNIDO, 2003), but their implementation in indoor microenvironments is challenged by weak enforcement, limited technical capacity, and low public awareness (Redi, 2024b).

At present, there is no empirical study in Addis Ababa that systematically examines how carbon monoxide levels fluctuate spatially and temporally within underground parking structures under varying operational conditions, nor how these levels relate to ventilation system performance and occupancy patterns during high-intensity events. Understanding these dynamics is critically important to safeguard the health of workers and users, optimize ventilation operations, and inform regulatory interventions.

To address these knowledge gaps, the present study investigates carbon monoxide concentrations across multiple zones, time periods, and operational scenarios at the Meskel Square Underground Parking Facility, while examining the role of traffic volume and ventilation operation on CO variability. This integrated approach not only responds to existing empirical gaps but also provides a locally relevant evidence base to inform more effective management and policy solutions for similar urban underground parking environments in Ethiopia.

1.3. Objectives of the Study

The main objective of the study is to assess the spatial and temporal variations of carbon monoxide (CO) concentrations and examine the effects of traffic volume, ventilation performance, and operational conditions in relation to established CO exposure limits within the Meskel Square Underground Parking Facility. The specific objectives include:

- To describe the spatial-temporal variations of CO concentration in the Meskel Underground Parking Facility.
- To determine the frequency and percentage of CO level exceedances beyond WHO and EPA 1-hour and 8-hour permissible limits.
- To explore the effects of zone, time period, day type, traffic count, and ventilation status on CO concentration levels.
- To evaluate the effectiveness of the ventilation system in maintaining acceptable indoor air quality.

1.4. Research Questions

The researcher aims to set the following research questions which will be answered by the finding of this study are:

- What are the spatial-temporal patterns of CO concentration across the facility?
- To what extent do CO concentrations exceed the 1-hour and 8-hour permissible exposure limits of WHO and EPA across the measurement periods?
- Which factors; zone, day type, time period, traffic count, ventilation status significantly influence CO concentration levels in the facility?
- How effective is the existing ventilation system in maintaining acceptable carbon monoxide (CO) levels and ensuring indoor air quality within the Meskel Square Underground Parking Facility?

1.5. Significances of the Study

The study will be a significant as it addresses a critical intersection of urban economic activity, environmental sustainability, and public health. By evaluating the effectiveness of existing ventilation systems and quantifying CO emission levels, this research will provide essential data to inform better management practices and can be used as a policy input for the construction and design of such mega-projects by public and private investors to ensure that they do not affect environmental health and to determine the minimum level of pollution in enclosed areas. Methodologically, the integration of spatial-temporal CO mapping and ventilation performance audits establishes a replicable mixed-methods framework for assessing air quality in similar urban settings, bridging gaps between environmental engineering and public health research. Empirically, the study will generate crucial data on CO levels and ventilation system effectiveness within a specific context, adding to the limited existing literature on indoor air quality in Ethiopian parking facilities and providing a baseline for future comparisons and interventions.

1.6. Limitation of the Study

This study encountered certain limitations, though mitigation strategies were employed to minimize their impact on the validity of the findings.

A primary limitation was the absence of portable CO detectors and air velocity measuring instruments, which restricted external validation of the facility's built-in CO sensors and direct measurement of ventilation airflow. To address this, the researcher relied on the available technical specifications of the installed CO sensors and interpreted the data with caution, while also assessing the sensors' operational responsiveness across zones and time periods in relation to traffic patterns.

The study design deliberately avoided manipulating the ventilation system during data collection, to uphold ethical standards and prevent potential exposure risks to facility users and employees. Instead, real-time observations of ventilation fan activity and traffic volumes were recorded to support the interpretation of CO level variations.

Limited access to complete fan performance data was another constraint; however, available design documents and technical catalogs were used to estimate ventilation capacity. Some external factors such as natural airflow, vehicle type, engine conditions, idling duration, ambient temperature, and humidity were not controlled for, which may have contributed to localized variations in CO concentrations. Addressing these factors was beyond the practical scope of this study but remains an area for future research.

Finally, as this study was conducted in a single underground parking facility; Meskel Square Underground Parking caution should be exercised in generalizing the findings to other settings. Nonetheless, the facility's detailed documentation allows for useful comparison in similar urban environments.

1.7. Delimitation (Scope) of the Study

This study is delimited to assessing carbon monoxide (CO) pollution levels and the effectiveness of ventilation systems within the first basement level (Basement 1) of the Meskel Square Underground Parking Facility in Addis Ababa, Ethiopia. The research focuses solely on carbon monoxide (CO) pollution, which is a primary pollutant linked to vehicular emissions in enclosed spaces. Other air pollutants (e.g., NO_2, SO_2, or PM) are excluded due to scope limitations. The scope is limited to evaluating spatial and temporal variations of CO concentrations across six specific zones: Ramp 1, Entrance/Exit Zone 1, Central Parking Zone 1, Central Parking Zone 2, Entrance/Exit Zone 2, and Ramp 2.

The study focuses on analyzing CO level variations over three time periods (morning, afternoon, and evening) and four day types (weekday’s non-bazaar, weekend’s non-bazaar, weekday’s bazaar, and weekend’s bazaar). The CO concentration data were collected using hourly sensor measurements and compared against international standards, namely WHO 1-hour and 8-hour exposure limits and EPA permissible limits.

In addition, the research evaluates key influencing factors on CO concentrations, including traffic count, ventilation status (on/off/mixed), day type, time of day, and parking zones. The ventilation performance is assessed by calculating the Air Changes per Hour (ACH) for each zone based on zone-specific volume and fan capacity, and comparing the results with the ASHRAE 62.1 ventilation standards.

The assessment of the ventilation system was limited to identifying the type, spatial placement, operational status, and general functionality of the installed mechanical ventilation units. This evaluation relied on available specification documents and catalog data to estimate ventilation capacity and air movement, supplemented by on-site inspection. However, the study did not conduct advanced ventilation performance modeling such as Computational Fluid Dynamics (CFD) analysis, due to resource and technical constraints.

1.8. Operational Definition

Carbon Monoxide (CO): A colorless, odorless, and tasteless gas produced by the incomplete combustion of fossil fuels. In this study, CO is the primary pollutant measured to assess indoor air quality in the underground parking facility.

CO Concentration (ppm): The amount of carbon monoxide measured in parts per million (ppm). This study records 1-hour and 8-hour average CO levels in accordance with international exposure standards.

CO Sensor: A fixed electronic device installed within the underground parking facility that detects and reports ambient carbon monoxide levels in ppm. These sensors are the primary instruments used in this study to collect CO data.

Underground Parking Facility: A below-ground structure designated for vehicle parking. For this study, it refers specifically to the Meskel Square Underground Parking in Addis Ababa, which contains two basements, one of which (comprising six zones) was selected for detailed CO monitoring.

Supply Fan: A mechanical ventilation fan used to push fresh outdoor air into the enclosed parking environment. In this study, supply fans are critical for diluting indoor air pollutants, including carbon monoxide.

Extract Fan: A mechanical ventilation component that removes indoor air from the parking facility to the outside environment. Its role in this study is to reduce pollutant buildup, particularly CO, by promoting air exchange.

Jet Fan (Centrifugal Fan): A type of high-speed fan used to create air movement within large enclosed spaces without ductwork. In this study, jet fans are positioned inside the parking area to direct airflow and aid in the horizontal distribution and dilution of pollutants such as CO.

Ventilation System: A system composed of supply, extract, and jet fans installed to control air quality and ensure the removal or dilution of pollutants. This study examines the type, location, and operational status of these systems.

Spatial Variation: Differences in CO concentration across different physical locations within the parking facility, including ramp zones, central zones, and entrance/exit zones.

Temporal Variation: Fluctuations in CO levels over different times of day (morning, afternoon, and evening) and types of day (weekday, weekend, bazaar, and non-bazaar).

Exposure Limit: The maximum permissible concentration of CO to which individuals can be exposed without adverse health effects. This study references WHO guidelines, including the 1-hour (25 ppm) and 8-hour (10 ppm) exposure limits.

1.9. Organization of the paper

This thesis is structured into five main chapters. Chapter One provides an introduction to the study, including the background, statement of the problem, research objectives and questions, significance, limitations, scope of the study and operational definitions. Chapter Two presents a review of relevant literature, covering theoretical perspectives, previous empirical findings, and conceptual frameworks related to carbon monoxide pollution, ventilation systems, and health impacts in enclosed environments. Chapter Three outlines the research methodology employed, including the study area, research design, data collection tools (such as structured checklist, observation, interviews with key stakeholders, and document reviews), sampling methods, and data analysis procedures used to examine spatial and temporal variations of CO levels and the effectiveness of the ventilation system. Chapter Four presents the results of the study along with a detailed discussion and interpretation of the findings in relation to existing literature and established standards. Finally, Chapter Five provides conclusions drawn from the study and offers recommendations for improving air quality management in underground parking facilities, as well as suggestions for further research.

CHAPTER TWO

REVIEW OF THE RELATED LITERATURE

2.1. Conceptual Definition

To facilitate understanding, this study will define the following terms:

- **Air Pollutions**: It is defined as any atmospheric condition in which certain substances are present in excessive quantity that can produce undesirable effects on human being and on the environment. These substances include gases (SOx, NOx, CO, HCs, etc) particulate matter (smoke, dust, fumes, aerosols) radioactive materials and many others (EPA, 2024a).
- **Carbon monoxide**: is a colorless, odorless, and toxic gas produced by incomplete combustion of carbon-containing fuels, such as gasoline in vehicles. The greatest sources of CO to outdoor air are cars, trucks and other vehicles or machinery that burn fossil fuels. A variety of items in your home such as unvented kerosene and gas space heaters, leaking chimneys and furnaces, and gas stoves also release CO and can affect air quality indoors(EPA, 2024b).
- **CO Pollution Concentration**: CO concentration is typically measured in parts per million (ppm) and indicates the level of CO present in a given volume of air. Safe levels in occupational settings are regulated by health authorities. For example, the Occupational Safety and Health Administration (OSHA) recommends a permissible exposure limit (PEL) of 50 ppm over an 8-hour workday (WHO, 2010) and 10000 $\mu g/m^3$ (EPA, 2003).
- **Environmental Health:** Environmental health encompasses those aspects of human health determined by physical, chemical, biological, social, and psychosocial factors in the environment (WHO, 2019).
- **Vehicular Pollution:** is defined as pollution caused by vehicles which comprises of exhaust (pollution) released into the air (environment) from a vehicle (car, truck, bus). Vehicular emissions constitute a threat, both to the environment and global health in terms of climate change and air pollution respectively (ATPS, 2013).
- **Underground Parking Facilities:** means a parking space located within the basement of a principal building or within a building or part thereof, the roof of which is underground

and below grade. Underground parking garages are either fully or partially closed. While only some of the partially closed garages are required by standard and regulations to install an electro-mechanical smoke control system, fully enclosed garages that exceed one underground level are always required to install such systems (Netanel D, 2011).

- **Ventilation Systems:** The ventilation of buildings is used to maintain indoor air quality and thermal comfort. The purpose of ventilation is to eliminate airborne contaminants, which are generated both by human activity and by the building itself. In order to attain these objectives, airflow rate should be controlled. The minimal airflow rate is determined by indoor air quality requirements so that the maximal concentration for every pollutant is lower than the maximum admitted (Claude-Alain Roulet, 2012).
- **Health Risks:** The Environmental Protection Agency (EPA, 2016) considers risk to be: "The chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor". Therefore, a human health risk is described as: "The likelihood that a given exposure or series of exposures may have damaged or will damage the health of individuals" (EPA, 2016).
- **Regulation of Air Pollutions:** Legislation establishing air quality standards to limit the amount of pollutants entering the environment. These include particulate matter (PM), acid gases, greenhouse gases, organic vapors such as hazardous air pollutants (HAPs), volatile organic compounds (VOCs), non-condensed gases (NCGs), aerosols, dioxins, oxides of nitrogen (NOx), metals and others (Ranjit and Pratima, 2016).
- **Managing Air Quality Implementation:** is the set of activities to ensure that control strategies are put into effect and that air quality goals and standards are fulfilled (EPA, 2024e).

2.2. Theoretical framework

This study is grounded in environmental health and indoor air quality (IAQ) theories that explain how confined built environments, such as underground parking facilities, influence pollutant accumulation, particularly carbon monoxide (CO). The framework incorporates theoretical principles and standard-setting guidelines from occupational safety, environmental engineering, and public health. The following theories are:

CO Dispersion in Enclosed Spaces: CO concentration varies across time and space based on emission sources (vehicle traffic), air movement, and ventilation effectiveness. This is explained by Indoor Air Quality and Pollutant Dispersion Theory (Seinfeld & Pandis, 2016), which supports analyzing spatial and temporal variations across different zones, time periods, and day types.

Health-Based Exposure Standards: The dose-response model in environmental health underpins assessment of CO exceedance against WHO (2010) and US EPA permissible limits (1-hour and 8-hour thresholds) (EPA, 2024c). These models link exposure duration and concentration to human health impacts.

Multifactorial Influences on CO Levels: The study uses Environmental Systems Theory and Hierarchical Modeling to analyze how fixed effects (zone, time, day type, traffic count, ventilation status) interact to influence CO levels. This supports the use of Mixed-Effects Models in SPSS to address repeated measurements within zones and times.

Ventilation Performance and Compliance: The evaluation of ACH (Air Changes per Hour) uses Ventilation Design Theory based on ASHRAE Standard 62.1(2019), which specifies minimum air exchange requirements. This supports determining compliance using zone-specific fan capacity and volume data.

2.3. Empirical Literature

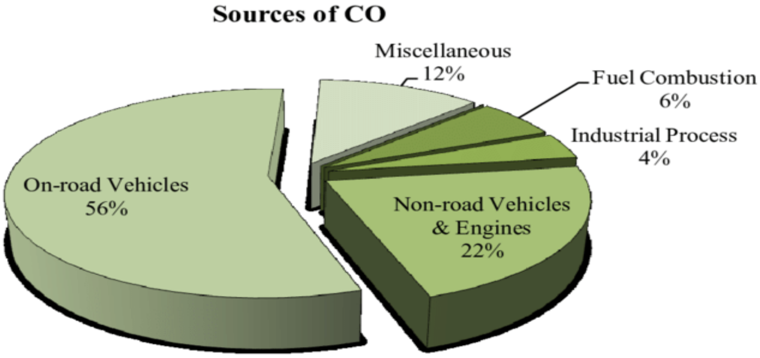
2.3.1. Carbon monoxide: Features and Sources

Carbon monoxide (CO) is a colorless, practically odorless, and tasteless gas or liquid, which results from the incomplete oxidation of carbon during combustion processes. It burns with a violet flame and is slightly soluble in water, but more readily soluble in alcohol and benzene. The specific gravity of CO is 0.96716, with a boiling point of -190°C, a solidification point of -207°C, and a specific volume of 13.8 cubic feet per pound at 70°F. Its auto-ignition temperature (in liquid form) is 1128°F, and it is classified as an inorganic compound (Cerullo, 2023).

According to Gizaw Z. and Teka Z. (2020), common sources contributing to elevated indoor concentrations of carbon monoxide include vehicle emissions, cooking indoors, and the use of kerosene for cooking. While indoor air can be significantly affected by household sources, the major contributors to outdoor CO pollution are cars, trucks, and various machinery that burn fossil fuels. The United States Environmental Protection Agency (EPA, 2024) further explains that multiple indoor sources contribute to CO emissions. These include unvented kerosene and gas space heaters, leaking chimneys and furnaces, and back-drafting from appliances such as furnaces, gas water heaters, wood stoves, and fireplaces. Additionally, gas stoves, generators, and other gasoline-powered equipment release CO into indoor air. Automobile exhaust from attached garages and tobacco smoke are also significant contributors. High indoor CO concentrations can result from incomplete oxidation during combustion in gas ranges and unvented gas or kerosene heaters, further compromising indoor air quality.

Worn or poorly adjusted and maintained combustion devices (e.g., boilers, furnaces) can be significant sources, or if the flue is improperly sized, blocked, disconnected, or is leaking. Auto, truck, or bus exhaust from attached garages, nearby roads, or parking areas can also be a source.

Figure 1: Sources of CO



Source: U.S. EPA (2011)

2.3.2. Standards for CO exposure

The OSHA PEL for CO is 50 parts per million (ppm). OSHA standards prohibit worker exposure to more than 50 parts of CO gas per million parts of air averaged during an 8-hour time period

(WHO, 2010). The WHO advises on guideline levels for various air pollutants that should not be surpassed in order to safeguard public health. The following table underscores WHO guidelines for CO levels in indoor air.

Table 1: WHO Guidelines for CO levels in indoor air

Concentration	**Averaging Time**
90 ppm/100 mg/m^3	15 Minute
50 ppm/60 mg/m^3	30 Minute
25 ppm/30 mg/m^3	1 Hour
9 ppm/10 mg/m^3	8 Hour

Source: WHO (2000)

2.3.3. Health Effects of Carbon Monoxide

Carbon monoxide is harmful when inhaled because it displaces oxygen in the blood, depriving vital organs such as the heart and brain of oxygen. High levels of CO can incapacitate you within minutes without warning, leading to loss of consciousness and suffocation (OSHA, 2012).

Carbon monoxide (CO) quickly crosses the membranes of the alveoli, capillaries, and placenta. Once absorbed, about 80-90% of CO binds to hemoglobin, creating carboxyhemoglobin (COHb), a specific marker of CO exposure in the blood. Hemoglobin has a 200-250 times greater affinity for CO than for oxygen. When exposed to a consistent CO concentration, COHb levels rise sharply at first, stabilize after roughly three hours, and reach a steady state after six to eight hours. In fetuses, the half-life of CO elimination is much longer than in pregnant mothers. The formation of COHb reduces blood's ability to carry oxygen and hinders the release of oxygen from hemoglobin, leading to tissue hypoxia even at low CO exposure levels (EPA & UNIDO, 2003).

At higher CO concentrations, the absorbed CO also binds to other heme-containing proteins, such as myoglobin, cytochrome oxidase, and cytochrome P-450. CO toxicity initially manifests in organs and tissues with high oxygen demands, such as the brain, heart, active skeletal muscles, and the developing fetus. Severe hypoxia from acute CO poisoning can result in short-term reversible neurological effects or prolonged and often delayed neurological damage.

Neurobehavioral impairments, including reduced coordination, tracking ability, driving skills, alertness, and cognitive function, can occur at COHb levels as low as 5.1-8.2%. Even in healthy individuals, maximal exercise capacity declines when COHb levels reach as low as 5%. A linear relationship exists between increased COHb levels (above 4%) and reduced maximal oxygen consumption, with a roughly 1% decrease in oxygen consumption for every 1% rise in COHb (EPA & UNIDO, 2003). U.S Department of Labor produced the following material on the effects of Carbon Monoxide at the different concentrations from the OSHA.

Table 2: Effects of Carbon Monoxide at Different Concentrations

PPM	**%**	**TIME**	**EFFECT**
35	0.0035	6 - 8 hrs	Headache & dizziness with constant exposure.
50	0.0050	8 hrs	Permissible Exposure Level - in any 8 hour period per OSHA.
100	0.01	2 - 3 hrs	Slight headache
200	0.02	2 - 3 hrs	Slight mild frontal headache, discomfort, loss of judgment, loss of vision, irritability. Should not be exposed to this level.
400	0.04	1 - 2 hrs	Frontal headache & nausea. Life threatening after 3 hours.
800	0.08	45 minutes	Dizziness, nausea, & convulsions insensible. Collapse within 2 hours & possible death
1,600	0.16	20 minutes	Headache, tachycardia, dizziness, & nausea. Confusion. Staggering. Death < 2 hours
3,200	0.32	5 - 10 minutes	Headache, dizziness & nausea. Unconscious 10-15 minutes. Death within 30 minutes
6,400	0.64	1 - 2 minutes	Headache, dizziness & nausea. Convulsions, respiratory arrest. Death < 20 minutes.
12,800	1.28	2 minutes	Unconsciousness after 2-3 breaths. Death < 3 minutes

Source: OSHA (2015)

2.3.4. Vehicular Air Pollutions

Motor vehicle emissions result from fuel combustion or evaporation. The most common types of transport fuels are gasoline (in leaded or unleaded form) for light-duty vehicles (such as cars) and diesel fuel for heavy-duty vehicles such as buses and trucks. Emissions from motor vehicles with spark ignition engines for example, gasoline-fueled vehicles are from the exhaust, engine crankcase, and fuel system (carburetor, fuel line, and fuel tank) (Bekir O and Surhid P.G, 1997). The major pollutants emitted from gasoline-fueled vehicles are CO, HC, NOx, and lead (only for leaded gasoline fuel). For a given fuel quality, concentrations of many of these pollutants are influenced by such factors as the air-fuel ratio in the cylinder at the time of combustion, ignition timing, combustion chamber geometry, engine parameters (for example, speed, load, and engine temperature), and use of emission control devices (Hui M et al. 2021). Let's look how light-duty gasoline-fueled vehicles have emission level at different driving modes.

Table 3: Exhaust Emissions from Uncontrolled Light-Duty Gasoline-Fueled Vehicles at Different Driving Modes (Parts Per Million)

Mode	**CO**	**HC**	**NOx**	**CO_2**
Idling	16	1.3	0.1	68
Accelerating: mph = Mile per hour.				
• 0–15 mph	2,997	536	62	10,928
• 0–30 mph	3,773	757	212	19,118
Cruising:				
• 15 mph	67	5.1	0.8	374
• 30 mph	30	3.0	2.0	323
• 45 mph	28	2.9	4.2	355
• 60 mph	29	2.9	6.4	402
Decelerating:				
• 15–0 mph	1,902	344	21	5,241

• 30–0 mph	1,390	353	41	6,111

Source: Bellomo and Liff (1984).

2.3.5. Devices and Measurements of Air Pollutions

Air quality measured is a fundamental aspect of environmental engineering that enables us to assess and monitor the levels of pollutants in the atmosphere. Gas analyzers and sensors are essential tools used in air quality measurement (Sachin B, 2023). These devices detect and quantify specific gasses or pollutants present in the atmosphere. For example, electrochemical sensors are commonly used to measure gasses such as carbon monoxide, nitrogen dioxide, and ozone. The determination of the atmospheric CO concentration is still a challenge; despite the variety of analytical techniques available, there is still remaining uncertainty (Karolina S, et.al, 2022).

2.3.6. Ventilation Systems

Parking garage ventilation is an essential consideration for building designers due to the role it plays in ensuring the safety, comfort, and well-being of the building occupants. Proper ventilation in parking garages is how pollutants, such as carbon monoxide, that can accumulate from the exhaust fumes vehicles emit, are removed (RWDI, 2024). Effective ventilation is also an opportunity to achieve energy and cost savings in the parking garage. Ground parking garages may have multiple types of ventilation designs available to dilute and remove air pollutants and ensure adequate air quality in the garage. According to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2019), the common types of ventilation systems used in underground parking are:

- **Natural Ventilation**: Natural ventilation occurs when the air in a space is exchanged outside without using mechanical systems such as fans. Common types of natural ventilation are made through open windows but can also be achieved through differences in temperature and pressure between spaces. However, opening a window or grounded structure is not a good choice for basement ventilation or underground structures (Huong and Thien, 2020).
- **Mechanical Ventilation**: Mechanical ventilation or forced system is through anair handling unit or directly into space by fans (Huong and Thien, 2020). There are two

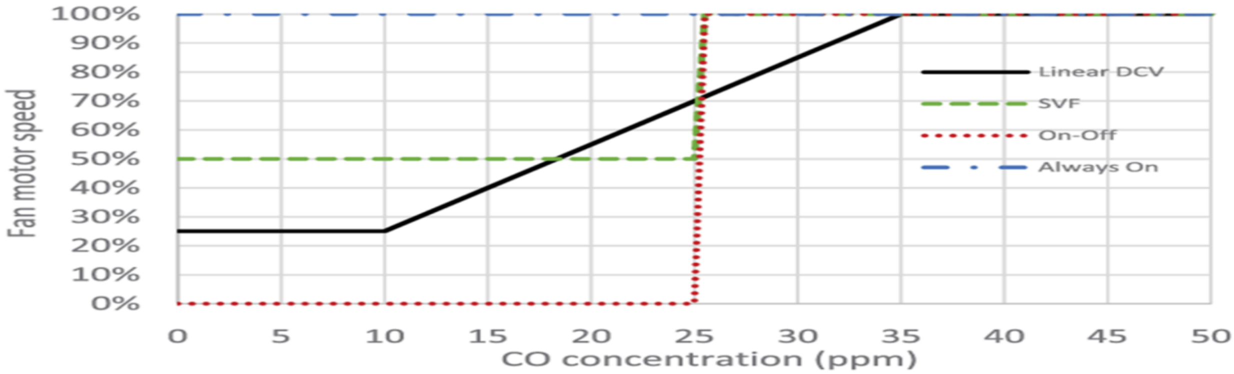
primary types of mechanical ventilation systems: exhaust ventilation, which removes air from a space, and supply ventilation, which brings fresh air in. Mixed-mode ventilation combines both to maintain a balance of air quality (ASHRAE, 2017). Jet fan ventilation systems are also mechanical ventilation systems available for day-to-day ventilation in underground car parks. Jet Fans work with the principal of pushing the air masses at discharge opening with the high air velocity they create and mobilize with the induction principle (Yu X et al., 2022). According to Yu X et al., (2022), There are two types of jet fans used in underground parking garages: axial and centrifugal. Axial fans discharge air parallel to the axis of the impeller rotation. Axial fans are often used in low-pressure, high-volume applications, such as cooling electronic components or ventilating enclosed spaces. But centrifugal fans discharge air perpendicular to the axis of the impeller rotation. Centrifugal fans are often used in applications that require higher pressure, such as air conditioning systems, industrial ventilation, or pneumatic conveying systems.

- **Demand-Controlled Ventilation (DCV)**: A DCV system is designed to supply a quantity of fresh air fitted with the need, ensuring the right quantity of fresh airflow and the right environmental conditions in terms of different parameters e.g., relative humidity (RH), temperature, carbon dioxide (CO2) or volatile organic compound (VOC). Monitors pollutant levels (e.g.CO, NO_2) using sensors and adjusts ventilation rates accordingly. They are energy-efficient and ensures compliance with air quality standards. (Therese O, 2023).

Ventilation Control Strategies

According to Afshin F, et al. (2020), there are four different ventilation control strategies; the simplest strategy, always-On, operates the fan at 100% of maximum speed during operating hours regardless of the CO concentration. In the On-Off strategy, the fan operates at 100% of maximum speed only when CO concentrations in any zone reach a threshold of 25 ppm; the fan does not operate when CO concentrations are below 25 ppm. This approach is commonly used in the industry, and a threshold concentration of 25 ppm was used based on the aforementioned American Conference of Governmental Industrial Hygienists (ACGIH) recommendations (many equipment manufacturers recommend using 25 ppm in practice as well). The Standardized Variable Flow (SVF) strategy is also commonly used in the industry as an energy saving approach whereby the fans operate at 50% of maximum speed until CO concentrations reach 25 ppm, at which point they increase to 100% of maximum speed. Finally, the Linear-DCV strategy assumes that VFDs control fan speed from a minimum of 25% of maximum speed until the average CO concentration in all zones reaches 10 PPM, at which point the fan speed increases linearly until the average CO concentration reaches 35 PPM (i.e., by 3% for every additional 1 ppm of average CO concentration in the space and the fans operate at maximum speed when average CO concentrations are 35 ppm and above.

Figure 2: Fan Motor Speed at Different Concentration



Source: Afshin F, et al. (2020)

Ventilation Rate Requirement for Enclosed Parking Garage

To determine the adequate ventilation rate for parking garages, two factors are typically considered: the number of cars in operation and the emission quantities. The number of cars in operation depends on the type of the facility served by the parking garage and may vary from 3% (in shopping areas) up to 20% (in sports stadiums) of the total vehicle capacity. The emission of carbon monoxide depends on individual cars including factors such as the age of the car, the engine power, and the level of car maintenance (ASHRAE, 2001). Enclosed parking garage ventilation systems shall automatically detect contaminant levels and stage fans or modulate fan airflow rates to 50% or less of design capacity provided acceptable contaminant levels are maintained for enclosed parking facilities, ANSI/ ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality specifies a fixed ventilation rate of below 7.62 L/s·m^2 (1.5 cfm/ft^2) of gross floor area. The CO level within a range of 9 to 35 PPM for average 1 to 8 hour. Therefore, a ventilation flow of about 11.25 air changes per hour is required for garages with 2.5 m (8 ft) ceiling height (ASHRAE, 2001).

So a fixed Air Change per Hour (ACH) rate is a critical parameter in ensuring adequate ventilation in underground parking facilities, especially during periods of high vehicle traffic when pollutant levels, particularly carbon monoxide (CO), can rapidly increase. According to the World Health Organization (WHO, 2021) and guidelines from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), an underground parking garage should maintain a minimum of 6 to 10 air changes per hour (ACH) under normal conditions, which can rise up to 20 ACH during peak traffic periods or emergency situations to effectively dilute and remove harmful emissions. These fixed rates ensure that fresh air replaces contaminated air at a rate fast enough to maintain indoor air quality and protect occupants from exposure to toxic gases. Additionally, the Chartered Institution of Building Services Engineers (CIBSE, 2015) supports similar recommendations, emphasizing that the required ACH should be aligned with the expected vehicle flow, pollutant concentration, and local air quality standards. Maintaining this ventilation performance is vital for occupant health and regulatory compliance in enclosed parking structures.

Factors influencing adoption of air pollution protective measures

The adoption of air pollution control measures is influenced by several factors. A robust regulatory framework with strict enforcement (e.g., emissions standards) and incentives or penalties plays a critical role (Tofikk R, 2024). Economic factors, such as the cost of implementing pollution control technologies and potential savings from efficiency improvements, can encourage or hinder adoption. The availability of advanced technologies and skilled personnel supports adoption. Public awareness, driven by advocacy and media, creates pressure on industries and policymakers (Ying JH., et al, 2024). Additionally, visible health and environmental impacts, such as smog and respiratory issues, often prompt action. Urban planning, infrastructure, and global climate commitments further influence the implementation of air pollution controls (Shubham S, 2023). Thus, addressing these interrelated factors can improve the effectiveness and adoption of pollution control strategies.

2.4. Empirical Review of Policies and Regulations on Air Pollution in Developed and Developing Countries

2.4.1. Air Pollution Policies in Developed Countries

Developed nations have implemented stringent policies and regulations to mitigate air pollution, largely driven by technological advancements, public health awareness, and international commitments. For instance, in the United States, the Clean Air Act (CAA) of 1970 set enforceable limits on emissions of pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen oxides (NOx). The Act requires industries and transport systems to meet national air quality standards, which has significantly reduced CO levels in urban areas (EPA, 2024). The implementation of advanced emission control technologies and regular air quality monitoring has made the CAA a model for other nations (Dockery et al., 1993).

In Europe, the European Union (EU) Ambient Air Quality Directive (2008/50/EC) sets legally binding limits for key pollutants, including CO, PM10, and PM2.5. Countries like Germany and the United Kingdom have adopted Low Emission Zones (LEZs) and incentivized the adoption of electric vehicles (EVs) to reduce vehicular pollution (EEA, 2020). A study by Kumar et al. (2018) highlights that cities implementing these regulations experienced significant improvements in air quality and public health.

2.4.2. Air Pollution Policies in Developing Countries

Developing countries face significant challenges in implementing and enforcing air pollution regulations due to rapid urbanization, industrialization, and resource constraints. For example, in China, the government introduced the Air Pollution Prevention and Control Action Plan in 2013, focusing on reducing coal consumption, controlling industrial emissions, and promoting clean energy sources. Empirical studies show that China's CO levels decreased by over 20% in major cities within five years of implementation (Zhang et al., 2019). However, enforcement remains uneven across regions, particularly in rural areas.

In India, the National Ambient Air Quality Standards (NAAQS) regulate major pollutants, including CO and PM. However, a report by the World Health Organization (WHO) indicates that Indian cities like New Delhi still face severe air pollution due to outdated vehicle emissions, poor enforcement, and dependence on fossil fuels (WHO, 2018). The introduction of Bharat Stage VI (BS-VI) vehicle emission standards in 2020 has shown promise in curbing vehicular emissions (Guttikunda & Goel, 2013).

In Africa, air pollution policies are less developed. For instance, Ethiopia has national environmental policies, but there are limited specific regulations for monitoring and mitigating CO emissions, especially in enclosed spaces such as underground parking facilities. A study by Alam and Eltahir (2019) highlights that African cities suffer from a lack of baseline data, technical expertise, and infrastructure to monitor air quality effectively.

2.4.3. Policy and Regulation of Air Pollutions in Ethiopia

Ethiopia's current policy, legal and regulatory landscape has a wide array of instruments that aim at ensuring clean air for all. Article 44(1), The Constitution of the Federal Democratic Republic of Ethiopia provides good foundation for air quality management by guaranteeing everyone the right to a clean and healthy environment.

Ethiopia's Environmental Pollution Control Proclamation (2002) aims to eliminate, and where not possible, mitigate the impacts of pollution as an undesirable consequence of social and economic development activities. It prohibits persons from engaging in any activities that pollute the environment by violating the relevant environmental standards.

Ethiopia has established air quality standards through the Federal Environmental Protection Authority (EPA) with the objective of safeguarding public health and protecting the environment. The most recent vehicle exhaust emission standards, outlined in the *Guideline on Ambient Environment Standards of Ethiopia* (EPA & UNIDO, 2003), specify limit values for pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), and suspended particulate matter (PM). According to this guideline, the acceptable CO exposure limits are set at 30,000 $\mu g/m^3$ (25 ppm) for a 1-hour exposure and 10,000 $\mu g/m^3$ (9 ppm) for an 8-hour exposure, which align with the World Health Organization (WHO) guidelines for CO concentrations in indoor air. However, these standards do not differentiate between vehicle categories or fuel types, and, as noted by UNEP (2018), they are not currently enforced.

Furthermore, the Addis Ababa City Administration Disaster Prevention, Audit, Inspection, and Qualification System Directive No. 163/2024, under the section on *Safety Standards for Parking Structures*, mandates that "parking areas should establish a system to ensure adequate air circulation." In parallel, the Occupational Safety and Health Directive issued by the Federal Ministry of Labour and Social Affairs, based on Proclamation No. 377/2003, sets the occupational exposure limit for CO at 50 ppm. However, this directive does not specify whether the limit applies to a 1-hour or 8-hour time frame, making it inconsistent with the EPA's ambient environmental standards and WHO guidelines. This inconsistency highlights the need for clearer, harmonized, and enforceable standards for CO exposure across different regulatory frameworks in Ethiopia.

2.5. Conceptual Framework

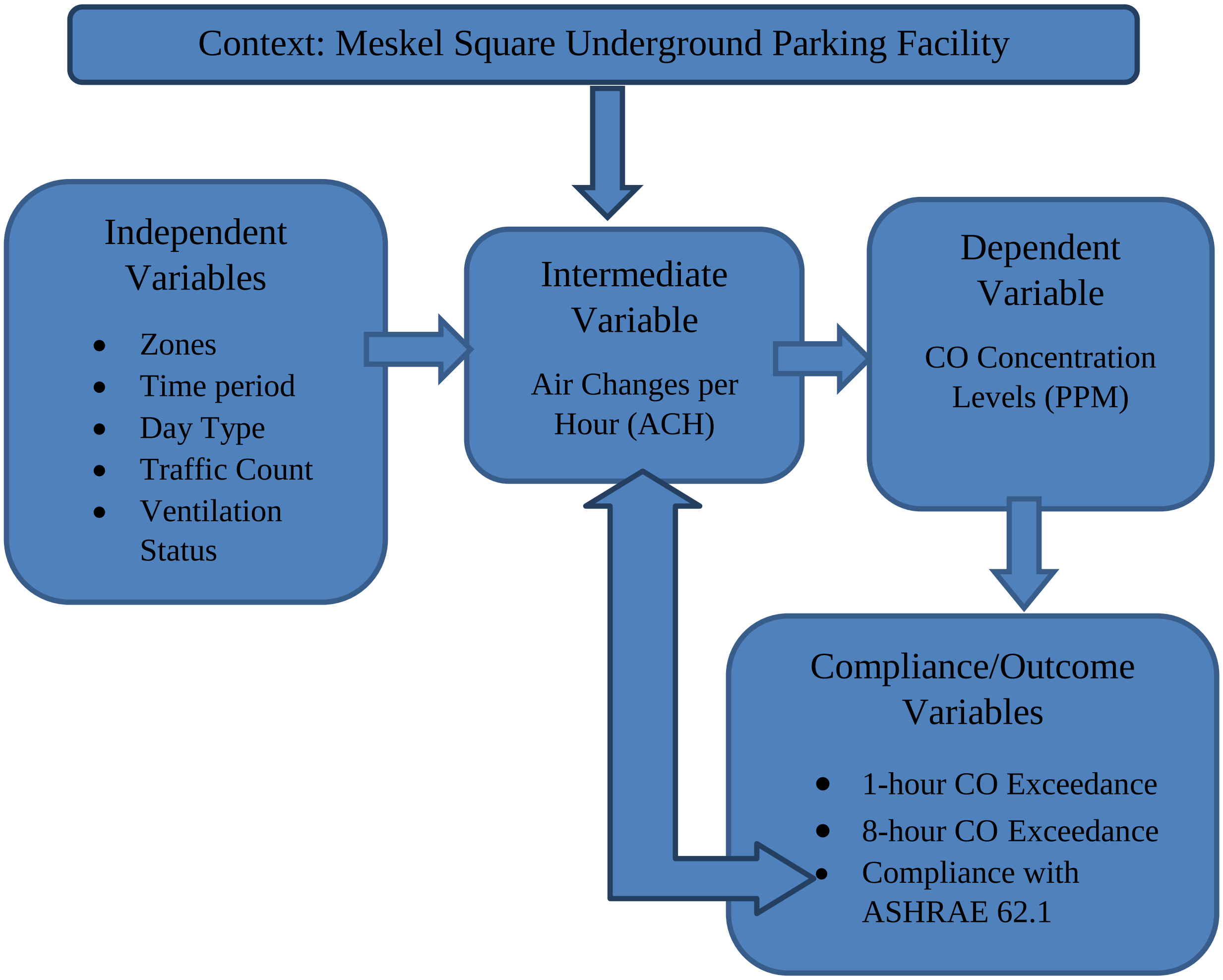
This study's conceptual framework (see Figure X for a visual representation) provides the theoretical lens through which the complex dynamics of Carbon Monoxide (CO) pollution within the Meskel Square Underground Parking Facility are understood and analyzed. It is directly informed by the Indoor Air Quality and Pollutant Dispersion Theories (Seinfeld & Pandis, 2016), which explain how CO is generated from vehicular emissions, disperses through air movement, and accumulates in confined spaces. Similarly, Environmental Systems Theory guides our understanding of how multiple fixed factors interact to influence CO levels, while Health-Based Exposure Standards and Ventilation Design Theory (ASHRAE 62.1, 2019) provide the benchmarks for assessing the resulting air quality and system performance.

At its core, the framework posits that CO concentration (the primary dependent variable, reflecting indoor air quality) is directly influenced by a set of independent variables representing the facility's physical layout (Zones), operational patterns (Time Periods, Day Types, Traffic Count), and existing engineering controls (Ventilation Status). The interaction of these factors determines the generation, transport, and dilution of CO.

Crucially, the framework then links these observed CO levels to health-based exposure standards (WHO and US EPA 1-hour and 8-hour permissible limits) to assess compliance and associated public health risks. The Air Changes per Hour (ACH), derived from fan capacity and zone volume, functions as a critical intermediate measure within this framework, directly reflecting the effectiveness of the ventilation system in diluting CO and maintaining acceptable indoor air quality according to industry standards.

In essence, this conceptual framework moves from identifying the environmental and operational factors that impose CO concentrations within the parking facility, to quantitatively and qualitatively assessing these concentrations against established health and engineering standards, and finally, to evaluating the ventilation system's performance as a key determinant of the overall air quality. It systematically maps the interplay between emission sources, dispersion mechanisms, control measures, and their ultimate impact on the health and safety of occupants within this unique urban infrastructure.

Figure 3: Conceptual Framework



Source: Researcher Own Construct (2025)

CHAPTER THREE

METHODOLOGY

3.1. Description of the Study Area

Meskel Square, located in the heart of Addis Ababa, Ethiopia, has been a major public gathering space for decades. It is widely known for hosting religious celebrations, particularly the Ethiopian Orthodox Tewahedo Church's Meskel Festival, which has taken place there for nearly 60 years (Ethiopian Monitor, 2021). Additionally, the square serves as a venue for public demonstrations and large-scale events.

In 2021, the Addis Ababa City Administration unveiled the Meskel Square Underground Parking Facility as part of the Grand Meskel Square-Addis Ababa City Hall redevelopment project, a state-of-the-art initiative designed to alleviate urban congestion while preserving the square's role as a civic and cultural hub (Office of the Mayor of Addis Ababa, 2021).

The underground parking facility spans 20,014.72 m^2, excluding the landscape and seating areas. It consists of two basement levels, divided into 12 zones, with a total capacity to accommodate 1,400 vehicles.

The facility operates 24/7, providing secure parking services to the public at a rate of 20 Birr per hour. In addition to parking services, the facility includes small retail shops available for rent. The parking lot only accommodates vehicles with a height restriction of 2.1 meters.

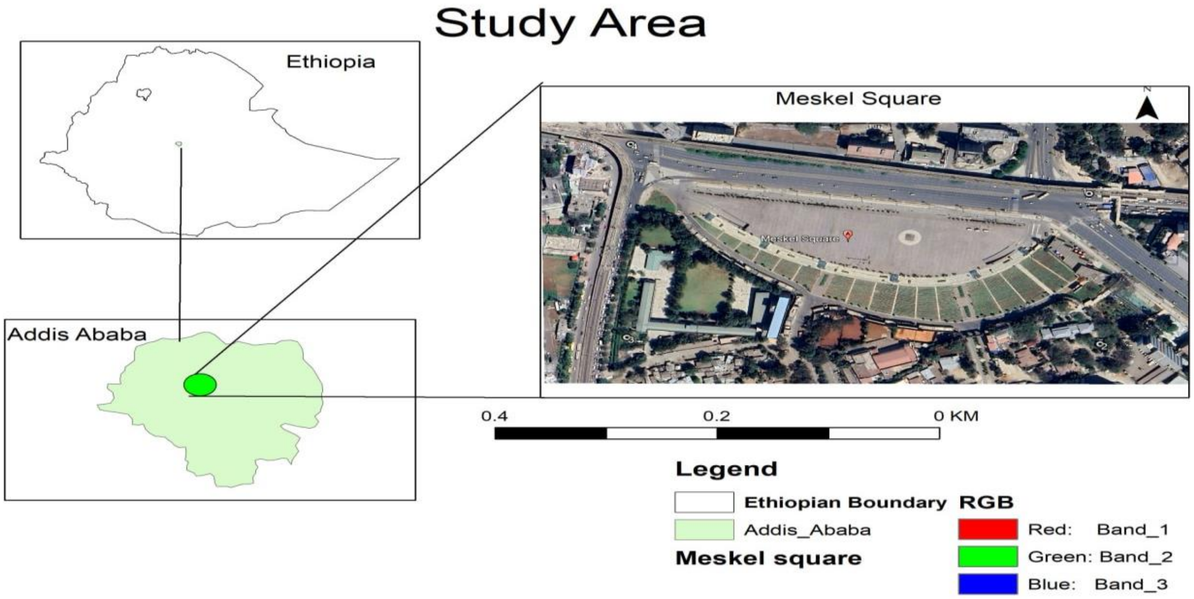
During major events, such as the New Year, Christmas, and Easter bazaars hosted by ECMDE, the parking facility reaches full capacity, as these events attract 1.5 to 2.5 million visitors (G/Michael, 2021). The facility serves a diverse range of customers, including over 200 contract customers who rent parking spaces on a monthly or yearly basis, as well as one-time and frequent customers.

According to the Facility Human Resource Director with a personal communication, the facility currently has 68 permanent employees and 3 contract employees, and also outsources about 140 employees, and provides services with a total of 211 employees, of which 110 are female and the remaining 101 are male.

The parking structure is equipped with essential ventilation and safety systems, including at least 6 CO sensors per zone at a distance 18 – 23 meters and supply fans, jet fans, and extract fans are installed to regulate air quality. When we look at the ventilation system in each zone in Basement 1, where this study was conducted, and the basement is equipped with a comprehensive mechanical ventilation system designed to manage air quality across its six zones. Each zone is fitted with both supply and extract fans, positioned to ensure proper air circulation and dilution of carbon monoxide and other vehicle emissions. As the researcher confirmed in the survey(2025), Ramp Zone 1 with a length of 47.5 m, a width of 52 m and a height of 3.8 m, contains two supply fans of type TA-HT 900-297-6-6, each with 6 poles, and two extract fans of type TA-HT 1120-406-12-6, each with 12 poles. Entrance/Exit Zone 1, with dimensions of 47.7 meters by 85.9 meters and a height of 3.8 meters, features two supply fans of type TA-HT 1000-297-6-6 and two extract fans of the same type as those in Ramp Zone 1, each with 6 poles. Central Parking Zone 1, measuring 39.7 meters by 88 meters with a height of 3.8 meters, is ventilated by two supply fans of type TA-HT 900-297-6-6 and two extract fans of type TA-HT 1120-406-12-6, each with 6 poles. Adjacent to it, Central Parking Zone 2, with dimensions of 39.7 meters by 85.9 meters and a height of 3.8 meters, also uses the same ventilation setup as Central Parking Zone 1. Entrance/Exit Zone 2, measuring 55.8 meters by 69 meters and 3.8 meters in height, includes two supply fans of type TA-HT 1000-297-6-6 with 12 poles and two extract fans of type TA-HT 1120-406-12-6 with 6 poles. Finally, Ramp Zone 2, with dimensions of 79.8 meters by 33.7 meters and a height of 3.8 meters, is equipped with two supply fans of type TA-HT 900-297-6-6-43, each with 6 poles, and two extract fans of type TA-HT 1120-406-12-6, also with 6 poles.

In addition the safety and security of the parking facility are enhanced through CCTV surveillance and an emergency control system. This well-structured underground parking facility plays a crucial role in managing traffic and providing secure parking solutions in Addis Ababa's bustling city center.

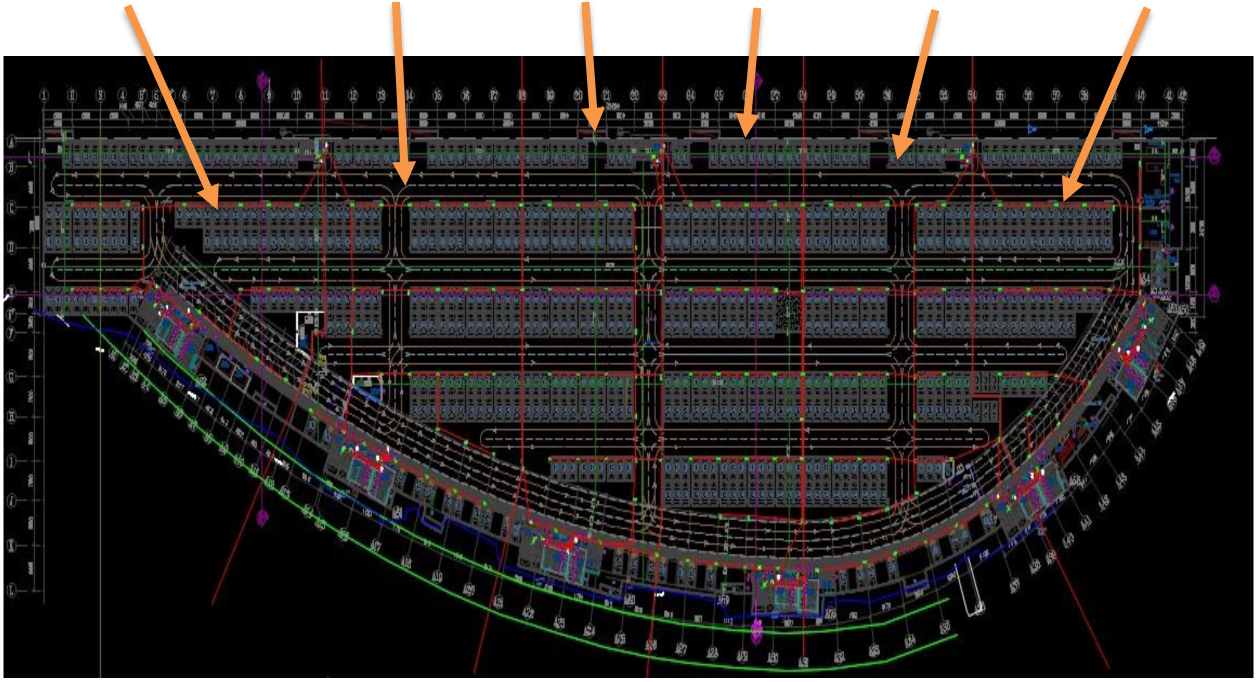
Figure 4: Meskel Square



Source: Own Construct from Google Earth Image (2025)

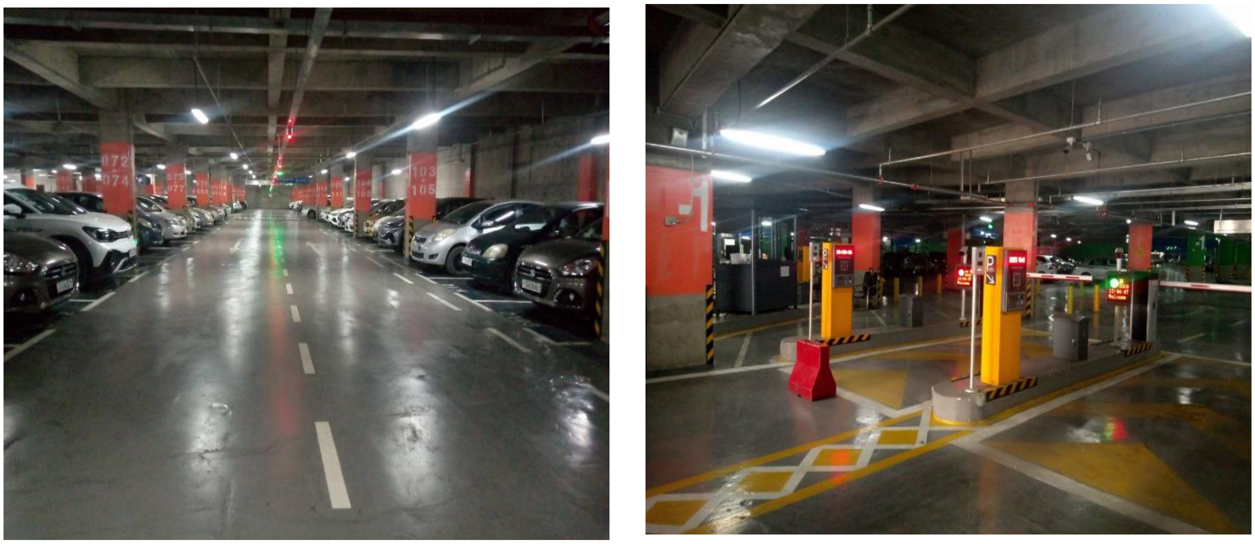
Figure 5: Meskel Square Underground Parking Floor Plan

Ramp Zone 2, Entrance/Exit 2, Central Zone 2, Central Zone 1, Entrance/Exit 1, Ramp Zone 1



Source: Exhibition Center and Market Development Enterprise (2025)

Figure 6: Meskel Square Underground Parking Facility



Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

3.2. Research Design and Approach

This study employs a descriptive and explanatory research design. The descriptive element maps the spatial and temporal variations of carbon monoxide (CO) levels across different parking zones, time periods, and day types. The explanatory component investigates the influence of factors such as traffic count, ventilation status, zone, and time on CO concentration levels using statistical modeling. This integrated design is suitable for environmental and public health research where both pattern identification and causal inference are essential (Creswell & Creswell, 2018).

A quantitative research approach is adopted to measure and analyze numerical data including sensor-based CO concentrations, zone-specific traffic counts, and calculated Air Change per Hour (ACH). This approach allows for the use of statistical models such as Mixed-Effects Models in SPSS to examine repeated measures and fixed effects (Neuman, 2014).

Complementing the quantitative analysis, the study includes a qualitative component through observation. These observational finding help contextualize operational aspects of ventilation performance and CO control measures. This mixed-methods integration provides deeper insights and supports interpretation of quantitative findings (Patton, 2015).

Ventilation compliance assessments were also conducted using technical data from fan catalogs, site inspections, and zone volume calculations to determine ACH and assess compliance with ASHRAE 62.1 standards.

3.3. Population and Sampling Techniques

This study employed a multi-layered purposive sampling strategy to ensure representative spatial-temporal coverage of carbon monoxide (CO) concentrations in the Meskel Square Underground Parking Facility. The environmental population consisted of six operational zones within the first basement level: Ramp Zone 1, Entrance/Exit Zone 1, Central Parking Zones 1 and 2, Entrance/Exit Zone 2, and Ramp Zone 2. Within each zone, three CO sensors were purposively selected and positioned at locations most likely to reflect emission and airflow variability near ventilation outlets, in the central zone area, and along primary traffic lanes. Measurements were recorded across four day types (weekdays and weekends, both bazaar and non-bazaar periods) and three daily time slots (morning, afternoon, and evening), repeated twice, resulting in a total of 432 observations (6 zones × 3 sensors × 4 day types × 3 time periods × 2 repetitions). This approach enabled robust spatial and temporal representation and was sufficient for applying mixed-effects modeling, which handles nested data structures and repeated measures effectively (Field, 2013; West, Welch, & Galecki, 2014). The choice of purposive sampling was based on both practical feasibility and its methodological appropriateness in environmental exposure studies where the aim is to capture variation under typical and high-risk operational conditions (Tongco, 2007).

Qualitative data were gathered through key informant interviews with purposively selected personnel, including three worker representatives from each work shift and two facility managers. These interviews provided valuable insights into operational practices, perceived air quality, ventilation system effectiveness, and challenges related to CO control within the facility.

3.4. Data Type, Sources, and Collection Methods

This study employed both primary and secondary data sources to comprehensively fulfill the research objectives. The primary data collection involved instrumental measurements, manual traffic observations, and key informant interviews (KIIs). Carbon monoxide (CO) concentrations were measured using portable CO sensors, strategically placed across six operational zones in the Meskel Square Underground Parking Facility to capture spatial and temporal variation under different day types (bazaar vs. non-bazaar; weekday vs. weekend) and time periods (morning, afternoon, and evening).

To contextualize CO concentrations, vehicle traffic volume was manually recorded by the researcher simultaneously during each one-hour CO measurement session. This manual approach was supplemented by real-time facility vehicle occupancy display screens, which provide digital counts of overall occupancy, allowing cross-verification and correction of potential observational discrepancies. Ventilation system status including fan operation (ON/OFF), airflow direction (supply/extract), and responsiveness was also manually recorded. Ventilation performance assessment was conducted through the calculation of Air Changes per Hour (ACH) for each zone using airflow data from manufacturer technical catalogs and zone volume measurements. These calculations were cross-checked against international standards such as ASHRAE 62.1 and NFPA 88A for compliance benchmarking.

Additionally, observation checklists were used to document physical conditions of fans, their accessibility, operational consistency, and any visual signs of malfunction. This qualitative information helped to triangulate quantitative ventilation performance results.

The secondary data sources included technical documents such as fan specification sheets, as well as regulatory and guideline standards from recognized international bodies: the World Health Organization (WHO), the United States Environmental Protection Agency (EPA), and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Together, these numerical and narrative data types supported a combination of descriptive, comparative, and explanatory analyses, enabling a holistic understanding of CO exposure dynamics and control mechanisms within the facility.

Figure 7: Lots Occupancy Displays

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

Figure 8: Data Collection

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

3.5. Reliability and Validity of Data Collection Instrument

To ensure the reliability and validity of data collection, the study utilized fixed Graystone CMD5B4000 electrochemical sensors, specifically designed for accurate CO monitoring in enclosed spaces like underground parking facilities. These sensors offer a high detection range (0–500 ppm), with an accuracy of ±5 ppm or 5% of the reading, and a response time of less than 35 seconds, ensuring timely and precise measurements. Their proven performance and 5–7 year operational lifespan support the instrument's technical reliability. Validity was reinforced through sensor calibration prior to deployment and strategic placement across zones to capture representative spatial-temporal CO variations. Additionally, observational checklists enhanced content validity by triangulating quantitative findings with operational context.

3.6. Method of Data Analysis

The study utilized both quantitative and qualitative analytical approaches to provide a comprehensive assessment of carbon monoxide (CO) concentration and its influencing factors in the Meskel Square Underground Parking Facility.

For quantitative analysis, descriptive statistics such as means, standard deviations, and frequencies were employed to summarize spatial-temporal CO concentration patterns across different zones, time periods (morning, afternoon, evening), and day types (weekdays vs. weekends, bazaar vs.

non-bazaar). CO exceedances beyond WHO and EPA 1-hour and 8-hour permissible limits were calculated to determine the frequency and proportion of high-exposure instances.

To examine the influence of operational and contextual variables on CO levels, a Linear Mixed-Effects Model (LMM) was applied. This model was suitable for the study's repeated measures design and nested data structure, accounting for both fixed effects (zone, time period, day type, traffic count, and ventilation status) and random effects (sensor-level variation). The analysis included Type III tests of fixed effects to determine statistical significance, estimates of fixed effects to quantify the magnitude of each predictor's impact, and estimated marginal means with post-hoc comparisons. Quantitative analyses were performed using SPSS version 30.

For the qualitative component, data from key informant interviews (with workers and facility managers) and structured observation checklists were analyzed using thematic coding. Triangulation was employed by comparing qualitative themes with quantitative results such as aligning worker-reported ventilation delays and manual fan control with measured CO concentrations and ventilation performance data.

Table 4: Summary of Analysis

Objective	Data Source	Data Type	Analysis Method	Software/Tool Used	Output/Indicators
1. To describe the spatial and temporal variations of CO concentration across zones, time periods, and day types.	- CO concentration (ppm) - Zone - Time Period (Morning, Afternoon, Evening) - Day Type (Weekday/Weekend,	Quantitative (Continuous & Categorical)	Descriptive Statistics (Mean, SD, Min, Max) Line/Bar graphs Cross-tabulation	SPSS Excel	Trends and variation across time and location

	Bazaar/Non-Bazaar)				
2. To determine the frequency and percentage of CO level exceedances beyond WHO and EPA 1-hour and 8-hour permissible limits.	- CO concentration readings - WHO/EPA thresholds (25 ppm / 9 ppm)specs, design documents)	Quantitative (Continuous)	Threshold comparison Frequency counts Percentage exceedance	Excel	% of samples exceeding health guidelines
3. To explore the effects of zone, time period, day type, traffic count, and ventilation status on CO levels.	- CO concentration - Zone - Time period - Day type - Traffic count - Ventilation status (On/Off/)	Quantitative (Mixed)	Linear Mixed Effects Model (LMM) Type III (Fixed Effects) Regression analysis	SPSS (Mixed Models)	Statistically significant predictors of CO
4. To determine the actual Air Changes per Hour (ACH) for each zone	- Airflow rate (m^3/hr) - Zone volume (m^3)	Quantitative (Ratio)	ACH Calculation per zone Compliance assessment	Manual Calculation	Zone-specific ACH values and compliance status

and compare with ASHRAE 62.1 ventilation standards.	- ACH = (Flow Rate ÷ Volume) × 60 - ASHRAE 62.1 standard values				

Source: Researcher own construct (2025)

3.7. Ethical Consideration

This study was conducted with strict adherence to ethical standards to ensure the rights, dignity, and safety of all participants and to maintain the integrity of the research process. Prior to data collection, permission was obtained from the relevant authorities managing the Meskel Square Underground Parking Facility. Participants involved in the questionnaire survey and key informant interviews were provided with clear information about the purpose, scope, and voluntary nature of the research.

Informed consent was obtained from all participants, and they were assured of the confidentiality and anonymity of their responses. No personal identifiers were recorded and data were used solely for academic and research purposes. Interview respondents were also informed of their right to withdraw from the study at any point without facing any consequences.

The research avoided any physical or psychological harm. Specifically, no manipulation of the facility's ventilation systems or CO levels was undertaken during measurement to prevent any potential health risks to facility users or employees. The study relied on non-intrusive methods such as fixed CO sensor readings and observational checklists.

All data collected were securely stored and analyzed in a manner that maintained privacy and confidentiality. The research process complied with ethical guidelines recommended by academic institutions and international research ethics standards.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Spatial-Temporal CO Level in the Meskel Square Underground Parking Facility

4.1.1. CO Levels across Zones

The descriptive analysis of CO levels within the Meskel Square Underground Parking Facility reveals significant spatial heterogeneity, with mean concentrations spanning a notable range from 5.29 ppm to 11.92 ppm. Specifically, Central Parking Zone 1 emerged as a primary hotspot, recording the highest mean concentration of 11.92 ppm (SD = 7.62), closely followed by Central Parking Zone 2 (mean = 10.51 ppm, SD = 7.43) and Ramp Zone 1 (mean = 10.19 ppm, SD = 7.46), all indicative of elevated exposure. In contrast, the Entrance/Exit zones exhibited considerably lower CO levels (Entrance/Exit 1: 5.44 ppm; Entrance/Exit 2: 5.29 ppm), with Ramp Zone 2 showing an intermediate mean of 7.81 ppm. The consistently substantial standard deviations across all zones (ranging from 5.57 ppm to 7.62 ppm) highlight a significant degree of temporal volatility, suggesting frequent, intermittent spikes in CO levels likely driven by dynamic traffic surges or potential lapses in ventilation efficacy. From a public health perspective, these findings carry critical implications: the 8-hour mean CO level in Central Parking Zone 1 (11.92 ppm) notably exceeds the WHO 8-hour limit of 9 ppm (WHO, 2010) by 32% and also surpasses the EPA 8-hour limit of 9 ppm (EPA, 2024c), suggesting potential health risks, particularly if such elevated exposures are recurrent or sustained (ATSDR, 2012; EPA IRIS, 2010). Moreover, peak exposures, calculated as mean plus one standard deviation, in the central zones can reach as high as 19.5 ppm, approaching the EPA 1-hour threshold of 35 ppm for acute exposure risks. The persistently elevated CO in these confined central zones aligns with indoor air quality theory, which attributes pollutant trapping to limited air exchange in enclosed spaces (Seinfeld & Pandis, 2016), thus posing chronic health risks, particularly to occupationally exposed groups like parking attendants, as prolonged CO exposure exceeding 9 ppm is associated with cardiovascular impairment (WHO, 2010). Worker interviews validate these risks, with attendants reporting:

> *I became an asthmatic when I started working here. I never had it before. Now I get sore throats and itchy eyes especially when I work at the central zone of the parking area"* Worker Representative 3 (WR 3),

> *"Headaches, throat problems, and breathing difficulties come when the parking lot is full"* Worker Representative 2 (WR 2).

Conversely, the significantly lower CO concentrations observed at the Entrance/Exit zones (5.29–5.44 ppm), falling below critical thresholds, underscore the benefits of natural ventilation in these areas, supporting ASHRAE's emphasis on strategic airflow design for effective pollutant dilution (ASHRAE 62.1, 2019). Operationally, this analysis mandates the urgent prioritization of mitigation efforts in Central Parking Zones 1 and 2. A directive strongly corroborated by qualitative evidence from facility workers and managers. Worker testimonials explicitly identify these zones as high-risk areas, with one attendant reporting:

> *"In the central parking zones, the air becomes very heavy and extremely unpleasant during events. I experience headaches, throat problems, and breathing difficulties that worsen in these sections"* (WR 1).

Furthermore, the observed high CO volatility across zones necessitates the implementation of real-time monitoring systems to effectively detect and manage intermittent spikes, particularly in the ramps and central zones where fluctuations can exceed 7 ppm.

Table 5: CO Levels across Zones within Meskel Square Ground Parking Facility

CO Level(PPM) * Zone			
CO Level(PPM)			
Zone	Mean	N	Std. Deviation
Ramp Zone 1	10.19	72	7.464
Entrance/Exit 1	5.44	72	5.566
Central Parking Zone 1	11.92	72	7.623
Central Parking Zone 2	10.51	72	7.425
Entrance/Exit 2	5.29	72	6.240

Ramp Zone 2	7.81	72	7.102
Total	8.53	432	7.357

Source: Researcher own survey (2025)

4.1.2. CO Levels across Time Periods

The analysis of CO concentrations within the Meskel Square Underground Parking Facility reveals a striking diurnal pattern, characterized by a progressive increase in mean CO levels from 4.69 ppm in the morning to 7.85 ppm in the afternoon, culminating in a peak of 13.05 ppm during evening hours, demonstrating a significant threefold rise and pronounced temporal volatility in air quality conditions. Concurrently, the standard deviations escalate (Morning: 4.20 ppm; Afternoon: 6.63 ppm; Evening: 8.10 ppm), indicating increasingly unstable pollution dynamics during periods of heightened activity. From a public health perspective, the mean morning concentration (4.69 ppm) comfortably adheres to both the WHO and EPA 8-hour exposure limits of 9 ppm (WHO, 2010; EPA, 2024c), representing a period of low chronic exposure risk. While afternoon levels (7.85 ppm) approach but remain below 8-hour standards, their high variability suggests frequent spikes potentially exceeding 14.48 ppm (mean + 1 SD), nearing the EPA 1-hour acute exposure threshold of 35 ppm during peak incidents. Critically, the evening mean of 13.05 ppm significantly surpasses WHO/EPA 8-hour limits by 45%, with peak exposures (mean + 1 SD = 21.15 ppm) reaching levels associated with neurophysiological effects in sensitive populations (WHO, 2010), aligning with epidemiological evidence linking evening commuter exposure to reduced cognitive performance (Lee et al., 2020). Operationally, this diurnal escalation highlights a peak-hour vulnerability in the evening, where high concentrations persist (mean = 13.05 ppm) despite potentially lower absolute traffic volumes compared to morning commutes, suggesting compounding factors such as ventilation fatigue or atmospheric inversion. Qualitative interviews directly attribute this to systemic ventilation failures during evening operations. Workers reported that ventilation systems fail to activate promptly during evening surges:

> *"When smoke increases in the evenings, experts must be notified manually to turn on fans. This takes time sometimes 30 minutes or more while we breathe thick air."* (WR 3)

Managers confirmed systems operate at minimal speeds in evenings to *"avoid disturbing customers with fans noise"* Facility Manager 1 (FM 1), prioritizing comfort over air quality.

The observed progressive increase in standard deviations further necessitates the implementation of real-time alert systems during afternoon and evening hours, when pollution volatility peaks.

Table 6: CO levels across Time Periods within Meskel Square Ground Parking Facility

CO Level(PPM) * Time Period			
CO Level(PPM)			
Time Period	Mean	N	Std. Deviation
Morning	4.69	144	4.199
Afternoon	7.85	144	6.630
Evening	13.05	144	8.102
Total	8.53	432	7.357

Source: Researcher own survey (2025)

4.1.3. CO Levels across Day Types

The analysis of CO concentrations across different day types at the Meskel Square Underground Parking Facility reveals pronounced variations directly linked to operational patterns and event-driven occupancy surges, with mean CO levels ranging from 5.35 ppm to 13.07 ppm. Weekends with bazaars exhibit the highest pollution burden, with a mean concentration of 13.07 ppm (SD = 9.61), followed by weekdays with bazaars at 8.76 ppm (SD = 6.23). In stark contrast, non-bazaar days consistently show substantially lower concentrations, with weekdays averaging 6.93 ppm and weekends at 5.35 ppm.

The exceptionally high standard deviation observed during weekend bazaars (9.61 ppm) is particularly concerning, indicating extreme temporal volatility and suggesting severe pollution spikes during peak event hours. These quantitative findings are fully corroborated by qualitative reports from workers who consistently described severe air quality deterioration during bazaar periods. As one worker (WR1) noted:

> *"During bazaar times, the parking lot becomes very heavy and extremely unpleasant to breathe."*

Another worker (WR2) linked these conditions directly to traffic surges:

> *"I feel tired and experience shortness of breath when there's a lot of traffic and the parking lot is full."*

These perceptions reflect real-time experience of peak CO accumulation during high-traffic events.

From a public health perspective, concentrations during non-bazaar days (5.35–6.93 ppm) comfortably remain below both the WHO 8-hour exposure limit of 9 ppm (WHO, 2010) and the EPA 8-hour threshold of 9 ppm (EPA, 2024), representing baseline compliance. However, during bazaar days, the mean levels on weekdays (8.76 ppm) approach but remain just below 8-hour limits, though their inherent volatility (SD = 6.23) implies frequent spikes potentially exceeding 15 ppm, a range associated with reduced cognitive function in occupational settings (Lee et al., 2018).

More critically, the mean concentration on bazaar weekends (13.07 ppm) significantly exceeds both WHO and EPA 8-hour limits by 45%, with peak exposures (mean + 1 SD = 22.68 ppm) reaching levels known to induce headaches, dizziness, and cardiovascular strain in sensitive populations (WHO, 2010). These quantitative risks align with workers' self-reported health complaints, including headaches, breathing difficulties, itchy eyes, fatigue, and even newly developed respiratory conditions:

> *"I have become asthmatic since I started working here" (WR3).*

Furthermore, operational interviews with facility managers reveal that these spikes are exacerbated by limitations in ventilation responsiveness during peak hours. FM1 confirmed that fans are often kept at low speeds to avoid noise disturbances during busy times, while WR1 reported that

> *"The ventilation system does not open quickly, and zones with damaged ventilation areas remain unfixed."*

Operationally, these findings underscore that bazaar events, especially on weekends, are major drivers of elevated CO levels, generating concentrations 2.4 times higher than non-bazaar weekends, thus posing significant event-based traffic risks. The extreme standard deviation during weekend bazaars (9.61 ppm) further necessitates the implementation of real-time monitoring and alert systems to activate contingency ventilation whenever CO concentrations exceed 15 ppm. In conclusion, bazaar events, particularly on weekends, transform the Meskel Square Underground Parking Facility into a high-exposure environment that violates health standards and endangers occupants, highlighting the critical need for event-specific interventions such as traffic quotas, targeted ventilation upgrades, and stricter operational protocols to mitigate these episodic health hazards.

Table 7: CO Levels across Day Types within Meskel Square Ground Parking Facility

CO Level(PPM) * Day Type			
CO Level(PPM)			
Day Type	Mean	N	Std. Deviation
Weekdays(Non-Bazaar)	6.93	108	5.317
Weekends(Non-Bazaar)	5.35	108	4.998
Weekdays(Bazaar)	8.76	108	6.225
Weekends(Bazaar)	13.07	108	9.609
Total	8.53	432	7.357

Source: Researcher own survey (2025)

4.2. Analysis of CO Concentration Exceedances against WHO and EPA 1-Hour and 8-Hour Exposure Limits

This section examines the extent to which measured carbon monoxide (CO) concentrations in the Meskel Square Underground Parking Facility exceed the 1-hour and 8-hour permissible exposure limits set by the World Health Organization (WHO) and the Federal Democratic Republic of Ethiopia Environmental Protection Agency (EPA). According to these international guidelines, the maximum allowable 1-hour average CO exposure is 25 ppm (EPA, 2003; WHO, 2010), while the 8-hour average limit is 9 ppm (both WHO and EPA). By analyzing the frequency and percentage of CO readings that surpass these thresholds across different spatial zones, time periods, and day types, this analysis identifies critical exposure risks and peak pollution periods within the facility. Rather than relying on overall or aggregated summary statistics, the 1-hour exceedance analysis was based on individual hourly mean CO levels recorded during specific time periods (morning, afternoon, and evening) across all zones and day types. Similarly, the 8-hour exceedance assessment was conducted by calculating the combined average of the three time periods per day (morning, afternoon, and evening) for each zone and day type, approximating a full operational exposure cycle. This detailed approach allows for a more accurate identification of specific locations and timeframes where CO levels pose health risks, supporting a more targeted evaluation of the facility's ventilation performance and control measures. Here is the collected carbon monoxide level data is summarized by averaging each time period measurements separately. But detailed individual measurements with traffic count and ventilation status data for each time period are provided in the appendix.

Table8: Average CO Level Data in the Meskel Square Underground Parking Facility

Day Type	**Time Period**	**Meskel Square Ground Parking Zones Mean CO Level(PPM)**						
		Ramp 1 Mean CO Level (PPM)	**Entrance/Exit 1 Mean CO Level (PPM)**	**Central Parking Area 1 Mean CO Level (PPM)**	**Central Parking Area 2 Mean CO Level (PPM)**	**Entrance/Exit 2 Mean CO Level (PPM)**	**Ramp 2 Mean CO Level (PPM)**	**Total Parking Area Mean CO Level (PPM)**
Weekdays (Non-Bazaar Time)	**Morning**	3.67	1.67	4.83	6.33	3.70	6.17	4.39
	Afternoon	5.17	3.00	8.50	8.00	2.80	4.83	5.39
	Evening	9.33	6.83	11.50	11.80	9.20	17.30	11.00
Weekdays Non-Bazaar Time Daily Average CO Level		6.06	3.83	8.28	8.71	5.23	9.43	6.92
Weekdays (Bazaar Time-2025 Easter Bazaar)	**Morning**	8.17	0.00	8.17	6.00	1.80	8.50	5.45
	Afternoon	10.50	3.83	13.70	10.00	4.30	5.83	8.02
	Evening	13.70	8.33	14.70	14.00	9.70	16.50	12.81

Weekdays Bazaar Time Daily Average CO Level		10.79	4.05	12.19	10.00	5.27	10.28	8.76
Weekends (Non-Bazaar)	**Morning**	4.17	0.83	5.17	5.00	0.00	1.67	2.81
	Afternoon	7.33	3.67	10.30	8.17	2.70	3.33	5.92
	Evening	11.30	6.17	11.30	9.17	2.80	3.17	7.33
Weekends Non-Bazaar Time Daily Average CO Level		7.60	3.56	8.92	7.45	1.83	2.72	5.35
Weekends (Bazaar Time)	**Morning**	7.67	6.00	9.33	6.83	2.70	4.17	6.11
	Afternoon	20.20	9.00	14.00	15.70	5.80	7.67	12.06
	Evening	21.20	16.00	31.50	25.20	18.00	14.50	21.06
Weekends Bazaar Time Daily Average CO Level		16.36	10.33	18.28	15.91	8.83	8.78	13.07

Source: Researcher own survey (2025)

4.2.1. Percentage of 8-Hour Exceedances[1]

This section presents a comprehensive spatial-temporal analysis of 8-hour average carbon monoxide (CO) concentrations across different zones of the Meskel Square Underground Parking Facility, benchmarked against the World Health Organization's (WHO) 8-hour exposure limit of 9 ppm. CO data were collected across three daily time segments (morning, afternoon, and evening), spanning weekdays and weekends, under both bazaar and non-bazaar operational conditions. Calculated as the percentage by which CO levels exceeded the 9 ppm threshold, the analysis highlights distinct exceedance patterns tied to traffic activity and ventilation performance.

Among the six monitored zones, Ramp 1 exhibited the highest 8-hour mean values, reaching 10.8 ppm during weekday bazaars (a 20% exceedance) and escalating to 16.3 ppm during weekend

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[1] **Table 1. WHO Guidelines for CO levels in indoor air**

Concentration	**Averaging Time**
90 ppm/100 mg/m^3	15 Minute
50 ppm/60 mg/m^3	30 Minute
25 ppm/30 mg/m^3	1 Hour
9 ppm/10 mg/m^3	8 Hour

Source: WHO (2000)

bazaars an 81% exceedance over the WHO limit. Ramp 2 followed a similar trend, recording 10.3 ppm on bazaar weekdays (14.4% exceedance) and a marginally compliant level of 8.78 ppm on bazaar weekends. Central Parking Zones 1 and 2 presented even more concerning figures. Central Zone 1 peaked at 12.2 ppm on weekday bazaars (35.6% exceedance) and 18.3 ppm on weekend bazaars (a staggering 103.3% exceedance), while Central Zone 2 reached 10.0 ppm (11.1%) and 15.9 ppm (76.7%) on bazaar weekdays and weekends, respectively. Although these zones recorded lower averages during non-bazaar periods (8.28–8.92 ppm), their persistent proximity to the threshold raises concern for chronic exposure.

These findings align with multiple international studies that reinforce the susceptibility of enclosed parking environments to CO accumulation. For instance, Nayef et al. (2020) in Kuwait found that enclosed shopping mall garages exhibited CO spikes of 88–195 ppm over 1-hour periods during peak traffic, especially in winter and summer seasons. Similarly, Chaloulakou et al. (2001) in Greece reported 1-minute CO peaks up to 138 ppm in multi-level parking structures, highlighting the rapid buildup of pollutants during congestion surges. In Indonesia, Rahmi et al. (2020) documented CO concentrations of 15,897–16,613 µg/Nm³ (~13.8–14.5 ppm) in basement residential parking facilities, raising significant chronic exposure concerns when converted to ppm. Serlly et al. (2021), also in Indonesia, observed average CO concentrations of 54.5 µg/m³ (~30.3 ppm) in factory settings, identifying non-carcinogenic health risks from sustained low-level exposure.

In comparison, the Meskel Square facility's 8-hour values are lower than extreme hourly peaks in Kuwait and Greece but comparable to the chronic exposure levels reported in Indonesian studies. This places the Meskel Square parking structure within a moderate-to-high risk bracket internationally, especially considering its event-driven usage pattern and manual ventilation operation. These values are especially concerning for occupational health, as WHO (2010) and studies by Lee et al. (2020) caution that sustained exposure to CO levels above 7 ppm can impair cardiovascular function and reduce cognitive alertness. Supporting this, interviews conducted with facility employees revealed direct health complaints—headaches, respiratory discomfort, and fatigue—even on regular workdays without event traffic. As WR1 stated,

> "*I have been experiencing headaches, throat problems, and breathing difficulties since I started working at this parking lot,*" while WR2 added,

> *"I feel tired, my eyes are itchy, and I've noticed shortness of breath, especially when the parking lot is full."*

By contrast, Entrance/Exit Zones generally demonstrated better air quality, with all periods remaining below the threshold except during bazaar weekends, when Entrance/Exit Zone 1 reached 10.3 ppm (14.4% exceedance) and Entrance/Exit Zone 2 peaked at 8.83 ppm. These lower readings reflect better natural ventilation and fewer vehicle idling instances, consistent with ASHRAE 62.1 (2019) guidelines and findings by Al-Waked et al. (2020), who noted improved pollutant dispersion in semi-open structures with higher airflow capacity.

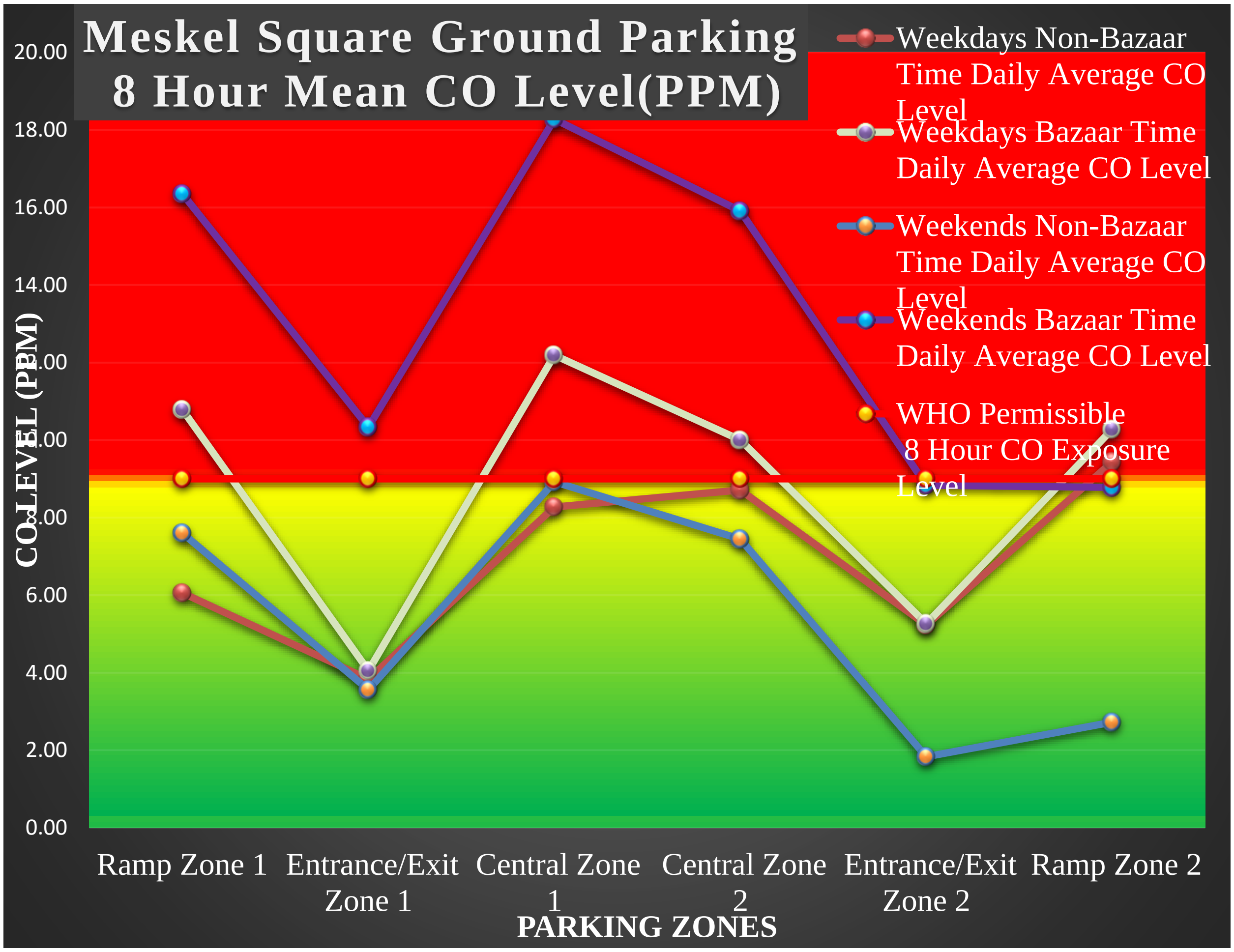
Table 9: Percentage Exceedance of WHO 8-Hour CO Limit (9 PPM) by Zone and Time Period

Parking Zone	Weekdays (Non-Bazaar Time)	Weekdays (Bazaar Time)	Weekends (Non-Bazaar Time)	Weekends (Bazaar Time)
Ramp 1	-32.67%	20.00%	-15.56%	81.11%
Entrance/Exit Zone 1	-57.44%	-55.00%	-60.44%	14.44%
Central Parking Zone 1	-7.99%	35.56%	-0.89%	103.33%
Central Parking Zone 2	-3.22%	11.11%	-17.33%	76.67%
Entrance/Exit Zone 2	-41.89%	-41.44%	-79.67%	-1.89%
Ramp 2	4.78%	14.44%	-70.00%	-2.44%

Source: Researcher own survey (2025)

Overall, this spatial-temporal assessment demonstrates that CO exposure risks are highest in central and ramp zones during weekend bazaars, when vehicle traffic and idling are most intense. The results go beyond descriptive figures by confirming that these exceedances carry real public health risks as supported by global evidence and firsthand worker reports—and underscore the need for event-specific mitigation strategies, including traffic quotas, real-time ventilation control, and proactive staff protection measures. Benchmarking against international studies reveals that Meskel Square is not an outlier but rather a representative case of how inadequate design, manual operations, and high traffic intensity combine to elevate CO risks in enclosed urban parking facilities.

Figure 9: Meskel Square Ground Parking 8-Hour Mean CO Level (Heat Map)



Source: Researcher own survey (2025)

4.2.2. Diurnal Analysis of CO Concentrations at Meskel Square Underground Parking Facility

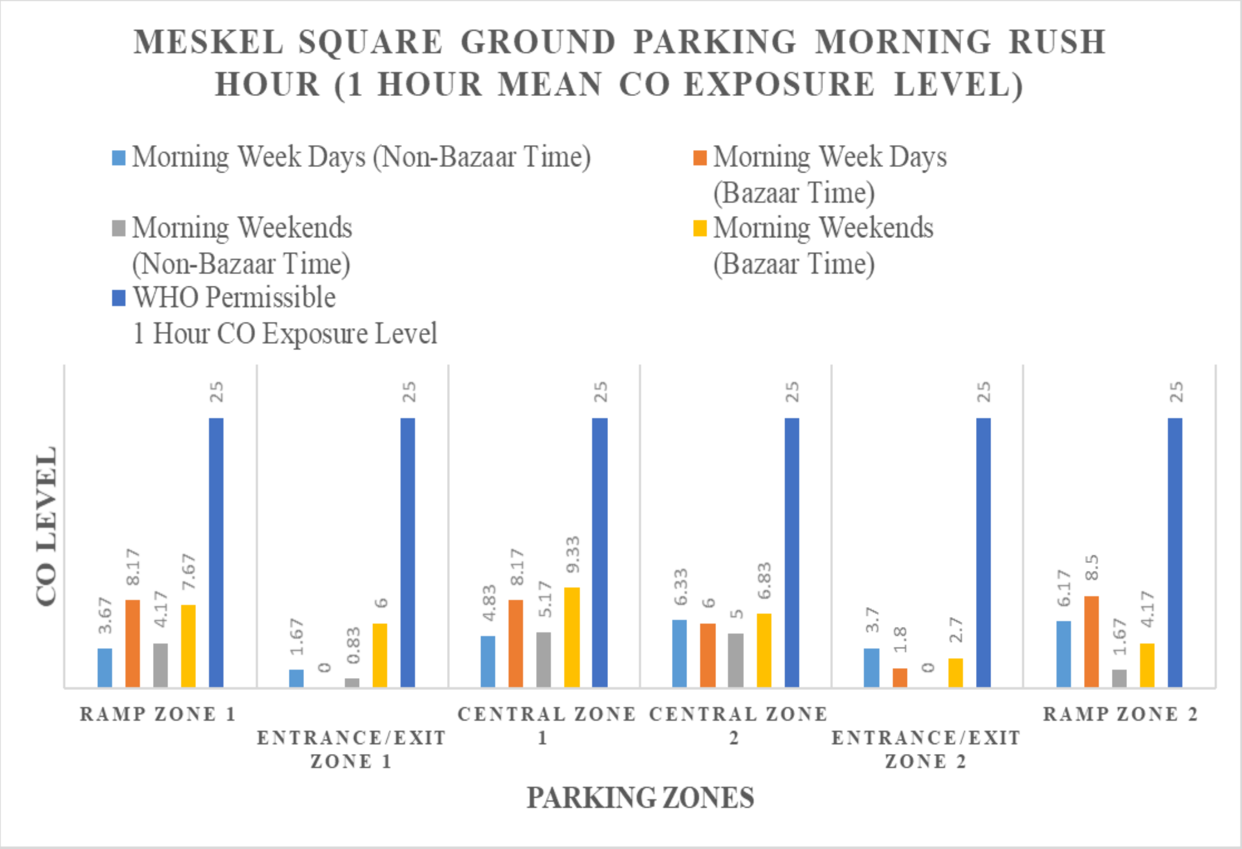
4.2.2.1.Analysis of CO Concentrations during the Morning Rush Hour

An analysis of CO concentrations during the morning rush hour in the Meskel Square Underground Parking Facility reveals spatial-temporal variations across different zones. The data indicates that CO levels are generally elevated during bazaar times compared to non-bazaar times across all zones, reinforcing the idea that increased activity associated with the bazaar significantly impacts CO concentrations(Andrew G. et al., 2022). A variation in CO levels is also observed across different zones during the morning rush hour, but generally all are much below WHO lower limit: Central parking zones tend to have higher CO levels, followed by ramp zones, with entrance/exit zones generally showing the lowest concentrations. CO levels during the morning rush hour on weekends are generally comparable to or slightly higher than those on weekdays, particularly during bazaar times. Overall, morning rush hour CO levels are generally lower compared to daily averages, which might indicate that the highest CO concentrations occur later in the day. Specifically, in the ramp zones, CO levels range from 3.67 ppm (weekday non-bazaar) to 7.67 ppm (weekend bazaar) in Ramp 1, and from 1.67 ppm (weekend non-bazaar) to 8.5 ppm (weekday bazaar) in Ramp 2. In the entrance/exit zones, CO levels range from 0 ppm (weekday bazaar & weekend non-bazaar) to 6 ppm (weekend bazaar) in Entrance/Exit Zone 1, and from 0 ppm (weekend non-bazaar) to 3.7 ppm (weekday non-bazaar) in Entrance/Exit Zone 2. In the central parking zones, CO levels range from 4.83 ppm (weekday non-bazaar) to 9.33 ppm (weekend bazaar) in Central Parking Zone 1, and from 5 ppm (weekend non-bazaar) to 6.83 ppm (weekend bazaar) in Central Parking Zone 2. Notably, none of the recorded 1-hour mean CO levels exceed the WHO 1-hour permissible limit of 25 ppm. These findings suggest that while CO levels are elevated during peak activity periods, particularly in central zones, the short-term exposure during the morning rush hour does not pose an immediate exceedance of the WHO 1-hour standard. In conclusion, the spatial-temporal variations in CO concentrations during the morning rush hour highlight that while CO levels are elevated during peak activity periods, particularly in central zones, the short-term exposure does not pose an immediate threat.

Figure 10: Visual Indicators (Red Lights R1/R2) Signal Exceedances

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

Figure 11: Meskel Square Ground Parking Morning Rush Hour (1 Hour) Mean CO Level

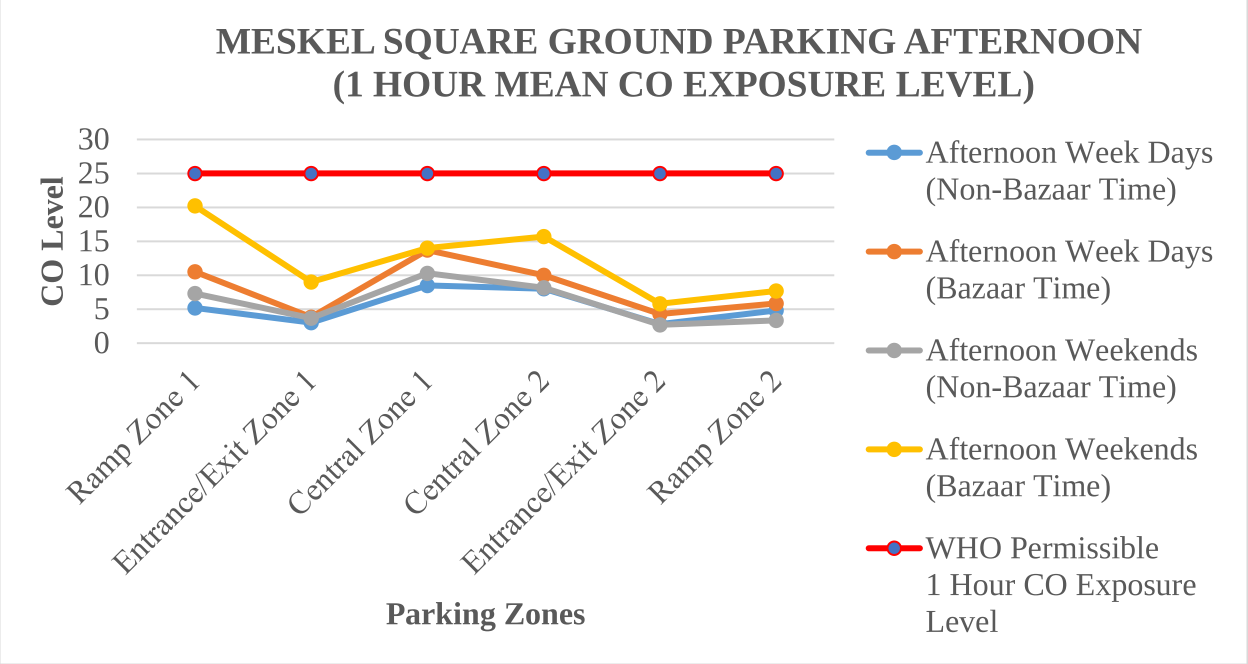


Source: Researcher own survey (2025)

4.2.2.2.Analysis of CO Concentrations during Afternoon Hour

Analysis of CO concentrations during the afternoon period in the Meskel Square Underground Parking Facility reveals notable spatial-temporal variations. CO levels during the afternoon are consistently elevated during bazaar times compared to non-bazaar times across all zones, further underscoring the significant influence of bazaar activity on CO concentrations within the parking facility. Central parking zones exhibit the highest afternoon CO levels, followed by ramp zones, with entrance/exit zones showing the lowest, a pattern consistent with morning rush hour data and suggestive of a persistent spatial distribution of CO. Afternoon CO levels on weekends, particularly during bazaar times, tend to be higher than those on weekdays. Notably, afternoon CO levels are generally higher than those observed during the morning rush hour, indicating a potential increase in CO concentrations as the day progresses. Specifically, in ramp zones, CO levels range from 5.17 ppm (weekday non-bazaar) to 20.2 ppm (weekend bazaar) in Ramp 1, and from 3.33 ppm (weekend non-bazaar) to 7.67 ppm (weekend bazaar) in Ramp 2. In entrance/exit zones, CO levels range from 3 ppm (weekday non-bazaar) to 9 ppm (weekend bazaar) in Entrance/Exit Zone 1, and from 2.7 ppm (weekend non-bazaar) to 5.8 ppm (weekend bazaar) in Entrance/Exit Zone 2. In central parking zones, CO levels range from 8.5 ppm (weekday non-bazaar) to 14 ppm (weekend bazaar) in Central Parking Zone 1, and from 8 ppm (weekday non-bazaar) to 15.7 ppm (weekend bazaar) in Central Parking Zone 2. It is important to note that none of the recorded 1-hour mean CO levels exceed the WHO 1-hour permissible limit of 25 ppm. However, levels in the central and ramp zones during bazaar times are approaching this limit. These findings highlight a potential trend of increasing CO levels throughout the day, with the central and ramp zones posing the greatest concern for afternoon CO exposure. In conclusion, the spatial-temporal variations in CO concentrations during the afternoon period indicate that CO levels are consistently elevated during bazaar times, with central parking zones exhibiting the highest concentrations. The trend of increasing CO levels from morning to afternoon, although not exceeding the WHO 1-hour limit, suggests that afternoon measurements in the central and ramp zones are approaching this limit, highlighting the need for further investigation and potential mitigation strategies.

Figure 12: Meskel Square Ground Parkig Afternoon Time Period (1 Hour) Mean CO Level

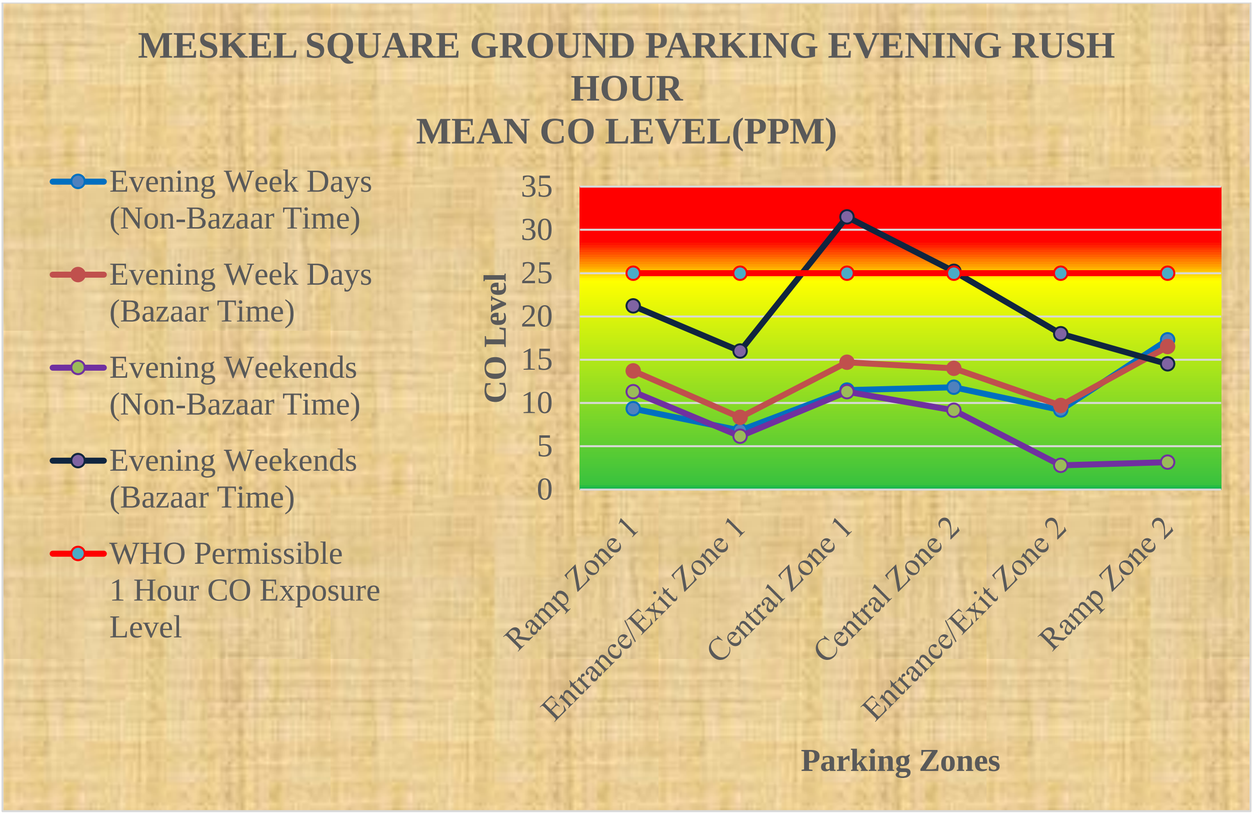


Source: Researcher own survey (2025)

4.2.2.3.Analysis of CO Concentrations during Evening Rush Hour

Analysis of CO concentrations during the evening rush hour in the Meskel Square Underground Parking Facility reveals that CO levels are the highest among the three time periods analyzed, with bazaar times showing a significant elevation in CO concentrations across all zones. Central parking zones and ramp zones generally exhibit the highest CO levels during this period. Specifically, in ramp zones, CO levels range from 9.33 ppm (weekday non-bazaar) to 21.2 ppm (weekend bazaar) in Ramp 1, and from 3.17 ppm (weekend non-bazaar) to 17.3 ppm (weekday non-bazaar) in Ramp 2. In entrance/exit zones, CO levels range from 6.17 ppm (weekend non-bazaar) to 16 ppm (weekend bazaar) in Entrance/Exit Zone 1, and from 2.8 ppm (weekend non-bazaar) to 18 ppm (weekend bazaar) in Entrance/Exit Zone 2. In central parking zones, CO levels range from 11.3 ppm (weekend non-bazaar) to 31.5 ppm (weekend bazaar) in Central Parking Zone 1, and from 9.17 ppm (weekend non-bazaar) to 25.2 ppm (weekend bazaar) in Central Parking Zone 2. Notably, during weekend bazaar times, both Central Parking Zone 1 (31.5 ppm) and Central Parking Zone 2 (25.2 ppm) exceed the WHO 1-hour permissible limit of 25 ppm, indicating a serious public health concern. The spatial-temporal variations in CO concentrations during the evening rush hour highlight that this period, particularly on weekends with bazaar activity, poses the greatest risk of CO exposure. In conclusion, the evening rush hour is characterized by elevated CO levels, with central parking zones exceeding the WHO 1-hour standard, indicating a serious public health concern.

Figure 13: Meskel Square Ground Parking Evening Rush Hour (1 Hour) Mean CO Level



Source: Researcher own survey (2025)

4.2.3. Percentage of 1-Hour Exceedances across Time Periods

The spatial-temporal analysis of 1-hour carbon monoxide (CO) exposure levels in Meskel Square Ground Parking reveals critical patterns and frequent exceedances of the WHO 1-hour permissible limit of 25 ppm, particularly during high-traffic weekend bazaars.

The WHO 1-hour exposure limit (25 ppm) was exceeded in six zones during specific periods. Exceedance percentages were calculated as: Exceedance % = (CO Level – 25 / 25) ×100.

Table 10: Summary of 1- Hour Exceedances across Time Periods

(Threshold = 25 ppm; Negative values indicate compliance, positive values indicate exceedance)

Time Period	Zone	Highest CO Level (ppm)	Exceedance %	Notes
Morning Rush Hour	All zones	9.33 (Central Zone 1)	-62.68% to -100%	No exceedances. Lowest levels in Entrance/Exit Zone 1 (0 ppm, -100%).
Afternoon Rush Hour	Ramp 1 (Weekends Bazaar)	20.2	-19.2%	Close to threshold but still compliant. High traffic (80/81 vehicles).(Annex 4)
Evening Rush Hour	Central Zone 1 (Weekends Bazaar)	31.5	+26%	Significant exceedance due to extreme traffic (128/130)(Annex 4) + ventilation OFF. (Tested by Mixed-Model)
Evening Rush Hour	Central Zone 2 (Weekends Bazaar)	25.2	+0.8%	Marginal exceedance (traffic = 95/95) (Annex 4).
All other time periods	All zones	<25 ppm	Negative	Safe levels observed. Ventilation often OFF but traffic below critical.

Source: Researcher own survey (2025)

The analysis of CO levels across Morning, Afternoon, and Evening Rush Hours at Meskel Square Ground Parking Zones reveals a clear pattern of compliance with the 25 ppm threshold in most zones and time periods, with isolated exceptions. During Morning and Afternoon Rush Hours, all zones reported CO levels well below 25 ppm, with exceedance percentages ranging from -62.68% to -100% (indicating no exceedance). The highest morning CO level was 9.33 ppm (Central Parking Zone 1, Weekends Bazaar Time), while the afternoon peak was 20.2 ppm (Ramp 1, Weekends Bazaar Time), both significantly below the threshold. However, Evening Rush Hours showed critical deviations: Central Parking Zone 1 during Weekends (Bazaar Time) recorded a 31.5 ppm CO level, resulting in a +26% exceedance, and Central Parking Zone 2 marginally exceeded the threshold at 25.2 ppm (+0.8%). These evening exceedances correlate with extremely high traffic counts 128/130 vehicles (ANNEX 4) or 92.0 (Table 11) in Central Zone 1 and inconsistent ventilation (e.g., Ventilation Status = OFF during peak congestion). Notably, Bazaar Time periods especially on weekends consistently drove higher CO levels due to increased vehicle activity and idling, while non-bazaar periods and weekdays remained within safe limits. The data underscores the need for targeted interventions, such as enhanced ventilation and traffic flow optimization, during weekend bazaar events to mitigate CO accumulation in high-risk zones like Central Parking areas. Overall, while the majority of timeframes and zones adhere to air quality standards, the evening rush hour on weekends demands urgent attention to prevent hazardous exposure levels.

Table 11: Average Traffic Count across the Different Zones of the Parking during CO Recording

Day Type	Time Period	Ramp 1	Ramp 2	Entrance/Exit Zone 1	Entrance/Exit Zone 2	Central Parking Zone 1	Central Parking Zone 2
Weekdays Non-Bazaar	Morning	7.0	9.5	19.75	13.0	10.0	11.25
Weekdays Bazaar	Morning	14.5	11.0	36.25	37.25	20.0	24.5

Weekends Non-Bazaar	Morning	10.75	8.5	44.75	36.75	33.5	23.0
Weekends Bazaar	Morning	49.5	46.25	108.5	111.0	90.5	95.0
Weekdays Non-Bazaar	Afternoon	11.0	14.5	19.75	17.75	12.0	9.0
Weekdays Bazaar	Afternoon	27.0	25.75	57.5	57.25	40.5	35.75
Weekends Non-Bazaar	Afternoon	12.25	12.25	51.75	55.75	33.75	33.75
Weekends Bazaar	Afternoon	56.5	55.25	113.0	114.5	97.5	92.0
Weekdays Non-Bazaar	Evening	13.15	15.1	16.2	20.3	10.15	7.85
Weekdays Bazaar	Evening	14.6	15.9	41.5	42.0	22.65	19.35
Weekends Non-Bazaar	Evening	9.0	9.0	57.5	57.5	28.5	28.5
Weekends Bazaar	Evening	54.0	55.5	103.5	107.0	92.0	86.0

Source: Researcher own survey (2025)

4.3. Triangulating Low CO Levels in VIP-Designated Zones with Observational and Contextual Data

The consistently low CO concentration observed in Ramp 2 during weekend non-bazaar periods as low as 1.67 ppm, compared too much higher levels in other ramps or during weekdays initially appeared as an outlier in the spatial-temporal CO variation analysis. This Finding Confirms J.C. Ho et al., (2003) statement that explains CO concentration does not increase linearly as well as follows a quadratic pattern, meaning CO levels may peak and then stabilize or drop under certain conditions. However, this finding is strongly supported by researcher observation and qualitative insights gathered through site investigation and usage pattern data (See Annex 5).

Based on researcher observations and information from facility management, Ramp Zone 2 is exclusively designated for vehicles belonging to a VIP government organization; Ethiopian Telecommunications (Ethio-Telecom) for the moment. This zone has been contracted specifically for their use. Due to the nature of their operations, parking activity primarily occurs on weekdays, while on weekends, including during bazaar events, there is no special activity in this zone. However, the vehicles with contracted rights to occupy the space may still remain parked there. This restricted access drastically reduces the number of engine startups, idling, and movement, the primary sources of CO emissions in the weekends.

Furthermore, this section's physical detachment from the main public traffic loops minimizes cross-zone air pollution spillover. The ventilation system, even if not optimally active during weekends (See Appendix), becomes relatively sufficient due to the near absence of new CO input.

Thus, the low CO readings during weekend non-bazaar times in Ramp 2 are not anomalies, but instead accurately reflect low human and vehicle activity, a pattern validated through observational data. This case demonstrates how functional zoning and usage exclusivity can significantly influence air quality outcomes in enclosed parking environments, especially when paired with even minimal ventilation.

4.4. Effects of Zone, Time Period, Day Type, Traffic Count, and Ventilation Status on CO Concentration Levels

To assess the multifactorial determinants of carbon monoxide (CO) concentration in the Meskel Square Underground Parking Facility, a Linear Mixed-Effects Model (LMM) was employed. This model is appropriate for repeated environmental measurements and nested data structures (Field, 2013). The Type III Tests of Fixed Effects revealed that all five independent variables had a statistically significant influence on CO levels, as indicated by their F-values and corresponding significance levels.

Table 12: Effects of Zone, Time Period, Day Type, Traffic Count and Ventilation Status on CO Concentration Levels

Type III Tests of Fixed Effects[a]				
Source	Numerator df	Denominator df	F	Sig.
Intercept	1	35.654	23.225	<.001
Day Type	3	406	15.150	<.001
Time period	2	406	90.382	<.001
Zone	5	12.259	6.487	.004
Ventilation Status	2	406	5.554	.004
Traffic Count	1	406	120.064	<.001
a. Dependent Variable: CO Level (PPM).				

Source: Researcher own survey (2025)

As we have shown in the table 11, the Mixed Model Analysis, specifically the Type III Tests of Fixed Effects, definitively addresses the research objective by revealing the significant influence of various environmental and operational factors on CO concentration levels (PPM) in the Meskel Square Underground Parking Facility. All hypothesized factors demonstrated a statistically significant impact on CO levels, with p-values (Sig.) below the conventional 0.05 threshold. The Intercept was highly significant (F=23.225, Sig. <.001), indicating a meaningful baseline CO level even when other predictors are at their reference points. Traffic Count emerged as the most dominant predictor, exhibiting the highest F-statistic (F=120.064, Sig. <.001), confirming a strong positive correlation where increasing vehicular activity directly leads to higher CO concentrations due to increased emissions. Similarly, Time Period showed a profound influence (F=90.382, Sig. <.001), indicating significant diurnal variations, with evening hours typically associated with elevated CO levels. Day Type also significantly affected CO concentrations (F=15.150, Sig. <.001), underscoring that distinct daily patterns, such as those influenced by weekend or bazaar activities, contribute to varying pollutant loads. Furthermore, Zone had a statistically significant effect (F=6.487, Sig.=.004), confirming that CO levels differ significantly across the distinct spatial areas of the parking facility, with central parking and certain ramp zones experiencing higher concentrations due to factors like vehicle density and airflow restrictions. Lastly, Ventilation Status also proved significant (F=5.554, Sig.=.004), highlighting the system's role in CO control including more detailed analyses later in the typically show that responsive, demand-controlled 'ON/OFF' ventilation modes are most effective at maintaining lower CO averages compared to continuous 'ON' or entirely 'OFF' states. Collectively, these findings underscore the complex interplay of operational and environmental variables in shaping indoor air quality within the facility, providing a robust empirical basis for targeted mitigation strategies.

4.4.1. Estimates of Specific Predictors

The Fixed Effects Estimates from the Mixed Model Analysis offer nuanced insights into the magnitude and direction of each factor's influence on CO levels, with all reported coefficients being statistically significant ($p < 0.05$) unless otherwise noted. Traffic count emerges as the most potent predictor, with a coefficient of 0.109 ppm per vehicle ($t = 10.957$, $p < 0.001$), indicating a strong linear relationship where each additional vehicle increases CO concentrations by 0.109 ppm, independent of other variables, a precision underscored by its narrow 95% confidence interval (0.090–0.129). Temporal factors exhibit substantial effects: relative to the reference category (weekends with bazaars), weekdays without bazaars significantly reduce CO by 3.722 ppm ($t = -5.662$, $p < 0.001$), while weekends without bazaars reduce it by 4.392 ppm ($t = -6.389$, $p < 0.001$), confirming bazaar days as high-pollution periods; similarly, compared to the reference time period (evening), morning shows 6.388 ppm lower CO ($t = -11.953$, $p < 0.001$), and afternoon shows 5.478 ppm lower ($t = -10.794$, $p < 0.001$), solidifying evening as the peak exposure window. Spatial variations among zones reveal localized hotspots, with Central Parking Zone 1 elevating CO by 6.339 ppm ($t = 2.934$, $p = 0.012$), Central Parking Zone 2 by 6.840 ppm ($t = 3.134$, $p = 0.008$), and Ramp Zone 1 by 5.745 ppm ($t = 2.648$, $p = 0.021$) relative to the likely cleaner Ramp Zone 2, while Entrance/Exit zones show no significant effects. Furthermore, ventilation status demonstrates critical operational impacts: compared to the reference (Ventilation Status On/Off), the OFF status significantly increases CO by 2.523 ppm ($t = 3.326$, $p < 0.001$) and even the ON status shows a smaller, marginally significant increase of 2.071 ppm ($t = 2.207$, $p = 0.028$), suggesting limited efficacy when ventilation is continuously active. The intercept (6.184 ppm, t =

3.218, p = 0.003) represents the baseline CO levels when all predictors are at their reference values (e.g., non-bazaar evenings in Ramp Zone 2 with On/Off ventilation), critically exceeding WHO's 8-hour limit (9 ppm) by 68%, thereby highlighting inherent air quality challenges. This comprehensive analysis quantifies the isolated contributions of each factor, providing a robust foundation for targeted air quality management, emphasizing the dominance of traffic volume, the critical need for spatial prioritization in central parking zones, the inadequacy of current active ventilation, and the necessity for temporal interventions during evenings and bazaar days.

Table 13: Estimates of Specific Predictors

Estimates of Fixed Effects [a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Intercept	6.184	1.922	30.347	3.218	.003	2.261	10.107
Weekdays Non-Bazaar	-3.722	.657	406.000	-5.662	<.001	-5.015	-2.430
Weekends Non-Bazaar	-4.392	.687	406	-6.389	<.001	-5.744	-3.041
Weekdays with Bazaar	-2.503	.609	406	-4.109	<.001	-3.701	-1.306
Weekends with Bazaar	0[b]	0	.	.	.	.	.
Morning	-6.388	.534	406	-11.953	<.001	-7.438	-5.337
Afternoon	-5.478	.508	406	-10.794	<.001	-6.476	-4.480
Evening	0[b]	0	.	.	.	.	.
Ramp Zone 1	5.745	2.170	12.456	2.648	.021	1.037	10.454
Entrance/Exit 1	-2.289	2.153	12.079	-1.063	.309	-6.977	2.399
Central Zone 1	6.339	2.161	12.255	2.934	.012	1.642	11.037
Central Zone 2	6.840	2.182	12.749	3.134	.008	2.116	11.564
Entrance/Exit 2	.381	2.167	12.383	.176	.863	-4.324	5.085
Ramp Zone 2	0[b]	0	.	.	.	.	.
Ventilation-ON	2.071	.939	406	2.207	.028	.226	3.916
Ventilation- OFF	2.523	.759	406	3.326	<.001	1.032	4.015
Ventilation- ON/OFF	0[b]	0	.	.	.	.	.

Traffic Count	.109	.010	406	10.957	<.001	.090	.129
a. Dependent Variable: CO Level (PPM).							
b. This parameter is set to zero because it is referenced.							

Source: Researcher own survey (2025)

4.4.2. Estimates of Covariance Parameters

The statistically significant residual variance (18.07 ppm²) observed in the linear mixed-effects model indicates that a considerable proportion of CO concentration variability was not fully explained by the fixed effects included in the model (zone, time period, day type, traffic count, and ventilation status). This finding is expected in real-world environmental exposure studies, particularly in dynamic and semi-enclosed spaces like underground parking facilities, where numerous uncontrolled or unmeasured factors can influence air quality. These may include momentary vehicle idling near sensors, differences in fuel type or vehicle age, microclimatic conditions (e.g., temperature, humidity), irregular maintenance of fans, or temporary obstructions to airflow.

Additionally, sensor-level variation, confirmed by the statistically significant random effect for Sensor ID (6.179 ppm², p = .029), underscores that equipment sensitivity or placement might have introduced some heterogeneity in readings. This reinforces the model’s robustness, as incorporating random effects allows for improved adjustment for such site-specific or instrumental variability. However, to address this limitation, the study recommends that future assessments include more granular real-time traffic behavior data, continuous meteorological readings, and periodic sensor calibration checks to reduce unexplained variability. This strengthens the model's validity while acknowledging the complex nature of indoor pollutant dynamics.

Table 14: Estimates of Covariance Parameters

Estimates of Covariance Parameters [a]							
Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		18.070	1.268	14.248	<.001	15.747	20.735
Intercept [subject = Sensor ID]	Variance	6.179	2.830	2.183	.029	2.518	15.163
a. Dependent Variable: CO Level (PPM).							

Source: Researcher own survey (2025)

4.4.3. Estimated Marginal Means and Pairwise Comparisons of CO Levels across Temporal, Spatial and Operational Factors

The estimated marginal means and pairwise comparisons from the mixed-effects model used in this study. These comparisons provide a clearer understanding of how CO concentrations vary across different day types, time periods, parking zones, ventilation statuses, and traffic volumes (Field, 2013). The analysis directly supports the core research objective of identifying key temporal, spatial, and operational determinants influencing CO pollution levels at the Meskel Square Underground Parking Facility. So based on those analysis the SPSS result is:

4.4.4. Estimated Marginal Means and Pairwise Comparisons across Day Type

The estimated marginal means for CO levels across different day types show a clear temporal influence. The highest CO concentration was observed during weekend bazaar days (M = 10.54 ppm, SE = 0.52), followed by weekday bazaars (M = 8.03 ppm, SE = 0.52), weekday non-bazaars (M = 7.00 ppm, SE = 0.52), and the lowest during weekend non-bazaars (M = 6.14 ppm, SE = 0.52). This pattern reflects the impact of increased traffic and idling activity during bazaars.

Table 15: Estimated Marginal Means (Day Type)

Estimates [a]					
				95% Confidence Interval	
Day Type	Mean	Std. Error	df	Lower Bound	Upper Bound
Weekdays(Non-Bazaar)	6.813[b]	.786	30.553	5.209	8.417
Weekends(Non-Bazaar)	6.143[b]	.783	30.076	4.545	7.742
Weekdays(Bazaar)	8.032[b]	.761	26.945	6.471	9.594
Weekends(Bazaar)	10.535[b]	.775	28.943	8.950	12.121
a. Dependent Variable: CO Level (PPM).					
b. Covariates appearing in the model are evaluated at the following values: Traffic Count = 36.06.					

Source: Researcher own survey (2025)

The results from the pairwise comparisons of estimated marginal means in the mixed-effects model reveal significant differences in carbon monoxide (CO) concentrations across different day types within the Meskel Square Underground Parking Facility. The highest CO levels were observed during weekend bazaar periods (M = 10.54 ppm), which significantly differed from all other day types. Specifically, the mean CO level during weekend bazaars was significantly higher than that of weekdays without bazaars (mean difference = 3.722, $p < .001$), weekends without bazaars (mean difference = 4.392, $p < .001$), and weekdays with bazaars (mean difference = 2.503, $p < .001$), even after Bonferroni correction for multiple comparisons. This clearly indicates that weekend bazaar operations are the most CO-intensive periods in the facility. Additionally, weekdays with bazaars also showed a significantly higher mean CO level than weekends without bazaars (mean difference = 1.889, $p = .012$), suggesting that the presence of a bazaar, rather than just the day type, is a primary driver of elevated indoor CO levels. In contrast, differences between weekdays and weekends in the absence of bazaars were not statistically significant ($p = 1.000$), nor was the difference between weekdays without and with bazaars ($p = .244$). These findings reinforce the conclusion that event-driven traffic surges, particularly during weekend bazaars, significantly elevate pollution levels within the underground facility. Therefore, targeted mitigation efforts such as activating ventilation systems more effectively or limiting vehicle access should be prioritized during these high-risk periods. The use of estimated marginal means with Bonferroni-adjusted pairwise comparisons is supported by statistical best practices in mixed-effects modeling, particularly for controlling Type I error in multi-group comparisons (Field, 2013; West, Welch, & Galecki, 2014).

Table 16: Pairwise Comparisons (Day Type)

Pairwise Comparisons [a]

(I) Day Type	(J) Day Type	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference [c]	
						Lower Bound	Upper Bound
Weekdays (Non-Bazaar)	Weekends(Non-Bazaar)	.670	.584	406	1.000	-.879	2.219
	Weekdays(Bazaar)	-1.219	.594	406	.244	-2.794	.355
	Weekends(Bazaar)	-3.722*	.657	406	<.001	-5.466	-1.979
Weekends (Non-Bazaar)	Weekdays(Non-Bazaar)	-.670	.584	406	1.000	-2.219	.879
	Weekdays(Bazaar)	-1.889*	.607	406	.012	-3.499	-.279
	Weekends(Bazaar)	-4.392*	.687	406	<.001	-6.215	-2.570
Weekdays (Bazaar)	Weekdays(Non-Bazaar)	1.219	.594	406	.244	-.355	2.794
	Weekends(Non-Bazaar)	1.889*	.607	406	.012	.279	3.499
	Weekends(Bazaar)	-2.503*	.609	406	<.001	-4.118	-.888
Weekends (Bazaar)	Weekdays(Non-Bazaar)	3.722*	.657	406	<.001	1.979	5.466
	Weekends(Non-Bazaar)	4.392*	.687	406	<.001	2.570	6.215
	Weekdays(Bazaar)	2.503*	.609	406	<.001	.888	4.118

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Dependent Variable: CO Level (PPM).

c. Adjustment for multiple comparisons: Bonferroni.

Source: Researcher own survey (2025)

4.4.5. Estimated Marginal Means and Pairwise Comparisons across Time Period

Time period also had a marked effect on CO levels. Evening periods recorded the highest CO concentrations (M = 11.84 ppm, SE = 0.42), followed by afternoon (M = 6.36 ppm, SE = 0.42), and morning (M = 5.45 ppm, SE = 0.42). This result reflects CO accumulation over the course of the day and increased idling during exit times.

Table 17: Estimated Marginal Means (Time Period)

Estimates [a]					
				95% Confidence Interval	
Time Period	Mean	Std. Error	df	Lower Bound	Upper Bound
Morning	5.448[b]	.729	22.755	3.940	6.957
Afternoon	6.358[b]	.746	24.876	4.822	7.894
Evening	11.836[b]	.751	25.608	10.291	13.382
a. Dependent Variable: CO Level (PPM).					
b. Covariates appearing in the model are evaluated at the following values: Traffic Count = 36.06.					

Source: Researcher own survey (2025)

The pairwise comparisons of Estimated Marginal Means for Time Period in the mixed model analysis reveal statistically significant differences in CO concentration across the day. The analysis adjusts for multiple comparisons using the Bonferroni correction and evaluates group means with traffic count held constant.

The results show that the evening period had the highest CO concentrations, with a statistically significant mean difference of 6.388 ppm compared to the morning period ($p < .001$), and 5.478 ppm higher than the afternoon period ($p < .001$). These findings are statistically significant at the 0.05 level, as indicated by the asterisks and p-values less than .001. This suggests that CO accumulation in the parking facility increases as the day progresses, likely due to higher traffic volumes, longer idling times, and decreased air dispersion in the evening hours.

Table 18: Pairwise Comparisons (Time Period)

Pairwise Comparisons [a]							
(I) Time Period	(J) Time Period	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference [c] Lower Bound	Upper Bound
Morning	Afternoon	-.910	.551	406	.299	-2.235	.416
	Evening	-6.388*	.534	406	<.001	-7.672	-5.103
Afternoon	Morning	.910	.551	406	.299	-.416	2.235
	Evening	-5.478*	.508	406	<.001	-6.698	-4.258
Evening	Morning	6.388*	.534	406	<.001	5.103	7.672
	Afternoon	5.478*	.508	406	<.001	4.258	6.698
Based on estimated marginal means							
*. The mean difference is significant at the .05 level.							
a. Dependent Variable: CO Level (PPM).							
c. Adjustment for multiple comparisons: Bonferroni.							

Source: Researcher own survey (2025)

In contrast, the comparison between morning and afternoon periods did not yield a statistically significant difference (Mean Difference = -0.910, p = .299), indicating that CO levels during these periods are relatively similar and not significantly different when controlling for traffic count.

This pattern emphasizes the critical public health concern during evening hours, especially in environments like underground parking facilities where pollutant dispersion is limited. The statistically significant differences between evening and other time slots underscore the need for stronger ventilation measures and emission control interventions during peak evening periods. These results align with the theoretical framework of temporal pollution peaks and support targeted mitigation strategies.

4.4.6. Estimated Marginal Means and Pairwise Comparisons across Zones

Spatial variation analysis revealed that Central Parking Zone 1 recorded the highest CO level (M = 11.88 ppm, SE = 0.82), closely followed by Central Parking Zone 2 (M = 11.38 ppm, SE = 0.82), and Ramp Zone 1 (M = 10.79 ppm, SE = 0.82). The lowest average was observed in Entrance/Exit Zone 1 (M = 2.76 ppm, SE = 0.82), highlighting a significant spatial disparity.

Table 19: Estimated Marginal Means (Zones)

Estimates [a]

Zone	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Ramp Zone 1	10.790[b]	1.548	12.918	7.443	14.137
Entrance/Exit 1	2.756[b]	1.565	13.492	-.613	6.125
Central Parking Zone 1	11.384[b]	1.549	12.946	8.036	14.732
Central Parking Zone2	11.885[b]	1.539	12.620	8.549	15.220
Entrance/Exit 2	5.425[b]	1.534	12.455	2.096	8.755
Ramp Zone 2	5.045[b]	1.565	13.492	1.676	8.414

a. Dependent Variable: CO Level (PPM).

b. Covariates appearing in the model are evaluated at the following values: Traffic Count = 36.06.

Source: Researcher own survey (2025)

The mixed-effects model's estimated marginal means revealed statistically significant differences in carbon monoxide (CO) levels among several parking zones within the Meskel Square Underground Parking Facility.

Specifically, Entrance/Exit Zone 1 consistently recorded significantly lower CO levels compared to several other zones. For instance, the mean CO level in Entrance/Exit 1 was 8.03 ppm lower than Ramp Zone 1 (p = .043), 8.63 ppm lower than Central Parking Zone 1 (p = .026), and 9.13 ppm lower than Central Parking Zone 2 (p = .017). These differences were statistically significant at the 0.05 level (Bonferroni-adjusted). This supports the spatial pattern observed earlier in the study, suggesting that entrance zones, particularly Entrance/Exit 1, tend to have better air quality likely due to more frequent air exchanges and shorter idling durations.

Meanwhile, no statistically significant differences were observed between zones such as Ramp Zone 1 and the central zones, or between Ramp Zone 2 and other zones, indicating that high CO concentrations are not uniformly distributed but are notably concentrated in the central and ramp areas with high traffic and poor ventilation dynamics.

Table 20: Pairwise Comparisons (Zones)

Pairwise Comparisons[a]

(I) Zone	(J) Zone	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference[c]	
						Lower Bound	Upper Bound
Ramp Zone 1	Entrance/Exit 1	8.034*	2.169	12.437	.043	.185	15.883
	Central Zone 1	-.594	2.152	12.065	1.000	-8.438	7.250
	Central Zone 2	-1.095	2.153	12.073	1.000	-8.939	6.750
	Entrance/Exit 2	5.365	2.152	12.049	.423	-2.479	13.209
	Ramp Zone 2	5.745	2.170	12.456	.310	-2.104	13.595
Entrance/Exit 1	Ramp Zone 1	-8.034*	2.169	12.437	.043	-15.883	-.185
	Central Parking Zone 1	-8.628*	2.158	12.183	.026	-16.474	-.783
	Central Parking Zone2	-9.129*	2.179	12.675	.017	-16.982	-1.276
	Entrance/Exit 2	-2.669	2.165	12.355	1.000	-10.517	5.178
	Ramp Zone 2	-2.289	2.153	12.079	1.000	-10.133	5.555
Central Parking Zone 1	Ramp Zone 1	.594	2.152	12.065	1.000	-7.250	8.438
	Entrance/Exit 1	8.628*	2.158	12.183	.026	.783	16.474

	Central Parking Zone2	-.501	2.158	12.180	1.000	-8.346	7.345
	Entrance/Exit 2	5.959	2.152	12.065	.254	-1.885	13.803
	Ramp Zone 2	6.339	2.161	12.255	.184	-1.507	14.186
Central Parking Zone2	Ramp Zone 1	1.095	2.153	12.073	1.000	-6.750	8.939
	Entrance/Exit 1	9.129*	2.179	12.675	.017	1.276	16.982
	Central Parking Zone 1	.501	2.158	12.180	1.000	-7.345	8.346
	Entrance/Exit 2	6.459	2.153	12.068	.165	-1.385	14.304
	Ramp Zone 2	6.840	2.182	12.749	.121	-1.014	14.694
Entrance/Exit 2	Ramp Zone 1	-5.365	2.152	12.049	.423	-13.209	2.479
	Entrance/Exit 1	2.669	2.165	12.355	1.000	-5.178	10.517
	Central Parking Zone 1	-5.959	2.152	12.065	.254	-13.803	1.885
	Central Parking Zone2	-6.459	2.153	12.068	.165	-14.304	1.385
	Ramp Zone 2	.381	2.167	12.383	1.000	-7.468	8.229
Ramp Zone 2	Ramp Zone 1	-5.745	2.170	12.456	.310	-13.595	2.104
	Entrance/Exit 1	2.289	2.153	12.079	1.000	-5.555	10.133
	Central Parking Zone 1	-6.339	2.161	12.255	.184	-14.186	1.507
	Central Parking Zone2	-6.840	2.182	12.749	.121	-14.694	1.014
	Entrance/Exit 2	-.381	2.167	12.383	1.000	-8.229	7.468
Based on estimated marginal means						
*. The mean difference is significant at the .05 level.						
a. Dependent Variable: CO Level (PPM).						
c. Adjustment for multiple comparisons: Bonferroni.						

Source: Researcher own survey (2025)

4.4.7. Estimated Marginal Means and Pairwise Comparisons of Ventilation Status

Ventilation status also significantly influenced CO levels. The OFF condition showed the highest mean CO level (M = 8.87 ppm, SE = 0.45), followed by ON (M = 7.77 ppm, SE = 0.58), and the lowest CO was observed when the system was ON/OFF (M = 6.35 ppm, SE = 0.46). This suggests intermittent fan operation during moderate exposure periods might have led to better dispersion.

Figure 14: Supply Fans (Axial Fans)

Figure 15: Jet Fans (Centrifugal Fans)

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

Table 21: Estimated Marginal Means (Ventilation Status)

Estimates [a]					
				95% Confidence Interval	
Ventilation Status	Mean	Std. Error	df	Lower Bound	Upper Bound
ON	8.421[b]	.913	54.070	6.590	10.251
OFF	8.873[b]	.635	13.141	7.503	10.243
ON/OFF	6.349[b]	.902	51.673	4.539	8.160

a. Dependent Variable: CO Level (PPM).
b. Covariates appearing in the model are evaluated at the following values: Traffic Count = 36.06.

Source: Researcher own survey (2025)

The analysis of variance for ventilation status showed a statistically significant effect on CO levels, F (2, 418) = 5.554, p = .004, indicating that how the ventilation system is operated has a meaningful impact on air quality within the Meskel Square Underground Parking Facility. Estimated marginal means revealed that CO levels were highest when ventilation was fully OFF (M = 8.87 ppm), moderately lower when the system was ON (M = 8.42 ppm), and lowest during ON/OFF operations (M = 6.35 ppm). Although the difference between OFF and ON conditions was not statistically significant (p = 1.000), the difference between OFF and ON/OFF was significant, with a mean reduction of 2.52 ppm under ON/OFF conditions (p = .003).

This result may seem counterintuitive, as one might expect the fully ON condition to yield the lowest pollution levels. However, this finding is explained by operational realities within the facility. According to key informant interviews with technical staff and employee representatives, the ON/OFF system is not automated but is instead manually adjusted based on perceived air quality or informal observations. In some cases, these manual adjustments are more responsive to real-time CO buildup, particularly during visible smoke or traffic congestion, thereby temporarily improving ventilation performance. By contrast, the fully ON condition often operates at low fan speeds, and as field measurements later demonstrate, the airflow delivered under this mode does not consistently meet the ASHRAE 62.1 minimum ACH requirements. Additionally, structural obstructions like ramps further limit effective airflow in some zones, even when fans are operational.

Therefore, while ON/OFF operation appears most effective in terms of average CO levels, this may reflect selective, albeit informal, manual adjustments during peak exposure times rather than systematic control. These findings emphasize the need for automated, sensor-triggered ventilation systems that respond precisely to rising CO concentrations across zones. They also underline the limitations of continuous low-speed ventilation, which may give a false sense of safety while failing to deliver adequate air exchange during critical periods.

Table 22: Pairwise Comparisons (Ventilation Status)

Pairwise Comparisons [a]							
(I) Ventilation Status	(J) Ventilation Status	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference[c]	
						Lower Bound	Upper Bound
ON	OFF	-.452	.765	406	1.000	-2.292	1.388
	ON/OFF	2.071	.939	406	.084	-.185	4.327
OFF	ON	.452	.765	406	1.000	-1.388	2.292
	ON/OFF	2.523*	.759	406	.003	.699	4.347
ON/OFF	ON	-2.071	.939	406	.084	-4.327	.185
	OFF	-2.523*	.759	406	.003	-4.347	-.699
Based on estimated marginal means							
*. The mean difference is significant at the .05 level.							
a. Dependent Variable: CO Level (PPM).							
c. Adjustment for multiple comparisons: Bonferroni.							

Source: Researcher own survey (2025)

While the Linear Mixed-Effects Model effectively accounts for the nested and repeated measures nature of the data, it was crucial to ensure that multicollinearity among the fixed effects did not unduly influence the reliability and interpretability of the coefficient estimates. Therefore, a collinearity diagnostic was performed on the independent variables (fixed effects) of the model. The results, as presented in the Collinearity Statistics section of the output, showed that all Variance Inflation Factor (VIF) values were well below the common threshold of 10, with the highest VIF being 1.270 (for Traffic Count) and the lowest being 1.025 (for Zone). Correspondingly, all Tolerance values were well above 0.10, ranging from 0.787 (Traffic Count) to 0.975 (Zone). These diagnostic statistics confirm the absence of significant multicollinearity among the fixed effects (Traffic Count, Day Type, Time Period, Zone, and Ventilation Status) (Hair et al., 2010). This finding further strengthens the confidence in the LMM's results, ensuring that the statistically significant influences and magnitude of effects identified for each predictor, as previously discussed, are robust and not a byproduct of highly correlated independent variables, thus supporting the validity of our conclusions regarding their unique contributions to CO concentration levels.

Table 23: Collinearity Diagnostics for Fixed Effects

Coefficients [a]

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations			Collinearity Statistics	
	B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
(Constant)	-1.994	1.623		-1.229	.220					
Traffic Count	.055	.010	.235	5.484	<.001	.416	.257	.209	.787	1.270
Day Type	1.653	.279	.252	5.929	<.001	.332	.276	.226	.806	1.241
Time Period	3.696	.355	.411	10.426	<.001	.465	.451	.397	.935	1.070
Zone	-.506	.166	-.118	-3.052	.002	-.092	-.146	-.116	.975	1.025
Ventilation Status	-.595	.615	-.038	-.968	.334	.027	-.047	-.037	.932	1.073

a. Dependent Variable: CO Level(PPM)

Source: Researcher own survey (2025)

4.5. Ventilation Compliance Analysis for Meskel Square Underground Parking Facility

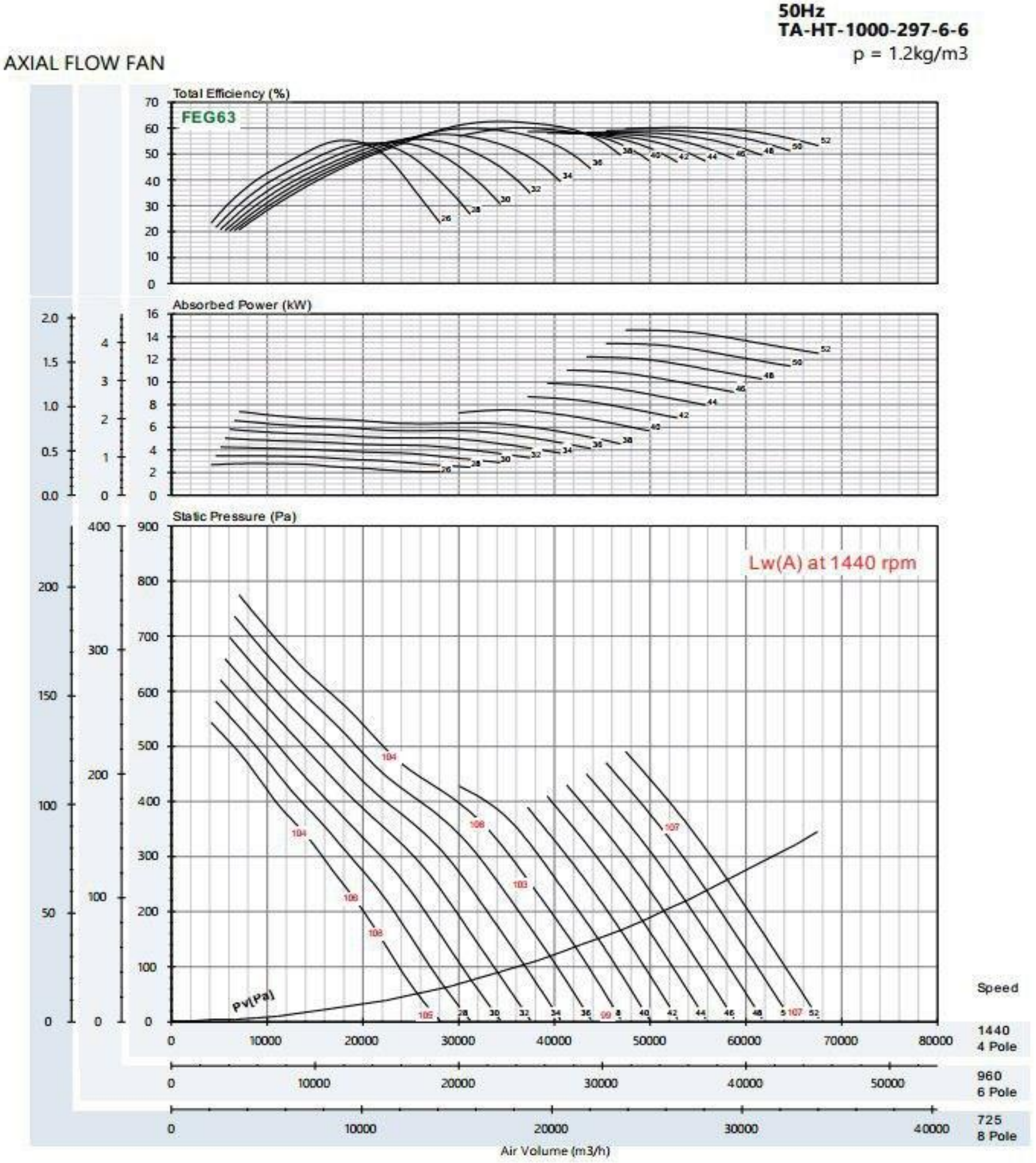
An assessment was conducted to evaluate whether the installed mechanical ventilation system in each zone of the Meskel Square Underground Parking Facility Basement 1 complies with the required air exchange rate (ACH) of **10**, which is the standard for enclosed parking garages during peak operation. According to NFPA 88A (2021) and ASHRAE 62.1 (2019) guidelines (10 ACH for enclosed parking), EN 50545 (CO sensor spacing ≤15–20 m), and EN 12101-7 (jet fan requirements). The key parameters assessed include:

- Zone dimensions (length × width × height)
- Calculated volume and required airflow
- Installed fan capacity (minimum and maximum airflow) from product specification graph.
- Compliance with the minimum and maximum fan airflow against the required airflow

Airflow Rate (m^3/h) = Room Volume (m^3) x Air Changes per Hour (ACH), so we can calculate air change per hour for each zones of the parking (Miller, S. L. et al, 2021)

ACH = Total Airflow Rate (Supply + Extract Fans) (m^3/h)/Zone Volume

Figure 16: Axial Fan Flow Graph [2]



Source: Picture taken by the researcher from product specification catalog (2025)

Based on the sample Entrance/Exit zone 1 axial fan product specifications installed at the Meskel Square Underground Parking Facility and the fan flow graph provided in the catalog, the researcher interpreted the graph to determine the minimum and maximum airflow rate (m³/h) of the fans, which was then used to calculate the air changes per hour.

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[2] From this graph, we want to know the fan's air flow capacity or air volume in cubic meters per hour, but let's read the overall condition of the fan shown in the graph.

1. Total Efficiency (%) (Top Graph in Each Set)

This curve shows how efficiently the fan converts input power into airflow at different air volumes. You can observe that efficiency generally decreases as the airflow increases (after reaching a certain optimal point). This is typical for many fans as the fan operates less efficiently at higher or lower volumes. Look at the highest efficiency points on each curve, which are typically at moderate air volumes. These are the points where the fan is most efficient (Tim D, 2023).

2. Absorbed Power (kW) (Middle Graph in Each Set)

This shows the electrical power consumed by the fan at various air volumes. As the air volume increases, the absorbed power also increases. This means the fan requires more power to move a larger volume of air. There is a steep increase in power consumption as the airflow rises, which indicates higher energy usage at larger volumes(G Squared Engineered Products, 2019)

3. Static Pressure (Pa) (Bottom Graph in Each Set)

The static pressure is the pressure difference the fan is able to generate in a system (often used to overcome resistance like filters or ducts). Static pressure generally decreases as the airflow increases. This is a typical characteristic of fans: as more air is moved, it becomes harder to maintain high static pressure. The static pressure is higher at lower airflows but drops as the fan operates at higher air volumes.(MINTEK, 2024)

4. Noise Levels (Lw(A) at 1440 rpm)

Purpose: This line shows the noise emitted by the fan at a speed of 1440 rpm.

Insight: As the air volume increases, the noise levels (in decibels) also tend to increase, especially at higher flow rates.It was also noted that the number of poles in an AC induction motor inversely dictates its rotational speed, and this speed directly influences the air volume or ventilation rate delivered by a fan. As evidenced by the formula $N_s = 120 \times f/p$, a higher number of poles results in a lower motor speed (N_s) at a constant frequency (f). The provided fan performance graphs illustrate this, showing lower rpm values for higher pole counts (e.g., 1440 rpm for 4-pole vs. 960 rpm for 6-pole). Consequently, a fan driven by a slower motor (due to a higher number of poles) will generally move a smaller volume of air per unit time, leading to a reduced ventilation rate. This relationship is supported by the fan laws, where air volume (Q) is directly proportional to the fan speed (N): $Q2=Q1\times (N2/N1)$. Therefore, increasing the number of motor poles reduces the fan speed, which in turn decreases the air volume and overall ventilation rate achieved by the fan system (ACI, 2023).

Figure 17: Axial Fans Product Specifications

Source: Picture taken by the researcher (2025)

Table 24: Ventilation Compliance Analysis of Meskel Square Ground Parking Zones

Zones	Volume (m³)	Installed Supply Fans Minimum Air Flow (m³/h)	Installed Extract Fans Minimum Air Flow (m³/h)	Total Installed Fans Minimum Air Flow (m³/h)	Installed Supply Fans Maximum Air Flow (m³/h)	Installed Extract Fans Maximum Air Flow (m³/h)	Total Installed Fans Maximum Air Flow (m³/h)	Required Airflow (10 ACH)- (m³/h)
Ramp Zone 1	9,386	2 × 14,000 = 28,000	-	28,000	2 × 30,000 = 60,000	-	60,000	6.4
Entrance /	15,570	2 × 18,000 = 36,000	2 × 24,000 = 48,000	84,000	2 × 39,000 = 78,000	2 × 53,000 = 106,000	184,000	11.8

Exit Zone 1								
Central Parking Zone 1	13,277	2 × 14,000 = 28,000	2 × 24,000 = 48,000	76,000	2 × 30,000 = 60,000	2 × 53,000 = 106,000	166,000	12.5
Central Parking Zone 2	12,958	2 × 14,000 = 28,000	2 × 24,000 = 48,000	76,000	2 × 30,000 = 60,000	2 × 53,000 = 106,000	166,000	12.8
Entrance /Exit Zone 2	14,630	-	2 × 24,000 = 48,000	48,000	-	2 × 53,000 = 106,000	106,000	7.2
Ramp Zone 2	10,218	2 × 14,000 = 28,000	2 × 24,000 = 48,000	76,000	2 × 30,000 = 60,000	2 × 53,000 = 106,000	166,000	16.2

Source: Researcher own survey (2025)

The ventilation performance of the Meskel Square Underground Parking Facility was evaluated across six main zones using installed fan specifications and airflow rates. The total airflow (combined supply and extract fans) was used to assess ventilation adequacy against international standards, particularly ASHRAE 62.1 and NFPA 88A, which recommend 6 to 10 ACH in enclosed parking structures to maintain acceptable air quality and prevent CO buildup. Ramp Zone 1, with a total volume of 9,386 m³, is equipped with supply fans capable of providing a total airflow ranging from 28,000 m³/h to 60,000 m³/h. However, extract fan performance remains unknown due to unavailable data for the 12-pole fans. Even considering only the supply fans, the ACH ranges from 2.98 to 6.39, indicating that the maximum airflow barely meets the lower bound of the recommended standard. In the absence of extract fan data, this zone's compliance remains inconclusive, though the lower range clearly falls below acceptable ventilation rates. These physical ventilation limitations directly align with findings from the linear mixed model analysis of ventilation status. Statistically, the highest CO levels were recorded when ventilation was fully OFF (M = 8.87 ppm), slightly reduced under continuous ON conditions (M = 8.42 ppm), and lowest under ON/OFF manual operation (M = 6.35 ppm). Interestingly, the difference between

OFF and ON was not statistically significant (p = 1.000), suggesting that merely keeping fans operational does not guarantee sufficient pollutant removal. This result is consistent with multiple worker complaints about fan ineffectiveness:

"The fans work, but it takes time to clear the smoke. Sometimes even when they run all day, the air still feels heavy" (WR1).

Entrance/Exit Zone 1, with a volume of 15,570 m^3, has well-documented fan performance. Combined airflow from both supply and extract fans ranges from 84,000 m^3/h to 184,000 m^3/h, resulting in ACH values between 5.4 and 11.83. These results suggest that at maximum airflow, the zone meets and slightly exceeds the upper ACH threshold, but the minimum airflow remains marginally below the lower bound, raising concerns during low ventilation operation. Central Parking Zone 1, measuring 13,277 m^3, also shows varying performance. The total ventilation rate provided by supply and extract fans ranges from 76,000 m^3/h to 166,000 m^3/h, translating to ACH values from 5.72 to 12.53. This indicates good compliance at maximum airflow, but marginal shortfall at the minimum level, especially in peak usage scenarios with many idling vehicles. Central Parking Zone 2, with a slightly smaller volume of 12,958 m^3, shows similar performance. The combined airflow of 76,000 m^3/h to 166,000 m^3/h results in ACH values between 5.87 and 12.83. As with Zone 1, this zone meets the standard at the upper range, but minimum airflow just falls short of the 6 ACH minimum, which could impact air quality if the fans are not operating at or near peak capacity. Entrance/Exit Zone 2, with a volume of 14,630 m^3, has extract fan data available but lacks reliable performance figures for the 12-pole supply fans. Based solely on the extract fan airflow (48,000–106,000 m^3/h), the ACH ranges from 3.28 to 7.25, which is insufficient at minimum levels and only marginally compliant at best. The absence of supply fan data makes it impossible to fully assess ventilation adequacy; however, these values suggest that without sufficient supply airflow, this zone may not consistently meet minimum ventilation standards. Ramp Zone 2, with a volume of 10,218 m^3, benefits from both supply and extract fan performance data. The combined total airflow of 76,000 m^3/h to 166,000 m^3/h results in ACH values ranging from 7.44 to 16.27, indicating strong compliance across both minimum and maximum performance levels. This zone demonstrates the most reliable and effective ventilation performance in the facility.

Although Ramp Zone 2 achieved the recommended minimum 6 ACH threshold (ranging between 7.44–16.27 ACH), both field observations and worker interviews revealed persistent issues of airflow obstruction and localized pollutant accumulation. As one worker representative noted:

> *"Even when the fans are running, some areas, especially around ramps and lower ceilings, still feel suffocating and smoky"* (WR3).

The interviews with facility managers provided further operational context. Although the facility was originally equipped with CO sensors in all zones and two-speed fans capable of high and low modes (aligned with standardized variable flow [SVF] systems), mentioned in the literature part[3]. However, these controls have not been fully automated. As confirmed by management:

> *"The fans are operated manually. The system has automatic capability, but we prefer to adjust manually when we see smoke or when the air feels heavy"* (FM1).

This reactive approach creates inconsistent and delayed responses to pollution build-up, particularly during sudden traffic congestion or bazaar events. Moreover, staff admitted that fan speed is often kept at a minimum to reduce noise disturbances for customers and employees:

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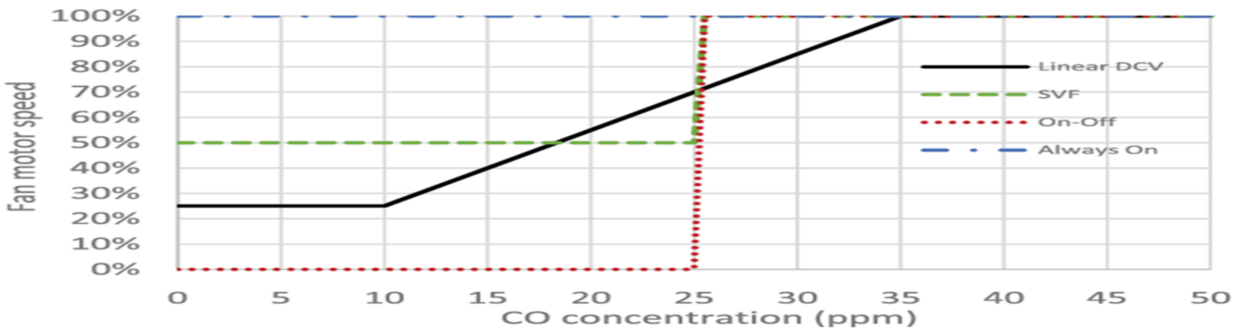
[3] As it has been mentioned in the second chapter (see 2.4.6.1 ventilation Control Strategies), The Standardized Variable Flow (SVF) strategy is also commonly used in the industry as an energy saving approach whereby the fans operate at 50% of maximum speed until CO concentrations reach 25 ppm, at which point they increase to 100% of maximum speed.



> *"We try to avoid using full speed unless there are complaints, because the fan noise is disturbing"* (FM2).

While the manual ON/OFF adjustment occasionally results in temporarily lower CO levels (as reflected in the lower mean CO under ON/OFF conditions), this reactive system is neither reliable nor sustainable. As one worker emphasized:

> *"There are times, especially during weekends and busy events, when the air quality worsens fast, but the fans are not turned up immediately because no one is monitoring continuously"* (WR2).

This problem is compounded during night shifts or off-peak supervision periods, where oversight is minimal, leaving staff and customers exposed to elevated CO concentrations for prolonged periods.

Figure 18: Meskel Square Ventilation Fans Control Panel

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

In summary, the triangulation of CO concentration data, ACH ventilation compliance, and operational practices reveals a misalignment between system design and real-world functionality. The results support an urgent need to upgrade the current fan control to a true DCV system, ensure consistent extract fan operation, and redesign fan placement and airflow paths to avoid dead zones and structural obstructions. Without these reforms, even zones with seemingly functional ventilation infrastructure will continue to underperform during high-risk periods, posing serious health risks to workers and facility users.

While the ACH (Air Changes per Hour) estimates derived from fan specifications suggest theoretical compliance with ASHRAE 62.1 standards in several zones of the Meskel Square Underground Parking Facility, these values do not reflect actual operational performance. Field observations and qualitative interviews reveal that fans are often manually controlled and deliberately operated at low speeds to minimize noise disturbance, particularly during customer-heavy periods. This practice significantly undermines the ventilation system's effectiveness and challenges the reliability of calculated ACH figures based on assumed maximum output. Therefore, the analysis explicitly acknowledges this discrepancy, aligning theoretical calculations with real-world constraints, and emphasizes the need for automated, sensor-driven fan activation to ensure safe and consistent ventilation performance under varying traffic conditions.

Figure 19: Obstructed Fans by Ramp Structure in the Ramp Zones

Source: Picture taken by the researcher from Meskel Square Ground Parking Facility (2025)

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study demonstrates that carbon monoxide (CO) exposure within the Meskel Square Underground Parking Facility is not only spatially and temporally variable but also frequently exceeds international health thresholds. Central parking zones and vehicle access ramps emerged as pollution hotspots, particularly during bazaar weekends and evening hours, highlighting the compounding effects of traffic intensity, poor ventilation design, and inadequate operational response. These findings confirm that the current ventilation and safety management systems are insufficient to mitigate CO risks under real-world conditions.

Beyond the facility level, this case underscores a broader urban environmental health concern in rapidly densifying cities like Addis Ababa. The results align with environmental health and indoor air quality theories, reinforcing that enclosed urban infrastructure without responsive control systems poses chronic occupational risks. The study calls for urgent reform of ventilation systems, stronger institutional accountability, and integration of indoor air quality into urban planning and transport management policies to ensure health-compliant and sustainable underground mobility infrastructure.

5.2. Recommendation

To address the risks identified, this study recommends the following interventions, situated within broader environmental management and urban health planning frameworks:

- **Implement Automated, Demand-Controlled Ventilation (DCV)**[4] Replace manual fan controls with CO-sensor-triggered systems that dynamically respond to real-time pollution

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[4] As it has been mentioned in the second chapter (see 2.4.6.1 ventilation Control Strategies), **Demand-Controlled Ventilation (DCV)**: A DCV system is designed to supply a quantity of fresh air fitted with the need, ensuring the right quantity of fresh airflow and the right environmental conditions in terms of different parameters e.g., relative humidity (RH), temperature, carbon dioxide (CO2) or volatile organic compound (VOC). (Therese O, 2023).

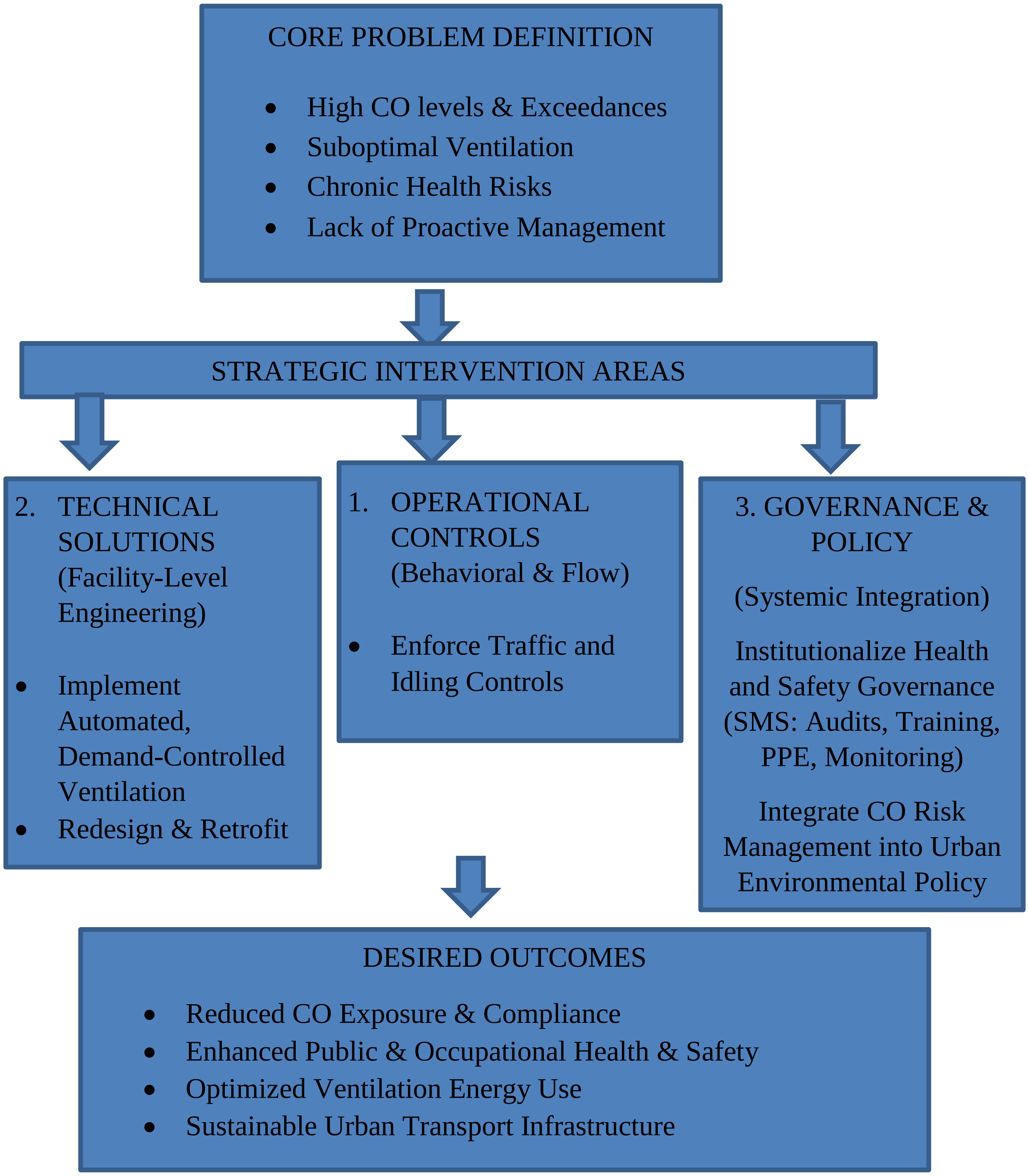
levels. This aligns with global best practices in energy-efficient indoor environmental control (ASHRAE 62.1, 2019) and reduces peak CO concentrations without unnecessary energy use.

- **Redesign and Retrofit Ventilation Infrastructure:** Zones falling below the 6 ACH threshold should be prioritized for redesign. Improved fan placement, airflow balancing, and retrofitting to reach ≥10 ACH will prevent pollutant accumulation and support compliance with ASHRAE and NFPA standards.
- **Institutionalize Health and Safety Governance:** Establish a formal Safety Management System (SMS) incorporating WHO (2010) and OSHA (2023) guidelines. This should include documented air quality audits, worker training, PPE provision, and exposure monitoring, especially for high-risk shift workers.
- **Enforce Traffic and Idling Control Measures:** Urban planners and facility operators should collaborate to develop operational policies limiting idling during peak events, coordinating traffic flow, and separating pedestrian and vehicle zones where feasible. These measures contribute to a healthier urban transport ecosystem.
- **Integrate CO Risk Management into Urban Environmental Policy:** The Addis Ababa City Administration, in partnership with environmental and health authorities, should treat indoor air pollution in public infrastructure as a public health concern. Periodic external audits, air quality disclosure, and integration of air quality metrics into event permitting and transport planning are essential for sustainable urban development (UNEP, 2021; World Bank, 2021).

Recommendations bridge facility-level fixes with metropolitan sustainability goals (SDG 3.9, 11.6), positioning Meskel Square as a testbed for replicable urban health innovation.

5.3. Implementation Framework for CO Mitigation in Underground Parking Facilities

Figure 20: Implementation Framework



Source: Researcher Own Construct (2025)

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Annex 1

College of Development Studies

Center for Environment and Development

MA Program of Environment and Sustainable Development

Checklist for Document Review

Item	**Yes**	**No**	**Notes/Location in Document**
CO sensor data logs (by zone and time)			
Maintenance records of ventilation systems			
CO incident or health complaint reports			
Ventilation design plans and fan specifications			
Policy and procedure documents for air quality and traffic control			
Records of WHO/EPA standard exceedances and corrective actions			
Records of CO monitoring available.			

Annex 2

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Observation Checklist for CO Pollution Assessment

Zone-Based Observations

- ☐ Fan operational status (ON/OFF/LOW/HIGH)
- ☐ Visible signs of congestion or idling vehicles
- ☐ Fan placement adequacy and obstructions
- ☐ Presence of CO warning indicators (e.g., lights, signage)

Temporal Observations

- ☐ Morning, afternoon, evening comparisons
- ☐ Bazaar vs non-bazaar periods

Ventilation & Traffic Factors

- ☐ Ventilation adjustments based on real-time CO levels
- ☐ Presence and enforcement of idling restrictions
- ☐ Door/exit airflow behavior (open/closed effect)

Annex 3

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CO Level Data Collection Sheet

Date	Day of Week	Time	Zone	Sensor ID	CO Reading (ppm)	Traffic Count	Ventilation Status	Notes

Annex 4

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Collected CO Level Data within Meskel Square Underground Parking Facility

Morning CO Level at Meskel Square Ground Parking Facility	**Ramp Zone 1**			**Ramp 1 Mean CO Level**	**Entrance/ Exit Zone 1**			**Entrance/Exit 1 Mean CO Level**	**Central Parking Area 1**			**Central Parking Area 1 Mean CO Level**	**Central Parking Area 2**			**Central Parking Area 2 Mean CO Level**	**Entrance/ Exit Zone 2**			**Entrance/Exit 2 Mean CO Level**	**Ramp Zone 2**			**Ramp 2 Mean CO Level**
	R1S1(PPM)	**R1S2(PPM)**	**R1S3(PPM)**		**EE1S1(PPM)**	**EE1S2(PPM)**	**EE1S3(PPM)**		**C1S1(PPM)**	**C1S2(PPM)**	**C1S3(PPM)**		**C2S1(PPM)**	**C2S2(PPM)**	**C2S3(PPM)**		**EE2S1(PPM)**	**EE2S2(PPM)**	**EE2S3(PPM)**		**R2S1(PPM)**	**R2S2(PPM)**	**R2S3(PPM)**	
Weekdays (Non-Bazaar Time)																								
Day 1(24/3/202)	0	5	7	4	5	0	0	1.67	0	7	7	4.67	5	5	9	6.33	0	7	15	7.3	11	7	6	8
Traffic Count	8/81				17/135				9/130				11/95				30/124				80/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				ON			

Day 2(27/3/2025)	0	5	5	3.33	5	0	0	1.67	0	6	9	5	0	7	12	6.33	0	0	0	0	8	5	0	4.33
Traffic Count	24/81				33/135				13/130				12/95				30/124				57/92			
Ventilation Status	OFF				OFF				OFF				OFF				ON				ON			
				3.67				1.67				4.83				6.33				3.7				6.17
Weekdays (Bazaar Time-2025 Easter Bazaar)																								
Day 1(08/4/2025)	10	9	8	9	0	0	0	0	6	7	8	7	0	7	11	6	0	0	5	1.7	12	5	11	9.33
Traffic Count	25/81				31/135				16/130				11/95				33/124				63/92			
Ventilation Status	OFF				ON/OFF				ON/OFF				ON/OFF				ON/OFF				OFF			
Day 2(11/4/2025)	7	8	7	7.33	0	0	0	0	7	10	11	9.33	6	0	12	6	0	0	6	2	11	0	12	7.67
Traffic Count	22/81				33/135				14/130				14/95				34/124				73/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				ON			
				8.17				0				8.17				6				1.8				8.5
Weekends (Non-Bazaar)																								

Day 1(16/3/2025)	0	7	6	4.33	0	0	0	0	5	6	8	6.33	0	5	9	4.67	0	0	0	0	5	0	0	1.67
Traffic Count	2/81				27/135				11/130				0/95				3/124				46/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				ON			
Day 2(22/3/2025)	0	5	7	4	5	0	0	1.67	0	6	6	4	0	6	10	5.33	0	0	0	0	5	0	0	1.67
Traffic Count	8/81				15/135				8/130				3/95				21/124				38/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				ON			
				4.17				0.83				5.17				5				0				1.67
Weekends (Bazaar Time)																								
Day 1(4/1/2025-2025 Christmass Bazaar	9	8	9	8.67	12	8	5	8.33	8	14	13	11.7	5	7	12	8	0	5	6	3.7	7	6	5	6
Traffic Count	9/81				28/135				19/130				6/95				15/124				44/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(13/4/202-2025 Easter Bazaar	6	8	6	6.67	0	11	0	3.67	5	6	10	7	5	0	12	5.67	0	0	5	1.7	7	0	0	2.33
Traffic Count	2/81				27/135				16/130				0/95				1/124				36/92			

Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
				7.67				6				9.33				6.83				2.7				4.17

Afternoon CO Level at Meskel Square Ground Parking Facility	**Ramp Zone 1**			**Ramp 1 Mean CO Level**	**Entrance/ Exit Zone 1**			**Entrance/Exit 1 Mean CO Level**	**Central Parking Area 1**			**Central Parking Area 1 Mean CO Level**	**Central Parking Area 2**			**Central Parking Area 2 Mean CO Level**	**Entrance/ Exit Zone 2**			**Entrance/Exit 2 Mean CO Level**	**Ramp Zone 2**			**Ramp 2 Mean CO Level**
	R1S1(PPM)	**R1S2(PPM)**	**R1S3(PPM)**		**EE1S1(PPM)**	**EE1S2(PPM)**	**EE1S3(PPM)**		**C1S1(PPM)**	**C1S2(PPM)**	**C1S3(PPM)**		**C2S1(PPM)**	**C2S2(PPM)**	**C2S3(PPM)**		**EE2S1(PPM)**	**EE2S2(PPM)**	**EE2S3(PPM)**		**R2S1(PPM)**	**R2S2(PPM)**	**R2S3(PPM)**	
Weekdays (Non-Bazaar Time)																								
Day 1(24/3/202)	0	7	11	6	9	0	0	3	8	7	10	8.33	6	8	11	8.33	5	0	7	4	9	5	0	4.67
Traffic Count	23/81				49/135				18/130				15/95				43/124				75/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(27/3/202)	0	5	8	4.33	9	0	0	3	7	8	11	8.67	5	7	11	7.67	0	5	0	1.7	10	5	0	5
Traffic Count	22/81				45/135				19/130				23/95				33/124				82/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
				5.17				3				8.5				8				2.8				4.83

Weekdays (Bazaar Time-2025 Easter Bazaar)																								
Day 1(08/4/202)	8	9	8	8.33	5	0	0	1.67	8	9	11	9.33	0	7	13	6.67	0	0	0	0	11	0	0	3.67
Traffic Count	32/81				64/135				27/130				17/95				40/124				81/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(11/4/202)	7	16	15	12.7	8	5	5	6	7	22	25	18	13	9	18	13.3	6	7	13	8.7	12	5	7	8
Traffic Count	60/81				108/135				71/130				35/95				29/124				41/92			
Ventilation Status	OFF				ON/OFF				OFF				ON/OFF				ON				OFF			
				10.5				3.83				13.7				10				4.3				5.83
Weekends (Non-Bazaar)																								
Day 1(16/3/202)	11	12	10	11	6	5	5	5.33	12	11	14	12.3	7	5	16	9.33	0	0	7	2.3	6	0	0	2
Traffic Count	14/81				81/135				27/130				3/95				7/124				38/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(22/3/202)	0	6	5	3.67	6	0	0	2	6	9	10	8.33	0	9	12	7	0	9	0	3	9	5	0	4.67
Traffic Count	2/81				12/135				8/130				2/95				8/124				32/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				ON			

				7.33				3.67				10.3				8.17				2.7				3.33
Weekends (Bazaar Time)																								
Day 1(4/1/2025-2025 Christ mass Bazaar	15	36	32	27.7	18	8	11	12.3	19	14	18	17	35	12	15	20.7	7	6	13	8.7	8	12	18	12.7
Traffic Count	80/81				128/135				125/130				89/95				103/124				31/92			
Ventilation Status	OFF				ON/OFF				ON/OFF				ON				ON/OFF				OFF			
Day 2(13/4/202-2025 Easter Bazaar	14	13	11	12.7	7	5	5	5.67	10	10	13	11	9	7	16	10.7	0	0	9	3	8	0	0	2.67
Traffic Count	55/81				102/135				76/130				36/95				22/124				41/92			
Ventilation Status	ON/OFF				ON				ON/OFF				ON/OFF				ON/OFF				OFF			
				20.2				9				14				15.7				5.8				7.67

Evening CO	**Ramp Zone 1**	**Ramp 1 Mean**	**Entrance/ Exit Zone 1**	**Entrance/ Exit 1**	**Central Parking Area 1**	**Central Parking**	**Central Parking Area 2**	**Central Parking**	**Entrance/ Exit Zone 2**	**Entrance/ Exit 2**	**Ramp Zone 2**	**Ramp 2 Mean**

Level at Meskel Square Ground Parking Facility	**R1S1(PPM)**	**R1S2(PPM)**	**R1S3(PPM)**		**EE1S1(PPM)**	**EE1S2(PPM)**	**EE1S3(PPM)**		**C1S1(PPM)**	**C1S2(PPM)**	**C1S3(PPM)**		**C2S1(PPM)**	**C2S2(PPM)**	**C2S3(PPM)**		**EE2S1(PPM)**	**EE2S2(PPM)**	**EE2S3(PPM)**		**R2S1(PPM)**	**R2S2(PPM)**	**R2S3(PPM)**	
Weekdays (Non-Bazaar Time)																								
Day 1(24/3/202)	5	13	14	10.7	12	7	6	8.33	11	14	12	12.3	7	12	12	10.3	10	14	0	8	18	13	12	14.3
Traffic Count	3/81				23/135				11/130				6/95				9/124				75			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(27/3/202)	7	9	8	8	11	5	0	5.33	7	11	14	10.7	7	14	19	13.3	7	15	9	10	26	16	19	20.3
Traffic Count	12/81				21/135				14/130				5/95				10/124				61/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
				9.33				6.83				11.5				11.8				9.2				17.3
Weekdays (Bazaar Time-2025 Easter Bazaar)																								
Day 1(08/4/202)	9	12	11	10.7	9	6	0	5	11	12	14	12.3	6	13	16	11.7	5	8	10	7.7	31	19	12	20.7
Traffic Count	6/81				47/135				23/130				8/95				14/124				61/92			

Ventilation Status	OFF				OFF				ON				OFF				OFF				OFF			
Day 2(11/4/202)	14	21	15	16.7	13	12	10	11.7	15	18	18	17	16	11	22	16.3	9	11	15	12	16	10	11	12.3
Traffic Count	17/81				87/135				45/130				8/95				19/124				53/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
				13.7				8.33				14.7				14				9.7				16.5
Weekends (Non-Bazaar)																								
Day 1(16/3/202)	15	17	15	15.7	12	9	8	9.67	13	12	19	14.7	9	7	19	11.7	0	6	11	5.7	7	0	0	2.33
Traffic Count	16/81				93/135				48/130				13/95				12/124				37/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
Day 2(22/3/202)	5	8	8	7	8	0	0	2.67	6	8	10	8	5	5	10	6.67	0	0	0	0	7	5	0	4
Traffic Count	2/81				22/135				9/130				4/95				13/124				38/92			
Ventilation Status	OFF				OFF				OFF				OFF				OFF				OFF			
				11.3				6.17				11.3				9.17				2.8				3.17
Weekends (Bazaar Time)																								
Day 1(4/1/2025-2025	29	39	18	28.7	20	13	19	17.3	31	35	40	35.3	31	24	30	28.3	28	20	16	21	12	16	10	12.7

Christmass Bazaar																								
Traffic Count	81/81				132/135				128/130				95/95				122/124				49/92			
Ventilation Status	ON				ON				OFF				ON/OFF				ON				OFF			
Day 2(13/4/202-2025 Easter Bazaar	14	14	13	13.7	19	15	10	14.7	25	28	30	27.7	22	18	26	22	14	11	19	15	13	6	30	16.3
Traffic Count	42/81				95/135				83/130				50/95				72/124				47/92			
Ventilation Status	ON/OFF				ON				OFF				ON/OFF				ON/OFF				OFF			
				21.2				16				31.5				25.2				18				14.5