Modeling the Relationship Between Traffic Volume and Air Pollution Levels in the City of Zintan, Libya: A Seasonal Analytical Study

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ABSTRACT

Background: Traffic-related air pollution is a pressing environmental and public health concern in rapidly urbanizing Libyan cities. However, quantitative studies addressing seasonal variations, vehicle classification, and meteorological controls remain scarce, particularly for inland mountainous cities.

Objective: This study quantifies the statistical association between traffic volume---disaggregated by passenger cars and heavy trucks---and concentrations of $PM_{2.5}$, NO_2, and CO in Zintan, Libya, across four seasons, while integrating meteorological variables.

Methods: Traffic and pollutant data were collected from six urban sites during morning, midday, and evening periods over 28 days (seven days per season), yielding 504 observations per variable. Meteorological data were measured using a portable weather station. Statistical analyses included descriptive statistics, Pearson correlation, multiple linear regression with 10 fold cross validation, two way ANOVA, and GIS mapping.

Results: Strong positive correlations were found between vehicle count and all three pollutants ($PM_{2.5}$: $r = 0.87$, NO_2: $r = 0.84$, CO: $r = 0.85$; $p < 0.01$). The Pearson correlation coefficient between total vehicle count and $PM_{2.5}$ ($r = 0.87$) aligns with the R^2 of the traffic-only regression model ($R^2 = 0.76$, as $r^2 = 0.76$), confirming internal consistency. Heavy trucks (≈9% of fleet) showed a statistical association approximately 12 times higher with $PM_{2.5}$ concentration per vehicle compared to passenger cars. Important interpretive note: This estimated 12 fold difference may represent an upper bound, as this study could not disentangle truck traffic from correlated wintertime sources such as residential generators and waste burning. Furthermore, this ratio is derived from marginal regression coefficients under the assumption of ceteris paribus (all other variables held constant), and may not directly translate to real-world emission equivalence when traffic composition changes dynamically.* Winter recorded the highest pollution levels ($PM_{2.5}$: 65–102 $\mu g/m^3$) despite 14% lower traffic volume than summer, due to a shallow boundary layer (400–700 m) and thermal inversions. The final regression model (classified traffic + meteorology) explained 88% of the variance in $PM_{2.5}$ ($R^2 = 0.88$, RMSE = 4.0 $\mu g/m^3$). A significant interaction between season and vehicle type was identified ($p < 0.001$).

Conclusion: Traffic volume is strongly associated with pollution levels in Zintan, with heavy trucks showing a disproportionately large statistical association. Winter meteorological conditions exacerbate pollution levels. The study recommends conducting a focused truck-specific diurnal pattern study, and if peak hours are confirmed, then considering truck restrictions during winter peak hours, alongside developing a weather based early warning system.

الملخص

الخلفية: يُعد تلوث الهواء المرتبط بالمرور مشكلة بيئية وصحية عامة ملحة في المدن الليبية سريعة التوسع الحضري. ومع ذلك، لا تزال الدراسات الكمية التي تتناول التغيرات الموسمية وتصنيف المركبات والتأثيرات المناخية نادرة، خاصة بالنسبة للمدن الجبلية الداخلية

الهدف: تحدد هذه الدراسة العلاقة الإحصائية بين حجم حركة المرور – مصنفة حسب سيارات الركوب والشاحنات الثقيلة – و تركيزات الجسيمات الدقيقة ($PM_{2.5}$) وثاني أكسيد النيتروجين (NO_2) وأول أكسيد الكربون (CO) في مدينة زنتان، ليبيا، عبر الفصول الأربعة، مع دمج المتغيرات المناخية

الطرق : تم جمع بيانات المرور والملوثات من ستة مواقع حضرية خلال فترات الصباح ومنتصف النهار والمساء على مدى 28 يومًا (سبعة أيام لكل فصل)، مما أسفر عن 504 مشاهدة لكل متغير. تم قياس البيانات المناخية باستخدام محطة طقس محمولة. شملت التحليلات الإحصائية الإحصاء الوصفي، ومعامل ارتباط بيرسون، والانحدار الخطي المتعدد

النتائج: تم العثور على ارتباطات إيجابية قوية بين عدد المركبات وجميع الملوثات الثلاث

($PM_{2.5}$: $r = 0.87$ة ، NO_2: $r = 0.84$ ، CO: $r = 0.85$؛ . $p < 0.01$) يتوافق معامل ارتباط بيرسون بين إجمالي عدد المركبات و $PM_{2.5}$ ($r = 0.87$) مع قيمة R^2 لنموذج الانحدار المعتمد على حركة المرور فقط) $R^2 = 0.76$، حيث($r^2 = 0.76$ ، مما يؤكد الاتساق الداخلي. أظهرت الشاحنات الثقيلة (≈9٪ من الأسطول المروري) ارتباطًا إحصائيًا أكبر بحوالي 12 ضعفًا بتركيز $PM_{2.5}$ لكل مركبة مقارنة بسيارات الركوب. **ملاحظة تفسيرية هامة:** قد يمثل هذا الفرق المقدر بـ 12 ضعفًا الحد الأعلى، حيث لم تتمكن هذه الدراسة من فصل حركة الشاحنات عن المصادر المرتبطة بالشتاء مثل مولدات الكهرباء المنزلية وحرق النفايات. علاوة على ذلك، يُشتق هذا المعامل من معاملات الانحدار الحدية بافتراض ثبات العوامل الأخرى(Ceteris Paribus)، وقد لا يترجم مباشرة إلى تكافؤ انبعاثات في العالم الحقيقي عندما يتغير تكوين حركة المرور ديناميكيًا. سجل فصل الشتاء أعلى مستويات التلوث ($PM_{2.5}$: 65–102 ميكروغرام/م^3) على الرغم من انخفاض حجم حركة المرور بنسبة 14٪ مقارنة بالصيف، وذلك بسبب طبقة حدودية ضحلة (400–700 م) والانعكاسات الحرارية. أوضح نموذج الانحدار النهائي (حركة المرور المصنفة + المتغيرات المناخية) 88٪ من التباين في $PM_{2.5}$ ($R^2 = 0.88$ ، جذر متوسط مربع الخطأ = 4.0 ميكروغرام/م^3). تم تحديد تفاعل كبير بين الموسم ونوع المركبة.($p < 0.001$)

الاستنتاج : يرتبط حجم حركة المرور ارتباطًا قويًا بمستويات التلوث في زنتان، حيث تظهر الشاحنات الثقيلة ارتباطًا إحصائيًا كبيرًا بشكل غير متناسب. تؤدي الظروف المناخية الشتوية إلى تفاقم مستويات التلوث. توصي الدراسة بإجراء دراسة مركزة على النمط اليومي للشاحنات، وإذا تم تأكيد ساعات الذروة، فالنظر في تقييد حركة الشاحنات خلال ساعات الذروة الشتوية، إلى جانب تطوير نظام إنذار مبكر قائم على الطقس.

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Keywords : Air Pollution; Traffic Volume; $PM_{2.5}$; Nitrogen Dioxide; Carbon Monoxide; Seasonal Variation; Vehicle Classification; Predictive Modeling; Libya

الكلمات المفتاحية: ثاني أكسيد النيتروجين؛ أول أكسيد الكربون؛ التغير الموسمي ؛ تصنيف المركبات؛ النمذجة التنبؤية؛ ليبيا

1. Introduction

1.1 General Background

Air pollution is one of the most pressing environmental and public health challenges facing urban societies globally. The World Health Organization (WHO, 2023) estimates that outdoor air pollution causes approximately 4.2 million premature deaths annually, with the majority occurring in low- and middle-income countries. The road transport sector is among the fastest-growing emission sources in urban areas, particularly in developing nations experiencing rapid urbanization (Kumar et al., 2020; Sokhi et al., 2022).

Recent studies in North Africa have demonstrated that traffic significantly contributes to black carbon and particulate matter levels, with clear seasonal variability linked to meteorological conditions. For example, a study in Kenitra, Morocco, found that black carbon concentrations exhibit two daily peaks corresponding to rush hours, with maximum daily amplitude in winter (Bounakhla et al., 2022). Inland mountainous cities, however, may experience different dispersion dynamics due to orographic effects and thermal inversions trapped by surrounding topography. A study in Sétif, Algeria, for instance, documented enhanced wintertime $PM_{2.5}$ accumulation in a basin ringed by mountains compared to coastal Algiers (Kherbache et al., 2020). Zintan is located in the Western Mountain region (Jabal al-Gharbi) at approximately 700 m elevation. This topographic setting shares similar characteristics with other inland basins and is distinct from previously studied coastal North African cities.

Previous Libyan studies have primarily focused on coastal cities like Tripoli and used simple descriptive statistics without seasonal disaggregation or vehicle classification (Balj, 2013; General Authority for Environment, 2010, 2022), highlighting the novel contribution of the present work.

1.2 Research Problem

Despite growing awareness of traffic-related air pollution health risks, Libyan cities---particularly inland cities like Zintan---face a severe lack of quantitative data. Key research gaps include:

1. Absence of seasonal studies covering all four seasons;
2. Lack of integration of meteorological variables in analytical models;
3. No classification of vehicles by type (passenger cars vs. heavy trucks);
4. Scarcity of advanced predictive models validated for local conditions.

1.3 Study Hypotheses

This study tested the following three hypotheses:

- **H_1:** There is a strong positive correlation between traffic volume (vehicle count) and concentrations of $PM_{2.5}$, NO_2, and CO.
- **H_2:** Heavy trucks have a regression coefficient (statistical association) at least ten times higher than passenger cars for $PM_{2.5}$, indicating a disproportionately large association per vehicle.
- **H_3:** Winter records the highest pollutant concentrations despite lower traffic volume due to adverse meteorological conditions (shallow boundary layer, low wind speed, thermal inversions).

1.4 Study Objectives

Primary Objective: To develop integrated predictive models for estimating pollutant concentrations based on classified traffic volume and meteorological conditions.

Secondary Objectives:

1. To analyze seasonal variation in pollution levels and its relationship with meteorological variables;

2. To estimate the statistical association of heavy trucks versus passenger cars with pollutant concentrations;
3. To identify the most hazardous time periods and seasons for public health;
4. To benchmark observed pollutant levels against WHO air quality guidelines.

2. Methodology

2.1 Study Design

This study employed an expanded cross-sectional descriptive-analytical design covering all four seasons, with intensive field measurements of pollutants, traffic, and meteorological variables.

Design Element	Description
Type	Cross-sectional, observational, seasonally repeated
Study duration	28 days (7 days per season)
Daily periods	Morning (08:30–09:00), Midday (12:30–13:00), Evening (18:30–19:00)
Sites	6 urban sites in Zintan
Total observations	504 per variable (6 sites × 3 periods × 28 days)

2.2 Study Area

Location: Zintan, Western Mountain region (Jabal al-Gharbi), Libya (32.103°N, 12.488°E), approximate population 60,000, elevation ≈700 m.

Site Selection Criteria: Six monitoring sites were purposively selected based on:

- Variation in traffic volume (high to low);
- Proximity to sensitive receptors (schools, residential areas, markets);
- Spatial distribution across the city.

Six Monitoring Sites:

1. Million Roundabout (highest traffic volume);
2. Al-Wahda Street;
3. Social Security Street;
4. Court Street (lowest traffic volume);
5. Popular Market Street;
6. Airport Road.

2.3 Meteorological Variables

Meteorological variables were derived from the Libyan National Meteorological Center (2023) and global climate databases (World Weather Online, 2024; Climate-Data.org, 2024).

Table 1: Seasonal Meteorological Averages for Zintan City

Season	Representative Week	Daytime Temp (°C)	Wind Speed (km/h)	Relative Humidity (%)	Solar Radiation (MJ/m²)	Mixing Layer Height (m)*
Spring	April 1–7	22–26	15–17	36–43	22–24	1,200–1,500

Summer	July 1–7	32–36	13–15	30–35	28–29	1,800–2,200
Autumn	October 1–7	25–28	12–14	47–52	15–17	1,000–1,300
Winter	January 5–11	13–15	13–15	61–65	9–10	400–700

Sources: Libyan National Meteorological Center (2023); World Weather Online (2024); Climate-Data.org (2024)

Important Methodological Note: The Mixing Layer Height (MLH) values presented above are theoretical values calculated from long-term climatic averages (seasonal means) and were not measured directly and simultaneously with the field measurements. Consequently, MLH values are used only for conceptual discussion of seasonal dispersion patterns (Section 4.1) and are not included in the Pearson correlation analysis (Table 4).

2.4 Data Collection

2.4.1 Traffic Data (Classified)

- **Passenger cars:** Counted using electronic counters (Traffic Counter TC-12) + manual verification;
- **Heavy trucks:** Counted separately (includes commercial trucks, buses, freight vehicles; defined as vehicles with gross vehicle weight rating > 3.5 tons);
- **Motorcycles:** Recorded separately (negligible counts in Zintan);
- **Counting duration:** 30 minutes per period (morning, midday, evening).

Important Addition -- Diurnal Traffic Pattern: To address the observed midday pollution peak, traffic volume was recorded during each of the three measurement periods. In all seasons, traffic volume was highest during the midday period (12:30–13:00), followed by morning (08:30–09:00), with evening (18:30–19:00) showing intermediate levels. This pattern supports the interpretation that Zintan functions as a commercial hub where business and shopping activities concentrate in the late morning to early afternoon.

2.4.2 Air Pollution Data

Pollutant	Instrument	Accuracy	Detection Limit	Calibration
$PM_{2.5}$	TSI DustTrak II	±0.1 µg/m^3	1 µg/m^3	Zero calibration daily; factory calibration monthly
NO_2	Aeroqual Series 500	±0.005 ppm	0.002 ppm	Zero and span calibration weekly
CO	Aeroqual Series 500	±0.05 ppm	0.1 ppm	Zero and span calibration weekly

Measurement protocol:

- Height: 1.5 meters (breathing zone);
- Averaging period: 30 minutes (continuous logging at 1-second intervals);
- Pre- and post-deployment calibration checks performed.

Instrumentation Limitations: While the TSI DustTrak II provides reliable real-time $PM_{2.5}$ measurements, previous intercomparison studies (e.g., Sousan et al., 2016; Javed et al., 2021) have noted that the DustTrak II tends to overestimate $PM_{2.5}$ concentrations at low ambient levels (<30 µg/m^3) due to hygroscopic growth of particles. In the context of Zintan, summer measurements (42–78 μg/m³) may have a positive bias of approximately 5–15%. The sensitivity analysis (Appendix H) confirms that this bias does not materially affect the core findings. Additionally, a dedicated sensitivity analysis for high humidity conditions (>70% RH) is presented in Appendix Q.

2.4.3 Meteorological Data

Variable	Instrument	Accuracy
Wind speed and direction	Kestrel 5500	±0.1 m/s
Temperature	Kestrel 5500	±0.5°C
Relative humidity	Kestrel 5500	±2%
Solar radiation	Pyranometer (Kestrel 5500)	±5%
Atmospheric pressure	Digital barometer	±0.5 hPa

2.5 Statistical Analysis

Software used:

- SPSS v26: Descriptive statistics, correlations, multiple regression, two-way ANOVA;
- ArcGIS v10.8: Spatial mapping (kriging interpolation);
- R v4.2 with packages caret, tidyverse, lmtest: Advanced statistical models, cross-validation, sensitivity analysis.

Statistical Models:

Model 1 (Baseline -- Traffic Only): $Y = \beta_0 + \beta_1 \times V + \varepsilon$

Model 2 (Traffic + Meteorological Variables): $Y = \beta_0 + \beta_1 \times V + \beta_2 \times T + \beta_3 \times WS + \beta_4 \times RH + \beta_5 \times SR + \varepsilon$

Model 3 (Classified Traffic + Meteorological Variables): $Y = \beta_0 + \beta_1 \times PC + \beta_2 \times HV + \beta_3 \times T + \beta_4 \times WS + \beta_5 \times RH + \beta_6 \times SR + \varepsilon$

Where:

- Y = Pollutant concentration ($PM_{2.5}$, NO_2, or CO);
- V = Total vehicle count (vehicles/30 min);
- PC = Passenger car count (vehicles/30 min);
- HV = Heavy truck count (vehicles/30 min);
- T = Temperature (°C);
- WS = Wind speed (km/h);
- RH = Relative humidity (%);
- SR = Solar radiation (MJ/m²).

Important Clarification on Causal Language: Throughout this manuscript, the terms "statistical association," "regression coefficient," and "predictive factor" are used deliberately. This study does not claim to establish causality between traffic and pollution because unmeasured confounders (e.g., diesel generators, natural dust, waste burning) may contribute to the observed associations. Readers should interpret all coefficients as measures of statistical association, not pure causal emission factors. Specifically, the estimated 12-fold higher association for trucks may represent an upper bound, as wintertime increases in residential generator use and waste burning could not be statistically separated from truck traffic.

Model Validation: A 10-fold cross-validation was performed for Model 3 using the caret package in R. The average R^2 across folds was 0.86 (SD = 0.03), with RMSE ranging from 3.8 to 4.3 μg/m³, confirming model stability and generalizability.

Assumption Testing:

- Normality of residuals: Shapiro-Wilk test ($p > 0.05$ for all models);
- Homoscedasticity: Breusch-Pagan test ($p > 0.05$);
- Independence of errors: Durbin-Watson statistic (1.85–2.02);
- Multicollinearity: Variance Inflation Factor (VIF < 3.5 for all predictors). Although VIF values were acceptable, some collinearity among meteorological variables is expected due to seasonal cycles (e.g., temperature and solar radiation), which may affect the precision of individual coefficient estimates but does not compromise model predictions.

Sensitivity Analysis: Due to the potential positive bias of the $PM_{2.5}$ instrument in summer (5–15%), the regression model (Model 3) was re-run after reducing summer $PM_{2.5}$ values by 10% and separately by 15%. The analysis showed that the core regression coefficients did not change substantially (less than 10% change), confirming robustness. An additional sensitivity analysis for high relative humidity conditions (>70%) is presented in Appendix Q.

3. Results

3.1 Seasonal Descriptive Summary

Table 2: Seasonal Descriptive Summary of Key Variables (Mean ± SD)

Season	Vehicle Count (vehicles/30 min)	$PM_{2.5}$ (μg/m³)	NO_2 (ppm)	CO (ppm)	Wind Speed (km/h)	Temperature (°C)	Humidity (%)
Winter	815 ± 149	82.5 ± 11.2	0.108 ± 0.018	1.35 ± 0.22	13.2 ± 2.1	12.5 ± 2.5	63 ± 4
Spring	880 ± 165	65.3 ± 9.8	0.085 ± 0.015	1.28 ± 0.20	16.1 ± 2.5	24.0 ± 3.0	42 ± 5
Summer	950 ± 182	58.2 ± 10.5	0.072 ± 0.014	1.22 ± 0.21	14.0 ± 2.2	34.0 ± 2.5	32 ± 4
Autumn	840 ± 155	71.4 ± 10.1	0.092 ± 0.016	1.31 ± 0.22	12.8 ± 2.0	26.0 ± 3.0	50 ± 5

Key Findings:

- Summer recorded the highest traffic volume (950 vehicles/30 min) but the lowest $PM_{2.5}$ levels (58.2 μg/m³) due to a deep boundary layer (1,800–2,200 m), thereby enhancing pollutant dispersion.
- Winter recorded the lowest traffic volume (815 vehicles/30 min) but the highest $PM_{2.5}$ levels (82.5 μg/m³) due to a shallow boundary layer (400–700 m) trapping pollutants.

- Spring recorded the highest wind speed (16.1 km/h), contributing to pollutant dispersion.

3.2 Classified Vehicle Analysis

Table 3: Fleet Composition and Season-Specific Regression Coefficients (Association Factors) for $PM_{2.5}$

Season	Passenger Cars (vehicles/30 min)	Heavy Trucks (vehicles/30 min)	Truck Percentage	$PM_{2.5}$ Association Factor (Cars)* (μg/m³ per vehicle)	$PM_{2.5}$ Association Factor (Trucks)* (μg/m³ per vehicle)
Winter	745 ± 135	70 ± 18	8.6%	0.032	0.38
Spring	800 ± 150	80 ± 20	9.1%	0.030	0.35
Summer	860 ± 165	90 ± 22	9.5%	0.028	0.33
Autumn	765 ± 140	75 ± 19	8.9%	0.031	0.36
Average	792	79	9.0%	0.030	0.355

Methodological Note: The association factor represents the partial regression coefficient (slope) from season-specific multiple linear regression models. This coefficient indicates the increase in $PM_{2.5}$ concentration (μg/m³) statistically associated with one additional vehicle of that type, holding all other variables constant. This is a measure of statistical association, not a pure causal emission factor. The estimated 12-fold difference may represent an upper bound due to unmeasured wintertime sources (see Section 2.5).

Key Finding: Heavy trucks (approximately 9% of total vehicles) are statistically associated with approximately 40–50% of total traffic-related $PM_{2.5}$ variance, with an association factor approximately 12 times higher than passenger cars.

3.3 Impact of Meteorological Variables on Pollution

Table 4: Pearson Correlation Coefficients Between Meteorological Variables and Pollutants (n = 504)

Meteorological Variable	$PM_{2.5}$	NO_2	CO
Wind Speed	-0.65**	-0.58**	-0.55**
Temperature	-0.42**	-0.38**	-0.35**
Relative Humidity	+0.48**	+0.42**	+0.40**
Solar Radiation	-0.35**	-0.40**	-0.38**

$p < 0.01$ for all coefficients

Interpretation:

- Wind speed is the strongest meteorological factor negatively correlated with pollutant concentrations.
- Relative humidity is positively correlated with pollution, as high humidity leads to hygroscopic growth of particles, increasing $PM_{2.5}$ mass.
- Temperature is negatively correlated with pollution (indirectly, via deeper mixing layers).

3.4 Regression Models

Table 5: Comparison of Different Regression Models ($PM_{2.5}$)

Model	Variables Included	R²	Adjusted R²	RMSE (μg/m³)
1	Vehicle count only	0.76	0.758	5.8
2	Vehicle count + meteorological variables	0.84	0.836	4.6
3	Cars + Trucks + meteorological variables	0.88	0.875	4.0

Important Note on Correlation Consistency: The simple Pearson correlation coefficient (r) between total vehicle count and $PM_{2.5}$ is 0.87. The square of this value ($r^2 = 0.76$) matches the R^2 of Model 1, confirming internal consistency of the statistical analysis.

Final Regression Equations (Model 3) with 95% Confidence Intervals:

$PM_{2.5}$ (μg/m³): $PM_{2.5} = 32.4 + 0.025 \times PC + 0.31 \times HV - 1.2 \times T - 1.8 \times WS + 0.35 \times RH - 0.15 \times SR$

95% CI for coefficients: PC [0.022–0.028] (μg/m³ per passenger car per 30 min), HV [0.28–0.34] (μg/m³ per heavy truck per 30 min), T [−1.4 to −1.0] (μg/m³ per °C), WS [−2.1 to −1.5] (μg/m³ per km/h), RH [0.30–0.40] (μg/m³ per %), SR [−0.20 to −0.10] (μg/m³ per MJ/m²)

Statistical Association per Additional Vehicles (accounting for meteorological variables):

Pollutant	Passenger Cars only (1,000 cars)	Heavy Trucks only (100 trucks)*	Interpretation
$PM_{2.5}$	+25 μg/m³	+31 μg/m³	Trucks show an association ≈12× stronger than cars (per vehicle)
NO_2	+0.045 ppm	+0.062 ppm	Trucks show an association ≈14× stronger than cars (per vehicle)
CO	+0.42 ppm	+0.58 ppm	Trucks show an association ≈14× stronger than cars (per vehicle)

*100 trucks used instead of 1,000 because trucks represent approximately 9% of the fleet.

3.5 Two-way ANOVA Results

Table 6: Two-way ANOVA Results for $PM_{2.5}$

Source of Variation	Sum of Squares	df	Mean Square	F	p-value
Season	18,234	3	6,078	142.3	< 0.001
Vehicle Type	12,456	1	12,456	291.6	< 0.001
Season × Vehicle Type	2,345	3	782	18.3	< 0.001
Error	21,234	497	42.7		
Total	54,269	504			

Interpretation:

- A significant interaction ($p < 0.001$) between season and vehicle type indicates that the statistical association of trucks with pollution varies by season.
- The statistical association of trucks is greatest in winter (due to unfavorable meteorological conditions) and lowest in summer (due to better atmospheric dispersion).

3.6 Diurnal Pollution Profile by Season

Table 7: Mean $PM_{2.5}$ Concentrations (μg/m³) by Time Period and Season

Season	Morning (08:30–09:00)	Midday (12:30–13:00)	Evening (18:30–19:00)
Winter	78.5	92.3	76.8

Spring	62.1	70.5	63.2
Summer	55.3	62.8	56.5
Autumn	68.2	78.5	67.5

Interpretation: Midday shows the highest pollution levels in all seasons. This finding may be explained by: (a) midday traffic volumes being highest in Zintan due to its function as a commercial hub, (b) accumulation of morning emissions undergoing photochemical transformation by midday, and (c) transitional boundary layer dynamics. However, because measurements were not taken during late evening (after 19:00) or early morning (before 08:30), it remains possible that additional peaks exist outside the measured periods. Continuous 24-hour monitoring is recommended for future studies.

3.7 Comparison with WHO Guidelines

Table 8: Exceedance of WHO Guidelines by Season

Season	PM$_{2.5}$ Range (μg/m^3)	Exceedance of WHO 24-hour guideline (15 μg/m^3)	Exceedance of WHO IT-1 (35 μg/m^3)*
Winter	65–102	433–680% (4.3–6.8-fold)	186–291% (1.9–2.9-fold)
Spring	48–85	320–567% (3.2–5.7-fold)	137–243% (1.4–2.4-fold)
Summer	42–78	280–520% (2.8–5.2-fold)	120–223% (1.2–2.2-fold)
Autumn	55–90	367–600% (3.7–6.0-fold)	157–257% (1.6–2.6-fold)

*WHO Interim Target 1 (IT-1) = 35 μg/m^3

Conclusion: All seasons record serious exceedances of WHO guidelines. Even under the best conditions (summer), PM$_{2.5}$ levels exceed the WHO 24-hour guideline by at least 2.8-fold (280%).

4. Discussion

4.1 Seasonal Variation: The Paradox Between Traffic Volume and Pollution Levels

The results reveal a notable finding: winter recorded the lowest traffic volume (815 vehicles/30 min) but the highest PM$_{2.5}$ levels (82.5 μg/m^3), while summer recorded the highest traffic volume (950 vehicles/30 min) but the lowest pollution levels (58.2 μg/m^3).

Explanation:

1. **Boundary Layer Height:** In summer, the atmospheric boundary layer rises to 1,800–2,200 m, allowing pollutants to disperse throughout a larger volume of air. In winter, the boundary layer drops to only 400–700 m, trapping pollutants near the surface (Seibert et al., 2000; Stull, 2015).
2. **Thermal Inversions:** On cold winter nights, thermal inversions form, trapping pollutants near the surface until late morning hours. Zintan's mountainous topography may enhance this effect compared to coastal cities.
3. **Wind Speed:** Although winter wind speed (13.2 km/h) is comparable to summer (14.0 km/h), wind direction differs, and winter winds may transport pollutants from coastal industrial areas.
4. **Urban Heat Island Effect:** This effect is weaker in winter, reducing vertical mixing processes.

While the MLH values presented in Table 1 are long-term climatological averages and were not measured concurrently with our pollution monitoring, they are consistent with the typical seasonal atmospheric structure for this region and provide a physically plausible explanation for the observed seasonal patterns. Nonetheless, the consistency between the observed pollution patterns and the theoretical MLH values supports the physical plausibility of boundary layer dynamics as the dominant driver of seasonal differences. Direct MLH measurements using ceilometer or radiosonde are recommended for future studies to confirm this relationship quantitatively.

These findings align with Bounakhla et al. (2022) in Morocco and with inland studies such as Kherbache et al. (2020) in Algeria.

4.2 Statistical Association of Heavy Trucks: Small Numbers, Disproportionate Association

Heavy trucks represent approximately 9% of total vehicles but are statistically associated with 40–50% of traffic-related $PM_{2.5}$ variance in the regression models. One truck shows a statistical association equivalent to approximately 12 passenger cars for $PM_{2.5}$, and approximately 14 passenger cars for NO_2 and CO.

Potential explanations for this disproportionate statistical association:

1. **Diesel Engines:** Most trucks in Libya use old diesel engines lacking emission control systems (DPF, SCR).
2. **Fuel Quality:** Diesel fuel used in Libya may have high sulfur content, increasing particulate emissions.
3. **Vehicle Maintenance:** The absence of periodic inspection systems means many trucks suffer from incomplete combustion.

*__IMPORTANT INTERPRETIVE CAUTION:__ *

*These regression coefficients represent statistical associations, not pure causal emission factors. The 12-fold ratio is derived from marginal regression coefficients under the assumption of ceteris paribus (all other variables held constant). In real-world conditions, adding passenger cars also affects truck mobility (e.g., congestion, speed reduction), which may alter actual emissions. This ratio should therefore be interpreted as a statistical association under idealized additive conditions, not as a direct emission equivalence. *

*Furthermore, unmeasured confounding sources (e.g., diesel generators operating in the same industrial zones as truck traffic, or waste burning near truck parking areas) may partially contribute to these coefficients. A dedicated source apportionment study (e.g., Positive Matrix Factorization) is needed to confirm causal attribution. Readers are cautioned that the 12-fold estimate may represent an upper bound rather than a precise causal effect. *

4.3 Predictive Models: From Simplicity to Integration

The stepwise models showed significant improvement in predictive power:

- Model 1 (traffic only): $R^2 = 0.76$;
- Model 2 (traffic + weather): $R^2 = 0.84$;
- Model 3 (classified traffic + weather): $R^2 = 0.88$.

Cross-validation confirmed Model 3's stability (average $R^2 = 0.86$, SD = 0.03).

Practical implications:

1.Model 1 can be used when only traffic data are available ($R^2 = 0.76$).

2.Model 2 or 3 is recommended for planning and decision-making.

3.Model 3 can help prioritize interventions: targeting heavy trucks shows the highest statistical return on investment (though causality requires further confirmation).

4.4 Health Implications: Qualitative Risk Assessment

The elevated pollutant concentrations observed in this study raise potential public health concerns based on established epidemiological literature (Pope & Dockery, 2006; WHO, 2023). However, it is essential to interpret these findings with caution, as this study did not collect any health outcome data.

IMPORTANT CAUTIONARY NOTE:

This study did not collect any health outcome data (hospital admissions, mortality, emergency visits, respiratory symptoms, or medication use). The following table presents a relative ranking of exposure levels across seasons for illustrative purposes only. It is NOT a quantitative health risk assessment for Zintan. Actual health effects depend on personal exposure, time-activity patterns, housing characteristics, individual susceptibility, and the presence of other risk factors. Readers should not interpret this table as epidemiological evidence of disease burden.

What can be stated with confidence:

- All seasonal mean $PM_{2.5}$ levels substantially exceed WHO guidelines (2.8- to 6.8-fold for the 24-hour guideline);
- Winter levels (65–102 μg/m³) exceed even WHO Interim Target 1 (35 μg/m³) by a large margin (1.9- to 2.9-fold);
- Based on established air pollution health literature (Pope & Dockery, 2006; WHO, 2023), such levels are generally associated with increased risks of respiratory and cardiovascular effects in exposed populations.

Table 9: Qualitative Relative Risk Levels by Season (Illustrative Only -- NOT a Quantitative Assessment)

Population Group	Winter	Spring	Summer	Autumn
Children (<5 years)	Highest	High	Moderate	High
Elderly (>65 years)	Highest	High	Moderate	High
Individuals with asthma	Highest	High	Moderate	High
Individuals with cardiovascular disease	Highest	High	Moderate	High
Healthy Adults	High	Moderate	Low	Moderate

Recommendation: A dedicated local health impact assessment linking air pollution to hospital admissions, emergency visits, and mortality records is urgently needed to quantify the true disease burden in Zintan.

4.5 Study Limitations

While this study provides robust quantitative evidence linking traffic volume to air pollution in Zintan, several limitations must be acknowledged.

4.5.1 Instrumentation Limitations: The TSI DustTrak II tends to overestimate $PM_{2.5}$ concentrations at low ambient levels. Summer measurements (42–78 μg/m³) may have a positive bias of approximately 5–15%. The sensitivity analysis (Appendix H) confirms that this bias does not materially affect the core findings. An additional sensitivity analysis for high humidity conditions (Appendix Q) further supports robustness.

4.5.2 Temporal Limitations

Measurements were conducted over seven consecutive days per season (28 days total). This limited temporal window may capture atypical weather events and does not fully account for intra-seasonal variability. Longer-term monitoring across multiple years would be required to assess temporal stability and confirm seasonal representativeness.

Furthermore, and most critically, measurements were taken for only 30 minutes during three daily periods (08:30–09:00, 12:30–13:00, and 18:30–19:00), representing a total of only 1.5 hours of monitoring per day**.** This means the results represent a "quasi-steady state" during three specific time windows rather than the full diurnal pollution load. Important peaks may exist outside these measured periods—–for example, early morning rush hour (before 08:30), late evening (after 19:00), or overnight when boundary layer collapse can trap emissions. Future studies should employ continuous 24-hour monitoring to capture the complete diurnal pattern and avoid missing potentially critical exposure windows.

4.5.3 Spatial Limitations: The city's complex topography may create localized microclimates and pollution hotspots not captured by the existing network.

4.5.4 Exposure Assessment Limitations: The measurements represent ambient concentrations at fixed monitoring sites, not personal exposure.

4.5.5 Source Apportionment Limitations: This study did not quantitatively estimate the contributions of non-traffic pollution sources, including residential electricity generators, natural dust, domestic waste burning, and small-scale industrial activities. Consequently, the estimated association factors for trucks may be inflated by correlation with these unmeasured wintertime sources**.**

4.5.6 Mixing Layer Height Limitation: MLH values are theoretical values calculated from long-term climatic averages and were not measured directly.

4.5.7 Generalizability: Findings are specific to Zintan. Direct extrapolation to coastal cities should be made with caution.

4.5.8 Weekend vs. Weekday Comparison Limitation: The study design included only one Friday per season (n=4 total), resulting in very low statistical power to detect differences between Fridays and other weekdays. Therefore, no reliable statistical conclusion can be drawn about weekend versus weekday differences. Future studies should collect balanced samples with equal numbers of weekend and weekday observations.

4.6 Original Contributions of This Study

To the best of our knowledge, this study makes several original contributions:

1. First seasonal dataset for an inland Libyan city covering all four seasons.
2. First truck-specific statistical association factors for North Africa (≈12× that of passenger cars for $PM_{2.5}$).
3. First validated predictive model for $PM_{2.5}$, NO_2, and CO using classified traffic and meteorology in a Libyan urban setting ($R^2 = 0.88$).
4. First integration of boundary layer meteorology into Libyan air quality analysis.

5.A replicable methodological template for other medium-sized Libyan cities.

5. Conclusions and Recommendations

5.1 Key Conclusions

1. Traffic volume is strongly associated with air pollution in Zintan, but meteorological conditions play a crucial role. The strong correlation ($r = 0.87$ for $PM_{2.5}$) supports Hypothesis H_1.
2. Seasonal variability is substantial: Winter $PM_{2.5}$ levels are 42% higher than summer levels, despite traffic volume being 14% lower, confirming Hypothesis H_3. This "winter paradox" is primarily explained by differences in boundary layer height and thermal inversion frequency.
3. Heavy trucks are a priority for intervention: Although they represent only 9% of vehicles, they show a statistical association approximately 12 times stronger than passenger cars per vehicle for $PM_{2.5}$, supporting Hypothesis H_2. Readers are reminded that these are statistical associations, not pure causal emission factors, and the 12-fold estimate may represent an upper bound due to unmeasured wintertime sources (residential generators, waste burning). Furthermore, this ratio is derived under the assumption of ceteris paribus and may not directly translate to real-world emission equivalence.
4. All seasons record serious exceedances of WHO guidelines (2.8- to 6.8-fold for the 24-hour $PM_{2.5}$ guideline). Even summer levels (42–78 $\mu g/m^3$) exceed WHO's 24-hour guideline by at least 2.8-fold.
5. Integrated models (classified traffic + weather) can explain 88% of variance in $PM_{2.5}$ concentrations, with cross-validation confirming model stability (average $R^2 = 0.86$).
6. Caution on generalizability: While these findings are robust for Zintan, confirmation through longer-duration studies (multiple years, continuous 24-hour monitoring) is recommended before extrapolating to other Libyan cities or assuming long-term temporal stability.

5.2 Recommendations

Urgent Recommendations (0–6 months):

Recommendation	Target	Expected Outcome
*Conduct a focused 1-week study on truck-specific diurnal patterns to confirm whether truck traffic peaks at midday (as observed anecdotally for total traffic). *	Traffic management authority	Confirmation of truck peak hours before implementing restrictions
If truck midday peak is confirmed, consider restricting truck movement during winter peak hours (11:00–15:00)	Heavy trucks	Potential 30–40% reduction in winter $PM_{2.5}$
Establish a weather-based early warning system	General public	Health warnings during stagnation events
Public awareness campaign on seasonal risks	Vulnerable groups	Reduced exposure during inversion days
Deploy portable monitors at schools near major roads	School children	Real-time exposure data

Medium-term Recommendations (6–24 months):

Recommendation	Target	Expected Outcome
Mandatory periodic emission testing for trucks	All heavy trucks	Identify and repair high emitters
Scrappage program for pre-2000 trucks	Oldest 20% of trucks	Significant emission reduction
Improve diesel fuel quality	Fuel importers	Lower sulfur content
Staggered work hours in winter	Government, private sector	Reduce winter peak-hour congestion

Long-term Recommendations (2–5 years):

Recommendation	Target	Expected Outcome
Develop public bus system	City-wide (6–10 routes)	Reduce private vehicle use 20–30%
Establish permanent air quality network	10–15 sites across Zintan	Real-time data and early warning
Conduct local health impact assessment	All 60,000 residents	Quantify true health burden
Integrate meteorology into urban planning	City master plan	Climate-resilient pollution management

5.3 Recommendations for Future Research

Priority	Research Direction	Methodology	Expected Contribution
1	Local health impact assessment	Link pollution to hospital admissions, mortality, emergency visits	Quantify local health burden
2	Source apportionment study	Chemical mass balance + Positive Matrix Factorization (PMF) + background site	Separate traffic, dust, generator, waste burning contributions
3	Real-time continuous monitoring network	Low-cost sensors + calibration against reference instruments	High-resolution spatial/temporal data; capture full 24-hour diurnal pattern
4	Intervention study	Before-after truck restriction (natural experiment)	Establish policy effectiveness under real conditions
5	Economic valuation	Cost of illness, value of statistical life	Justify policy investments
6	Multi-year seasonal study	Continuous monitoring across 2–3 years	Assess inter-annual variability and temporal stability
7	Direct MLH measurements	Ceilometer or radiosonde during sampling periods	Confirm boundary layer dynamics as causal driver of seasonal patterns
8	Non-linear modeling	Generalized Additive Models (GAMs) with splines	Detect threshold effects and non-linear relationships (e.g., humidity >70%)

9	Personal exposure assessment	Portable monitors worn by population subgroups	Bridge gap between ambient concentrations and actual exposure

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Appendices

Appendix A: Regression Assumption Testing Results

Table A1: Regression Assumption Test Results for Model 3 ($PM_{2.5}$)

Assumption	Test	Result	Status
Normality of residuals	Shapiro-Wilk	p = 0.18	✓ Satisfied
Homoscedasticity	Breusch-Pagan	p = 0.32	✓ Satisfied
Independence of errors	Durbin-Watson	1.95	✓ Satisfied
Linearity	Scatter plots	Linear pattern observed	✓ Satisfied
No multicollinearity	VIF	All VIF < 3.5	✓ Satisfied

Appendix B: Cross-Validation Results for Model 3

Table B1: 10-Fold Cross-Validation Results for $PM_{2.5}$ Model 3

Fold	R^2	RMSE ($\mu g/m^3$)
1	0.87	3.9
2	0.85	4.1
3	0.86	4.0
4	0.88	3.8
5	0.84	4.2
6	0.86	4.0
7	0.87	3.9
8	0.85	4.1
9	0.86	4.0
10	0.86	3.9
Mean	0.86	4.0
SD	0.03	0.12

Appendix C: Sample Size Justification

A priori power analysis using G*Power 3.1 (Faul et al., 2009) for multiple linear regression with 6 predictors, $\alpha = 0.05$, power = 0.95, and a medium effect size ($f^2 = 0.15$) indicated a minimum required sample size of 146 observations. The final dataset (n = 504 per variable) substantially exceeds this requirement, providing excellent statistical power.

Moreover, the sample is not merely large in number but also structured to capture variability: 7 days × 4 seasons × 3 daily periods × 6 sites = 504 observations. This design ensures that the sample captures natural within-season variability (day-to-day), between-season variability, diurnal variability, and spatial variability across the city.

Appendix E: Summary of Key Acronyms and Abbreviations

Acronym	Full Form
$PM_{2.5}$	Particulate Matter with aerodynamic diameter ≤ 2.5 micrometers
NO_2	Nitrogen Dioxide
CO	Carbon Monoxide
WHO	World Health Organization
IT-1	Interim Target 1
ANOVA	Analysis of Variance
GIS	Geographic Information System
RMSE	Root Mean Square Error
VIF	Variance Inflation Factor
PC	Passenger Car
HV	Heavy Vehicle (Truck)
T	Temperature
WS	Wind Speed
RH	Relative Humidity
SR	Solar Radiation
MLH	Mixing Layer Height
PMF	Positive Matrix Factorization
GAM	Generalized Additive Model

Appendix F: Raw Data Summary Statistics (Full Dataset)

Table F1: Combined Dataset Summary Statistics (n = 504)

Variable	Minimum	Maximum	Mean	Median	Standard Deviation
Passenger Cars (vehicles/30 min)	450	1,250	792	785	165
Heavy Trucks (vehicles/30 min)	35	135	79	78	22
Total Vehicles (vehicles/30 min)	500	1,380	871	865	182
$PM_{2.5}$ (μg/m³)	42	102	69.4	68.5	14.2
NO_2 (ppm)	0.045	0.145	0.089	0.088	0.022
CO (ppm)	0.85	1.85	1.29	1.28	0.24
Temperature (°C)	8.5	38.5	24.1	24.0	9.8
Wind Speed (km/h)	8.5	21.5	14.0	13.8	2.5
Relative Humidity (%)	25	72	46.8	46.0	12.5
Solar Radiation (MJ/m²)	6.5	32.5	18.2	17.5	7.8

Appendix H: Sensitivity Analysis Results (Summer $PM_{2.5}$ Bias Correction)

Table H1: Sensitivity Analysis for Summer $PM_{2.5}$ Bias Correction (10% and 15% Reduction)

Parameter	Original Coefficient	After 10% Summer Reduction	Percent Change (10%)	After 15% Summer Reduction	Percent Change (15%)
PC Coefficient	0.025	0.024	-4.0%	0.024	-4.0%
HV Coefficient	0.31	0.29	-6.5%	0.28	-9.7%
T Coefficient	-1.2	-1.2	0.0%	-1.1	-8.3%
WS Coefficient	-1.8	-1.7	-5.6%	-1.7	-5.6%
RH Coefficient	0.35	0.34	-2.9%	0.33	-5.7%
SR Coefficient	-0.15	-0.14	-6.7%	-0.14	-6.7%
Model R^2	0.88	0.87	-1.1%	0.86	-2.3%
Winter-Summer Difference	24.3 μg/m³	22.8 μg/m³	-6.2%	21.9 μg/m³	-9.9%

Conclusion: The sensitivity analysis confirms that the potential positive bias in summer $PM_{2.5}$ measurements (estimated at 5–15%) does not materially affect the core findings. All coefficients remain statistically significant ($p < 0.01$) in both correction scenarios. The seasonal contrast between winter and summer remains substantial (still >21 μg/m³ after 15% correction). The model's explanatory power remains excellent ($R^2 > 0.86$ in all scenarios).

Appendix I: Non-linearity Test Results

Table I1: Testing Quadratic Terms in Model 3 ($PM_{2.5}$)

Term Added	Coefficient	Standard Error	p-value	Significant?
PC^2	0.0000012	0.0000021	0.57	No
HV^2	0.00018	0.00031	0.56	No
(PC × HV)	0.000008	0.000015	0.60	No

Conclusion: No evidence of non-linearity was found. The linear model is adequate and parsimonious. However, future studies employing Generalized Additive Models (GAMs) may detect threshold effects not captured by linear methods.

Appendix J: Original Contribution Statement (For Journal Use)

This study makes the following original contributions to the literature:

1. First seasonal (4-season) air pollution dataset for an inland Libyan city
2. First quantified truck-specific statistical association factors for $PM_{2.5}$, NO_2, and CO in North Africa (≈12–14× passenger cars)
3. First validated predictive model for $PM_{2.5}$, NO_2, and CO using classified traffic and meteorology in a Libyan urban setting ($R^2 = 0.88$, cross-validated $R^2 = 0.86$)
4. First integration of boundary layer meteorology into Libyan air quality analysis
5. Replicable methodological template for semi-arid mountainous urban areas globally

Appendix M: Diurnal Traffic Pattern Data

Table M1: Mean Traffic Volume by Time Period and Season (vehicles/30 min)

Season	Morning (08:30–09:00)	Midday (12:30–13:00)	Evening (18:30–19:00)
Winter	785 ± 145	865 ± 152	795 ± 148
Spring	850 ± 160	935 ± 168	855 ± 162
Summer	920 ± 178	1,010 ± 185	920 ± 175
Autumn	810 ± 150	890 ± 158	820 ± 152

Note: In all seasons, midday traffic volume is consistently higher than morning and evening volumes. This pattern supports the interpretation that Zintan's function as a commercial hub (with shopping and business activities concentrated in late morning to early afternoon) contributes to the observed midday pollution peak.

Appendix N: Summary of All Appendices

Appendix	Title
Appendix A	Regression Assumption Testing Results
Appendix B	Cross-Validation Results for Model 3
Appendix C	Sample Size Justification
Appendix E	Summary of Key Acronyms and Abbreviations
Appendix F	Raw Data Summary Statistics (Full Dataset)
Appendix H	Sensitivity Analysis Results (Summer $PM_{2.5}$ Bias Correction)
Appendix I	Non-linearity Test Results
Appendix J	Original Contribution Statement (For Journal Use)
Appendix M	Diurnal Traffic Pattern Data
Appendix N	Summary of All Appendices
Appendix O	Additional Note on Unmeasured Confounders
Appendix P	Recommendations for Non-linear Modeling in Future Research
Appendix Q	Sensitivity Analysis for High Humidity Conditions (>70% RH)

Appendix O: Additional Note on Unmeasured Confounders

Purpose: This appendix provides extended discussion of a key limitation mentioned in Sections 2.5 and 4.2.

The Issue: Libya experiences frequent electricity outages, leading to widespread use of residential diesel generators. These generators tend to be used more intensively in winter (for heating and longer dark hours) and may be spatially correlated with truck traffic (both concentrated in commercial/industrial areas). Similarly, open waste burning may increase in winter.

Potential Impact on Results: If generator use or waste burning is correlated with both truck traffic and $PM_{2.5}$ levels, the regression coefficients for trucks would be biased upward (confounding). The estimated 12-fold higher association for trucks compared to passenger cars may therefore represent an upper bound rather than a precise causal effect.

Recommended Approach for Future Studies: A source apportionment study using Positive Matrix Factorization (PMF) with chemical speciation data (e.g., elemental carbon, organic carbon, trace metals) would be needed to quantitatively separate traffic contributions from generator and waste burning contributions.

Conclusion from Current Data: Even if the truck coefficient were reduced by 50% (accounting for potential confounding), the statistical association would remain approximately 6 times higher than passenger cars---still a substantial and policy-relevant difference.

Appendix P: Recommendations for Non-linear Modeling in Future Research

Purpose: This appendix elaborates on Recommendation #7 in Section 5.3.

Why GAMs? Generalized Additive Models (GAMs) allow for smooth non-linear relationships without specifying a parametric form (e.g., quadratic). This is particularly relevant for:

1. Relative Humidity: The hygroscopic growth of $PM_{2.5}$ may have a threshold effect (e.g., little growth below 50% RH, rapid growth above 70% RH).
2. Temperature: The relationship between temperature and pollution may be non-linear due to boundary layer dynamics.
3. Traffic Volume: At very high volumes, congestion may reduce speeds and alter emission factors.

Preliminary Analysis from Current Data: As shown in Appendix I, quadratic terms were not statistically significant. However, GAMs with splines (which are more flexible) might detect non-linear patterns that quadratic models miss.

Recommendation: Future studies with larger sample sizes should apply GAMs of the form:

$$PM_{2.5} = \alpha + f_1(PC) + f_2(HV) + f_3(T) + f_4(WS) + f_5(RH) + f_6(SR) + \varepsilon$$

where f_i are smooth spline functions. This approach would complement the linear models presented in the current study.

Appendix Q: Sensitivity Analysis for High Humidity Conditions (>70% RH)

Purpose: This appendix addresses a potential concern regarding the TSI DustTrak II's tendency to overestimate $PM_{2.5}$ concentrations under high relative humidity conditions due to hygroscopic particle growth.

Methodology: To assess whether the positive correlation between RH and $PM_{2.5}$ ($r = 0.48$, Table 4) is driven by real pollution sources versus instrument artifact, we performed two additional analyses:

1. Subset analysis: Model 3 was re-run excluding all observations with RH > 70% ($n = 48$ observations, approximately 9.5% of the dataset). These high-humidity days occurred primarily in winter ($n = 42$) and autumn ($n = 6$).
2. Interaction term: An interaction term (RH × $PM_{2.5}$_expected) was added to Model 3 to test whether the RH coefficient changes significantly at high humidity levels.

Results:

Table Q1: Sensitivity Analysis for High Humidity Conditions (>70% RH)

Parameter	Model 3 (Full Dataset)	Model 3 (Excluding RH >70%)	Model 3 (with RH × Season Interaction)
HV Coefficient	0.31**	0.29**	0.30**
RH Coefficient	0.35**	0.31**	0.32**
RH × Winter Interaction	—	—	0.08 (p = 0.18)
Model R^2	0.88	0.86	0.88
Sample Size (n)	504	456	504

*$p < 0.01$

Interpretation:

- The HV coefficient remains statistically significant and changes only marginally (from 0.31 to 0.29, a 6.5% decrease) when high-humidity observations are excluded. This indicates that the core finding regarding trucks is robust to humidity artifacts.
- The RH × Winter interaction term is not statistically significant (p = 0.18), suggesting that the relationship between RH and $PM_{2.5}$ does not differ dramatically between winter (where high humidity coincides with high pollution) and other seasons.
- The small reduction in the RH coefficient after excluding high-humidity days (from 0.35 to 0.31) suggests that approximately 10–15% of the observed RH-$PM_{2.5}$ correlation may be attributable to instrument hygroscopic artifact, while the remainder reflects real physical processes (e.g., aerosol liquid water content, enhanced secondary aerosol formation).

Conclusion: The sensitivity analysis confirms that the potential instrument bias under high humidity conditions does not materially affect the study's core conclusions. The statistical association of heavy trucks with $PM_{2.5}$ remains strong and significant even after excluding high-humidity observations. Future studies using gravimetric verification or heated inlet systems are recommended to further minimize humidity-related artifacts.