



Original Research

Altitude-dependent gaseous emissions from freight trucks along the China-Pakistan Economic Corridor in Pakistan

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ARTICLE INFO

Article history:

Received 16 June 2022

Received in revised form

10 November 2022

Accepted 14 November 2022

Keywords:

Truck emissions

High altitude

China-Pakistan Economic corridor

Emission factors

ABSTRACT

Recent increases in emissions from freight transport have caused strong concerns about air quality in Pakistan, following the rapid development of projects related to the China-Pakistan Economic Corridor (CPEC). This study reported the first measurements of on-road truck emissions in Pakistan and investigated their dependence on altitude along CPEC routes. Emissions from 70 trucks were measured on CPEC highways located in Islamabad (540 m above sea level), Sost (2800 m above sea level), and at the Khunjerab Pass (4693 m above sea level). Calculated emission factors for carbon monoxide, hydrocarbons, and nitrogen oxides from heavy-duty trucks in Islamabad were 12.94 ± 1.46 , 15.21 ± 1.67 , and 10.69 ± 1.34 g km⁻¹ (95% confidence level), respectively, for pre-Pak-II trucks, and 12.75 ± 2.80 , 14.24 ± 3.53 , and 10.24 ± 2.34 g km⁻¹ (95% confidence level), respectively, for Pak-II trucks, representing 2–20 times higher values than the emission standards in Pakistan and India. An altitude increase of approximately 4000 m, with the associated changes in meteorology and fleet characteristics, induced an average increase of 103.6%, 86.3%, 124.5%, and 133.6% in the emission factors of carbon monoxide, hydrocarbons, nitrogen oxides, and carbon dioxide, respectively. Moreover, on-road emissions along the CPEC were mainly influenced by truck types. This study will support the budget evaluation of transport emissions from the CPEC trade fleet.

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1. Introduction

The China-Pakistan Economic Corridor (CPEC) project, part of the Chinese Belt and Road Initiative, has strengthened road-based trade and economic cooperation between China and Pakistan and is intended as a model of regional cooperation [1]. Recently, with the promotion of environmental sustainability, efforts have focused on transforming the CPEC transport structure [2–4]. In Pakistan, however, emission-intensive [5] road-based transport remains the dominant mode for freight [6], accounting for 96% of domestic freight in 2018 [7]. Because of the rugged local topography and the limited economic development level of Pakistan, road freight between Islamabad and the Khunjerab Pass, on the last CPEC section within Pakistan, is difficult to replace with cleaner transportation

means such as ships or pipelines. Moreover, road freight relies heavily on trucks, and emissions from diesel trucks contribute markedly to total transport-induced emissions [8], which result in serious health and environmental problems [9–13], including particulate pollution [14], acid precipitation, and global warming [15].

Furthermore, the altitude difference between Islamabad and the Khunjerab Pass strongly affects vehicular emission characteristics because high altitudes affect driving patterns and modify the load and pressure conditions inside combustion engines [12,16]. Both regulated and unregulated emissions are substantially affected by altitude changes [17]. Although numerous studies have investigated the impact of altitude on diesel vehicle performance, the correlation between altitude and pollutant emissions has not been clearly established. Human, Ullman, and Baines [17] measured emissions from two diesel engines, one naturally aspirated and one turbocharged, both at low altitudes and in simulated high-altitude conditions. Results indicated that engine operation at 1800 m

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above sea level resulted in emissions of nitrogen oxides (NO_x) reduced by approximately 10%, whereas emissions of carbon monoxide (CO), hydrocarbons (HC), particulate matter, and aldehydes were higher than those at low altitude by a factor of 2–4 and 1.2–2 for the naturally-aspirated and turbocharged engines, respectively. He et al. [18] coupled an engine bench with an altitude simulation system to evaluate the effects of altitude from sea level to 2000 m. Their experimental results indicated that CO, HC, and smoke emissions increased by 35%, 30%, and 34%, respectively, every 1000 m. However, high-altitude NO_x emissions depend on the engine type and operating conditions. Wang et al. [19] found that CO emissions from a light-duty diesel vehicle were 209% higher at an altitude of 2990 m than at sea level, whereas NO_x emissions decreased after rising with altitude.

Unfortunately, previous studies of air pollution in Pakistan were limited to megacities and seashore cities, where altitude variation is negligible, and fleet structure is different from that of highways, so emission characteristics in high-elevation areas in Pakistan could not be assessed. For example, Shah and Zeeshan [20] reported that light-duty vehicles were the main contributors to pollutant emissions in Islamabad, using local data for their scenario analysis. A study from Khwaja et al. [21] focused on emissions in Karachi (10 m above sea level), nearly unaffected by altitude. Ali and Athar [22] studied the central congested area of Lahore (217 m above sea level), the second largest city in Pakistan. Therefore, their results did not reflect the impact of altitude variations on effective emissions from freight transport by heavy-duty trucks.

For these reasons, this study was designed to characterize effective emissions from diesel trucks in Pakistan, especially in high-altitude areas, to better understand the road emission budget while considering the impact of altitude, which is crucial to achieving both the economic and environmental goals of the CPEC. Roads connecting the cities of Islamabad, Sost, and Khunjerab were selected for random on-site truck emission tests. Then truck emission factors in Pakistan were compared with those from other countries. Subsequently, emission factors were further categorized by altitude to quantify the impact of altitude variations on the emissions. Finally, the multiple linear regression method investigated how other factors, such as ambient conditions, model year, and truck type, affect the emissions.

2. Materials and methods

2.1. Study domain

In Pakistan, the highway network comprises 47 national highways, expressways, and motorways extending over 12,000 km [23]. For this study, three cities along the Karakoram highway were selected to provide a range of representative environmental and operating conditions, such as ambient temperature, relative humidity, and road grade. These cities (red stars in Fig. 1) were Islamabad (33°41' N, 73°03' E), Sost in Gilgit-Baltistan (35°21' N, 75°54' E), and Khunjerab (36°51' N, 75°25' E), all located in northeast Pakistan at altitudes of 540, 2800, and 4693 m above sea level, respectively. In these cities, several environmental and operating parameters were recorded simultaneously.

2.2. Experimental design and methods

Experiments were conducted at three distinct altitudes, as mentioned in the previous section. Before each experiment, the truck engine was warmed to the nominal cruising mode operating temperature. The measurement apparatus was also warmed, the pitot tube and manometer were cleaned, and the analyzer was zeroed and stabilized. As shown in Fig. 2, a pitot tube was coupled

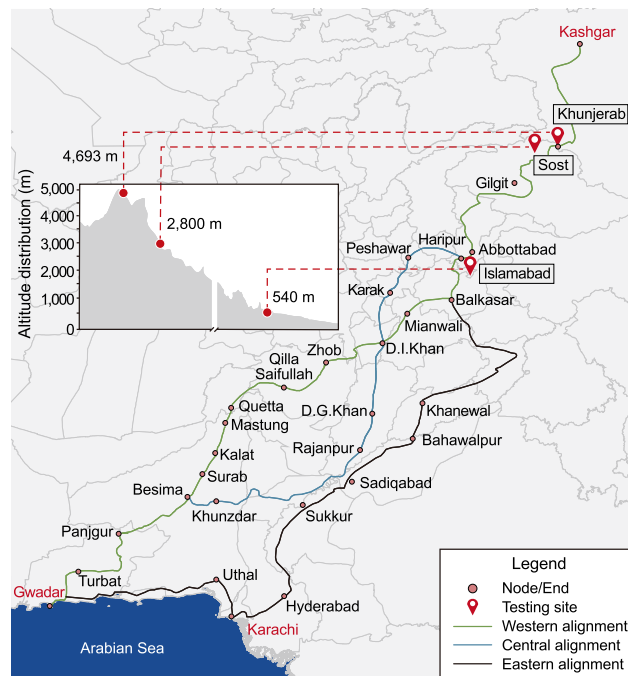


Fig. 1. On-road testing locations in Pakistan: Islamabad, Sost, and the Khunjerab Pass; the altitude profile on this portion of the Karakoram highway (inset) is also shown.

with a digital manometer (MAN-45 Professional Digital Manometer) to measure the difference between static and dynamic pressures, which was then used to calculate the tailpipe exhaust gas speed and flow rate. Additionally, a gas analyzer (FGA4500, Infrared Industries) was used to measure the CO, HC, NO_x, and carbon dioxide (CO₂) concentrations, as well as the temperature of the exhaust gases. The route length at each site was approximately 1 km. To evaluate the average speed over that distance, a Global Positioning System speedometer app coupled with Google Maps was used, showing both the instant and average truck speeds along the nominal route. Concurrently, ambient environmental conditions, including atmospheric temperature, pressure, and relative humidity, as well as operating parameters, notably the truck model year and type, were recorded.

In total, 70 trucks were randomly selected on the Karakoram highway at Islamabad, Sost, and Khunjerab in September 2020 and categorized based on the number of vehicle axles. Trucks with two axles were designated as light-duty trucks (LDTs) and others as heavy-duty trucks (HDTs). The selected trucks included 47 trucks tested at the lowest altitude (Islamabad), 20 trucks tested at a higher altitude (Sost), and only three six-axle trucks tested at the Khunjerab Pass because of the rough weather and limited resources in the Khunjerab area (see Table S2). In addition, because governmental regulations were not strictly applied by transport sector

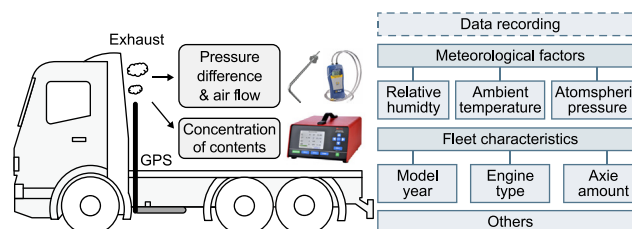


Fig. 2. Schematic diagram of the emission measurement methodology.

companies, neither diesel oxidation catalysts nor diesel particulate filters were equipped on any of the selected trucks.

2.3. Data processing

The measured parameters were exhaust gas temperature, altitude, truck speed, CO, HC, NO_x, and CO₂ concentrations, and pressure differences. To derive emission factors in grams per kilometer, we first used equation (1) to derive tailpipe exhaust gas speed, from which we then calculated volume flow rates:

$$v_{\text{exhaust},j} = \left(\frac{2\Delta P_j}{\rho_{\text{exhaust},j}} \right)^{1/2} \quad (1)$$

where ΔP_j is the pressure difference (Pa) for truck j ($j = 1, 2, \dots, 70$) and $\rho_{\text{exhaust},j}$ (kg m^{-3}) is the total exhaust gas density for truck j . The density was set to that of air in the same temperature and pressure conditions, in accordance with results from a previous study [24]. The volume flow rate was calculated by multiplying the truck velocity with the exhaust tailpipe cross-section area.

Then, we used equation (2) to derive the pollutant concentrations in milligrams per cubic meter and converted them into grams per kilometer using equations (3) and (4):

$$\rho_{i,j} = C_{i,j} \times \frac{M_{i,j}}{M_{\text{air}}} \times \rho_{\text{air}} \times 10^{-6} \quad (2)$$

$$m_{i,j} = \rho_{i,j} \times A_j \times v_{\text{exhaust},j} \quad (3)$$

$$EF_{d,i,j} = \frac{m_{i,j}}{v_{\text{Truck},j}} \quad (4)$$

where i represents the pollutant species ($i = \text{CO, HC, NO}_x, \text{CO}_2$) from truck j ; $\rho_{i,j}$ is the density of gas i from truck j in mg m^{-3} ; $C_{i,j}$ is the mixing ratio in ppm (parts per million, in volume or number of molecules), converted from dry basis (details given in the **Method** section of the Supporting Information); $M_{i,j}$ is the average molar mass of gas i in the exhaust from truck j in g mol^{-1} ; M_{air} is the average molar mass of air in g mol^{-1} ; ρ_{air} is the air density in kg m^{-3} ; $m_{i,j}$ is the emission rate in mg s^{-1} ; A_j is the tailpipe cross-section area for truck j in m^2 ; $EF_{d,i,j}$ is the distance-based emission factor of gas i from truck j in g km^{-1} ; and $v_{\text{Truck},j}$ is the speed of truck j in km h^{-1} . From these equations, we calculated average emission factors (in g km^{-1}) for each pollutant using data collected from each truck.

To compare our results with current emission standard limits and with previous studies, especially for HDTs, we also calculated fuel-based emission factors that we then used to derive effective brake-specific emission factors, using equations (5) and (6) [25,26]:

$$EF_{f,i,j} = \frac{EF_{d,i,j} \times W_C \times 1000}{0.273 \times EF_{d,\text{CO}_2,j} + 0.429 \times EF_{d,\text{CO},j} + 0.866 \times EF_{d,\text{THC},j}} \quad (5)$$

$$EF_{p,i,j} = \eta_j \times EF_{f,i,j} \times 10^{-3} \quad (6)$$

where, $EF_{f,i,j}$ is the fuel-based emission factor in g per kg fuel; W_C is the carbon mass ratio of diesel fuel, set to 0.866 [27]; $EF_{d,\text{CO}_2,j}$, $EF_{d,\text{CO},j}$, and $EF_{d,\text{THC},j}$ are the distance-based emission factors for CO₂, CO, and total HCs (THC), respectively, in g km^{-1} ; $EF_{p,i,j}$ is the brake-specific emission factor in g kWh^{-1} ; and η_j is the assumed engine efficiency derived from previous studies [28,29].

Subsequently, we applied multiple linear regression to

investigate the dependence of the emission factors EF_i for each pollutant i , in g km^{-1} , on meteorological factors and vehicle-specific information. The fitted result is defined as:

$$EF_i = \sum_{m=1}^i \beta_m X_m \quad (7)$$

where EF_i is the emission factor for pollutant i , in g km^{-1} , and β_m is the regression coefficient for each influencing factor X_m .

3. Results and discussion

3.1. Typical on-road truck emission level in Pakistan

We compared our results with values reported in previous studies and with current emission standards in Pakistan, India, and China to evaluate effective truck emissions in Pakistan relatively to neighboring countries. To account for the low economic development level of Pakistan, we compared our results with looser emission standards among those currently applied in India and China. Furthermore, average city altitudes in previous studies were approximately 200 m in India and 100 m in China; therefore, we selected the low-altitude city, Islamabad (540 m above sea level) for the comparison.

As shown in Fig. 3a, compared with previous studies in India [30] and China [31], LDTs in Pakistan emitted more HC and NO_x, with emission factors of 10.61 ± 0.86 and $7.07 \pm 0.54 \text{ g km}^{-1}$ (95% confidence level), respectively, whereas the CO emission factor, $9.17 \pm 0.70 \text{ g km}^{-1}$ (95% confidence level), was lower than that in India from trucks produced before 1991. In terms of emission standards, the HC value was approximately three times higher than the least-constraining standard, while CO and NO_x emission factors

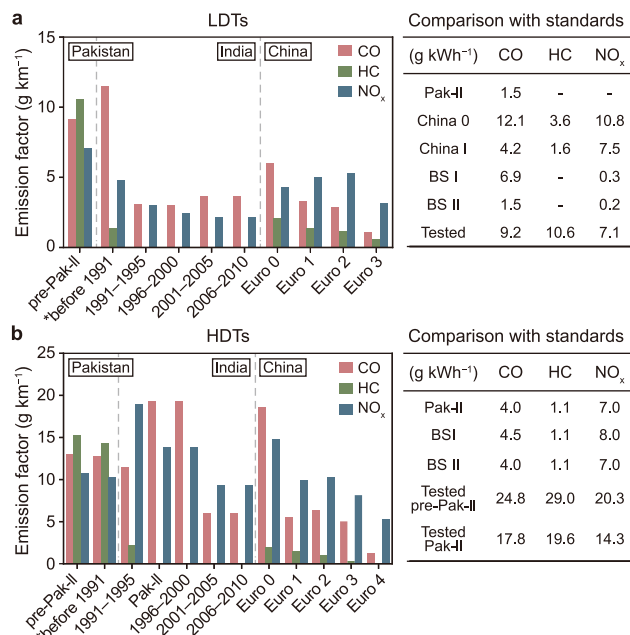


Fig. 3. Comparison of the measured emission factors for carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_x) with previous studies (left, histograms) and with emission standards (right, tabulated values) from light-duty trucks (LDTs, **a**) and heavy-duty trucks (HDTs, **b**). Values for Pakistan were calculated in this study; data for India were from NEERI [32] (label with asterisks) before 1991 and from Baidya and Borken-Kleefeld [30] in subsequent periods; data for China were from Hong, Yao, Zhang, Shen, Qiang, and He [31]. The BS abbreviation in the tables represents the “Bharat Stage” emission standards in India.

were within the “China 0” standard for medium-duty trucks and were higher than the emission standards in both India and Pakistan. For HDTs, emission factors for CO, HC, and NO_x were 12.94 ± 1.46 , 15.21 ± 1.67 , and 10.69 ± 1.34 g km⁻¹ (95% confidence level), respectively, for HDTs produced before 2012, and 12.75 ± 2.80 , 14.24 ± 3.53 , and 10.24 ± 2.34 g km⁻¹ (95% confidence level), respectively, for HDTs produced after 2012. Fig. 3b shows that the CO emission factor from HDTs in Pakistan was similar to that measured from trucks sold before 2000 in India [30,32], and to that measured from HDTs complying with the “Euro 0” emission standard in China. The NO_x emission factor in Pakistan was also comparable to those in India [30,32] and China [31]. In terms of emission standards, emission factors from HDTs in Pakistan represented four, twenty, and two times the limits for CO, HC, and NO_x, respectively, in Pakistan, India, and China, independently of the truck production dates relatively to 2012, when the Pak-II regulation was implemented.

For CO₂ emissions, not subjected to limiting regulations, pre-Pak-II LDTs in Islamabad presented an emission factor of 303.63 ± 23.01 g km⁻¹ (95% confidence level). For HDTs, the CO₂ emission factors were 434.07 ± 47.36 and 413.69 ± 99.66 g km⁻¹ (95% confidence level) for pre-Pak-II and Pak-II trucks, respectively.

Our results showed that, in Islamabad, trucks produced markedly higher gaseous pollutant emissions than previously measured values and emission standards. Although previously-planned subsidies or incentives have not been provided by the Pakistan government because of the ongoing economic crisis, except for electric vehicle imports, stricter regulations on truck emissions, especially from HDTs, should be implemented to improve air quality. These regulations should later be followed by inspection and penalty mechanisms to achieve emission levels comparable with the standards. Moreover, investment in infrastructure should also contribute to emission reduction, for example, by shifting freight transport from road to rail. More importantly, the effects of truck emissions on climate should be considered in the policy-making process, to achieve synergistic mitigation of pollutants and greenhouse gases, thereby improving CPEC sustainability.

3.2. Characteristics of truck emissions depending on altitude

Emission factors for CO, HC, NO_x, and CO₂ were also calculated at higher altitudes. Fig. 4 shows emission factors from LDTs and HDTs at the three altitudes selected for our study. There is a clear relationship between the measurement altitude and the emission factors, with more pollutants, including CO₂, emitted from trucks at higher altitudes, not only because of changes in environmental factors but also because of variations in the truck fleet characteristics at different sites. When the altitude increases, temperature and pressure both decrease quickly, and the fleet generally includes

newer models of trucks with larger engines. These factors affect the emission characteristics, especially their intensity.

For LDTs, data were available only in Islamabad (540 m above sea level) and Sost (2800 m above sea level); average CO, HC, NO_x, and CO₂ emissions increased with increasing altitude by 39.4%, 40.5%, 44.8%, and 100.0%, respectively. For HDTs, however, gas emission increases between Islamabad and Sost were comparatively smaller than for LDTs, with values of 22.6%, 16.1%, 19.0%, and 64.7% for CO, HC, NO_x, and CO₂, respectively. Between Sost and the Khunjerab Pass, HDT carbon dioxide emissions increased by 24.3%, and NO_x was approximately 20% higher. CO and HC emission increases were comparable to those from LDTs between Islamabad and Sost, with average values of 45.7% and 40.8% for CO and HC, respectively. The total increase of CO, HC, NO_x, and CO₂ emissions from HDTs between Islamabad and Khunjerab Pass was 78.6%, 63.4%, 92.9%, and 104.7%, respectively. Averaged over all samples, the altitude difference between Islamabad and the Khunjerab Pass (approximately 4000 m) induced emission factor increases of 103.6%, 86.3%, 124.5%, and 133.6% for CO, HC, NO_x, and CO₂, respectively. When altitude increased, atmospheric conditions, which affect the performance of internal combustion engines, were altered. For example, ambient air pressure and oxygen content both decreased with increasing altitude, causing a reduction of the air–fuel ratio and deteriorating the combustion, thereby resulting in higher CO and HC emissions. For NO_x, on the one hand, lower oxygen concentrations at higher altitudes inhibited NO_x formation; on the other hand, a greater equivalence ratio and prolonged ignition delay induced an increase in the combustion temperature [18,33,34], inducing higher NO_x emissions. Simultaneously, the weaker engine output also increased fuel consumption [35–38], consequently producing more CO₂. Truck characteristics and fleet composition also significantly impacted the emission pattern. As shown in Table S2 and Fig. S1, for example, rated engine power at different sites showed that trucks powered by large engines were generally captured at higher altitudes, causing more emissions. This general increasing trend of emission factors with increasing altitude, combined with measured values at lower altitudes that were consistently higher than in other countries, showed that trucks on CPEC roads between the study sites emitted consistently more gaseous pollutants than in other locations in Pakistan or the neighboring countries. Therefore, the study of emission increases should concentrate on this area.

To further investigate the emission changes induced by altitude variations and eliminate the impact of truck types, we selected three trucks with similar rated engine power, one per city (details in Table S3). When the altitude increased from 540 to 2800 m and then to 4693 m (above sea level), the CO, HC, and NO_x emission factors first decreased by 26.9%, 23.8%, and 37.2%, respectively, from 540 to 2800 m, before increasing from 2800 to 4693 m, representing a total net increase of 15.6%, 9.4%, and 12.9%, respectively, over the full altitude range. Conversely, CO₂ presented a consistent upward trend, increasing by 5.0% and 35.5% from 540 to 2800 m and from 2800 to 4693 m, respectively. This could be attributed to model year differences: the truck selected at a low altitude (540 m above sea level) was produced in 2010, whereas the other trucks were produced in 2019. The government of Pakistan had issued official regulations on new vehicles stating that, from July 1st, 2012, all imported or locally manufactured diesel vehicles must apply the “Pak-II” emission standard [39], more stringent than the preceding standards and in line with the “Euro 2” standard. The model year of the trucks selected in the intermediate and high-altitude cities was 2019, and therefore they benefited from notable technological improvements compared with the truck selected in Islamabad, which showed reduced emissions. However, when comparing both 2019 trucks, selected at 2800 and 4693 m and with identical rated

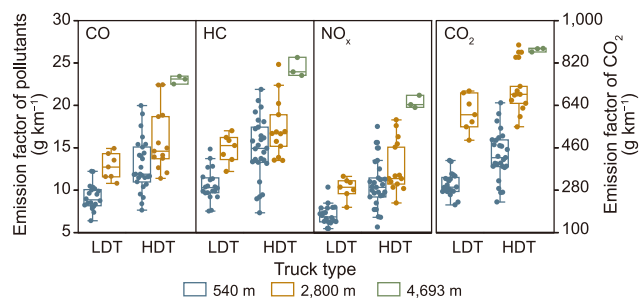


Fig. 4. Emission factors for CO, HC, NO_x, and carbon dioxide (CO₂) from LDTs and HDTs in Islamabad (blue), Sost (yellow), and Khunjerab (green). The altitude of each city is given in the figure key.

power and model year, the altitude increase caused an emission increase. In addition, we further selected two-axle trucks with identical (107 horsepower) rated powers and the same model year (before 2012), at 540 and 2800 m, and compared their emission factors. The result showed that the altitude difference between the sites was related to increased emission factors for all measured gases.

A previous study from Kouser et al. [40] estimated that a maximum of 7000 trucks will use the CPEC daily once the project is complete. On this basis, we calculated future gaseous emissions from trucks along the CPEC, focusing on the portion of the road with a marked altitude difference from Islamabad to the Khunjerab Pass (details given in the **Results** section of the Supporting Information). Assuming identical fleet structure and exhaust tailpipe control technologies, annual average emissions of CO, HC, NO_x, and CO₂ could reach 12,780, 14,799, 10,322, and 424,218 metric tons, respectively, in the lower-altitude sector (540–1940 m above sea level); 10,780, 12,016, 8,585, and 489,212 metric tons, respectively, at intermediate high altitudes (1940–3293 m above sea level); and 3,718, 3,940, 3,289, and 141,585 metric tons, respectively, at the highest altitudes (3293–4693 m above sea level) after the completion of the CPEC, representing a serious environmental threat. Applying the 20- and 100-year global warming potential calculations from the previous studies [41,42] (see **Table S5**), total CO₂-equivalent emissions on the CPEC portion between Islamabad and the Khunjerab Pass could represent 2,173,142 and 1,731,079 metric tons. Moreover, considering the geographical proximity of the Tibetan Plateau, further analysis of simultaneous emissions from pollutants and greenhouse gases along the CPEC in Pakistan should be conducted to quantify the impact of freight transport by trucks on air quality and climate and to evaluate potential mitigation policies.

3.3. Analysis of factors influencing truck emissions

We applied multiple linear regression to investigate the factors influencing truck emissions in Pakistan. We selected two categories of factors. The first included meteorological factors such as ambient temperature, relative humidity, and atmospheric pressure. The second category included vehicle-related information such as the number of axles, model year, and rated engine power. After assessing model performance, we focused on ambient temperature, relative humidity, number of axles, model year, and rated engine power. Fig. 5 illustrates the regression results. The calculated correlation coefficients for CO, HC, NO_x, and CO₂ were 0.77, 0.70, 0.75, and 0.83, respectively (see Fig. 5). Fitted regression equations are presented in **Table S4**. Residual histograms and P–P plots (see **Figs. S2–S5**) showed a normal distribution and symmetric scatter (see **Figs. S2–S5**) of the residuals around zero for all gases, indicating a conclusive regression.

The fitted coefficients calculated for the meteorological factors indicated that temperature and relative humidity harmed all gases. For a temperature increase of 1 °C, decreases of 0.21, 0.21, 0.17, and 12.3 g km⁻¹ were calculated for CO, HC, NO_x, and CO₂, respectively. Conversely, the decrease induced by a relative humidity increase was 1–2 orders of magnitude smaller than for temperature, especially for CO, HC, and NO_x. We also quantified the impact of truck characteristics on the emission factors in this study. The number of axles was the most important factor for all pollutants; we believe this is because bigger trucks produce higher emissions. As technology and emission standards improve, emissions from new trucks are lower than those from older models. In this study, the correlation of the model year with emissions was negative. However, this impact was insignificant, indicating that, although emissions controls for road freight transport have been implemented in

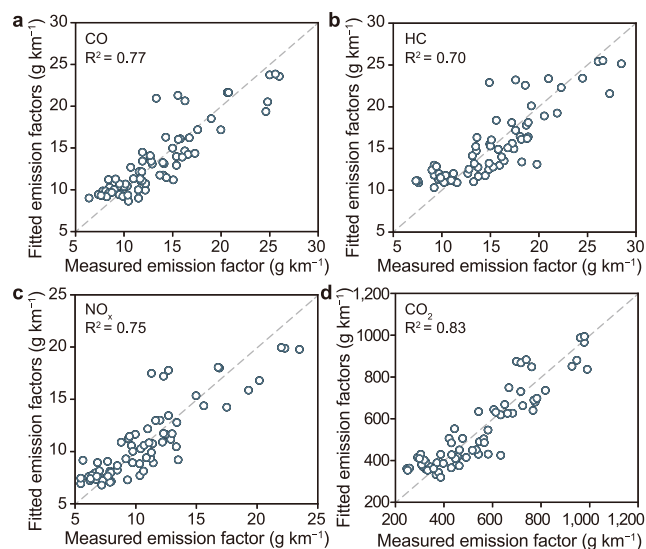


Fig. 5. Multiple linear regression analysis of the emission factors for CO (a), HC (b), NO_x (c), and CO₂ (d).

Pakistan, replacing old vehicles needs to accelerate. Finally, the impact of rated engine power on emissions was limited in our study, which could be explained by the discrepancy between effective operating conditions for each truck and rating conditions.

3.4. Uncertainty estimation

Uncertainties in the emission factor evaluation in our study derived primarily from the following aspects.

- (1) Sample sizes: although the response of vehicle emissions to an altitude increase depends on the vehicle [43], we calculated emission factors for specific pollutants using the average of all samples to represent the complete fleet, thereby neglecting the effective fleet structure;
- (2) Operating conditions: higher operating speed implies higher fuel consumption to overcome air resistance, which subsequently results in variations in both fuel consumption and engine power. Thus, output power and additional performance parameters differ between studies, causing discrepancies in emission factors estimates. However, with limitations from data granularity and following Li et al. [44], we restricted our truck selection to vehicles operating in cruising mode, their most frequent operation state, and we limited the type of road to highways to determine localized emission factors and the associated influencing parameters. Further investigation is needed to minimize these uncertainties;
- (3) Environmental conditions: real measurement conditions can differ notably between studies because of distinct geological, topographic, and meteorological conditions such as road grade, generally increasing with increasing altitude, and temperature profile near the ground;
- (4) Analyzing equipment: measurement error intrinsic to the used apparatus also causes uncertainties in emission factor estimation [45]. In our study, for example, there were variations of gas concentrations measured by the analyzer and truck speed between each test (**Figs. S6–S7**).

4. Conclusion

Emissions from diesel trucks are major contributors to total emissions of atmospheric pollutants in Pakistan. Because of the clear potential of the CPEC to become an important freight transport hub within the Belt and Road Initiative, with the increasing freight transport demand and the vulnerability of the adjacent Tibetan Plateau, the study of transport emissions along the CPEC in Pakistan has become necessary and should be undertaken quickly. However, few studies have yet attempted to quantify effective truck emissions in Pakistan, especially at high altitudes, or to investigate the impact of altitude and local operating conditions on emission factors. In this study, we reported the first tailpipe emission measurements from 70 trucks selected in three cities in Pakistan at altitudes between 540 and 4693 m above sea level. By comparing previous studies and emission standards in China and India, we showed that emissions in Pakistan were significantly higher than in the neighboring countries and higher than emission standards. Emission factors for LDTs in Islamabad were comparable with the “China 0” emission standard for medium-duty trucks, except for HC, with an emission factor three times higher than the standard. Moreover, HC emissions from HDTs in Islamabad were up to 20 times higher than the corresponding emission standards in Pakistan and India. Then, we investigated the dependence of truck emissions on altitude and determined that, on average, when the altitude increased, more gaseous pollutants and carbon dioxide were emitted because both the local environmental conditions and the fleet characteristics changed. Among the factors influencing emissions, the type of truck was statistically the main contributor to truck emission variations, whereas the rated engine power induced the smallest variations.

This study is important to anticipate and assess emission increases resulting from the substantial traffic expected along the CPEC in the near future, to help local governments and the international community better understand truck emissions in high-altitude areas. Future research directions include calculating net total truck emissions along the CPEC by extending the data presented in this study to the detailed truck population in related areas and monitoring all CPEC traffic. Consequently, the possible environmental impact in Pakistan caused by CPEC traffic should also be investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by the National Natural Science Foundation of China (grant numbers 41822505 and 42061130213 for H. L.). H. L. is also supported by the Royal Society of the United Kingdom through a Newton Advanced Fellowship (NAF\R1\201166).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ese.2022.100226>.

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