

# The Impact of Fuel Type on Emissions in High-altitude Cities: A PEMS Study of LPG/Gasoline and Gasoline Vehicles

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**Abstract.** To determine whether liquefied petroleum gas (LPG)/gasoline dual-fuel vehicles reduce atmospheric pollution in high-altitude cities compared to gasoline vehicles, experiments were conducted on two LPG/gasoline and two gasoline vehicles in a high-altitude city using a portable emissions measurement system (PEMS), and real-world emissions from two gasoline vehicles in a low-altitude city were also analyzed. The emission factors were obtained and the effects of driving mode, speed, and acceleration on emission characteristics were examined. Results show that the mean emission factors of CO<sub>2</sub>, CO, and NO<sub>x</sub> for LPG/gasoline-fueled vehicles in high-altitude cities are 159.22±11.81, 18.38±9.72 and 1.53±0.46 g/km, and those for gasoline-fueled vehicles are 226.64±27.80, 1.46±0.83 and 0.22±0.17 g/km. For gasoline vehicles in low-altitude cities, the emission factors are 188.01±4.82, 2.21±0.67 and 0.07±0.003 g/km. Unlike CO<sub>2</sub>, CO and NO<sub>x</sub> emissions from LPG/gasoline vehicles are higher than those from gasoline vehicles. Further analysis indicates that idle and accelerating modes significantly affect CO and NO<sub>x</sub> emissions. In high-altitude tests, these two modes account for about 24.5% and 31.2% of total testing time, respectively, with higher emissions than low-altitude vehicles (22.5% and 27.7%). Generally, gasoline-fueled vehicles exhibit better gaseous pollutant emissions behavior than LPG/gasoline-fueled ones. These findings can serve as a reference for developing emission inventories and emission-control strategies in high-altitude cities.

**Keywords:** Real-world emissions; LPG; gasoline; high-altitude.

## 1. Introduction

Vehicle emissions are a significant source of air pollution, especially in urban areas. According to data from the Ministry of Ecology and Environment of China, there were approximately 298.4 million vehicles in China by the end of 2017, emitting about 43.6 million tons of pollutants in 2018. To address this issue, China has been formulating stricter vehicle emissions standards. The Ministry of Environmental Protection of China issued the Stage 6 (China 6) emissions standards for light-duty vehicles at the end of 2016 [1], which was implemented in stages from July 1, 2020. This standard not only tightens emissions limits for various pollutants but also improves measurement methods, such as introducing the Worldwide Light-Duty Test Cycle (WLTC) and Real Driving Emissions (RDE) testing [2]. Among different vehicle emissions measurement methods, PEMS has gained prominence in recent years. It can measure and record tailpipe emissions, engine speed, vehicle velocity and position, and environmental parameters on a second-by-second basis. Compared to other methods, PEMS provides a more realistic reflection of vehicle emissions under actual driving conditions [3, 4].

Lhasa, the capital of the Tibet Autonomous Region, is a high-altitude city with unique geographical and environmental conditions. With the development of tourism and urbanization, vehicle emissions have become the primary source of air pollution in Lhasa [5-7]. To mitigate urban atmospheric pollution, Lhasa began promoting gaseous fuels for vehicles in public transportation in

2009. By the end of 2016, about 70% of taxis in Lhasa were equipped with LPG/gasoline dual-fuel engines. However, few studies have investigated the real-world emissions of LPG/gasoline vehicles in high-altitude cities.

This study aims to measure the emissions of LPG/gasoline-and gasoline-fueled vehicles in a high-altitude city and gasoline-fueled vehicles in a low-altitude city using PEMS. The results will enhance the understanding of real-world emissions from light-duty gasoline and LPG/gasoline-fueled vehicles under high-altitude conditions and provide a basis for controlling vehicle emissions and improving air quality in high-altitude cities.

## 2. Experimental investigation

### 2.1 Measurement system

A SEMTECH-DS PEMS manufactured by Sensors, Inc. (USA), was used to measure the vehicle's emissions. The concentrations of CO<sub>2</sub> and CO were measured using a non-dispersive infrared analyzer (NDIR) with an accuracy of  $\pm 3\%$ . The concentrations of NO and NO<sub>2</sub> were measured using a non-dispersive ultraviolet (NDUV) analysis unit with an accuracy of  $\pm 3\%$ . The ambient temperature, pressure, and relative humidity were measured using a remote weather probe. The position, speed, and altitude of the test vehicles were monitored second-by-second using the global positioning system (GPS). The exhaust flow from the vehicles or engines was tested using an exhaust flow meter (EFM). The transient mass emissions of gaseous pollutants were calculated from the exhaust flow and pollutant concentrations using post-processing software. Given Lhasa's unique high-altitude environment (0.62 bar air pressure, 0.62 times sea-level), PEMS use here is rare. Therefore, a Sensors technician was hired for testing during the experiment. Before the test begins, the external power supply is used to preheat the sampling line to about 190 °C. For analyzers and condensers, the line also needs to preheat to the corresponding temperature. A leak-test was conducted after preheating: First, the sampling line is sealed, then the internal sampling pump is used to establish a certain vacuum degree; then the sampling pump is turned off, and the sampling line is tested to be leakage by checking the reduction of vacuum degree. After the leak testing, high-purity nitrogen was used to zero the NDIR and NDUV modules, and then spanning gas was used to calibrate pollutants such as CO, CO<sub>2</sub>, NO, and NO<sub>2</sub> to reduce or eliminate possible zero errors and span errors. A laptop was connected to the SEMTECH-DS unit during the zeroing, calibration, and monitoring of the PEMS and the collection of the experimental data. Fig. 1 shows a sketch of the on-road real driving emissions test system installed in a vehicle[8].

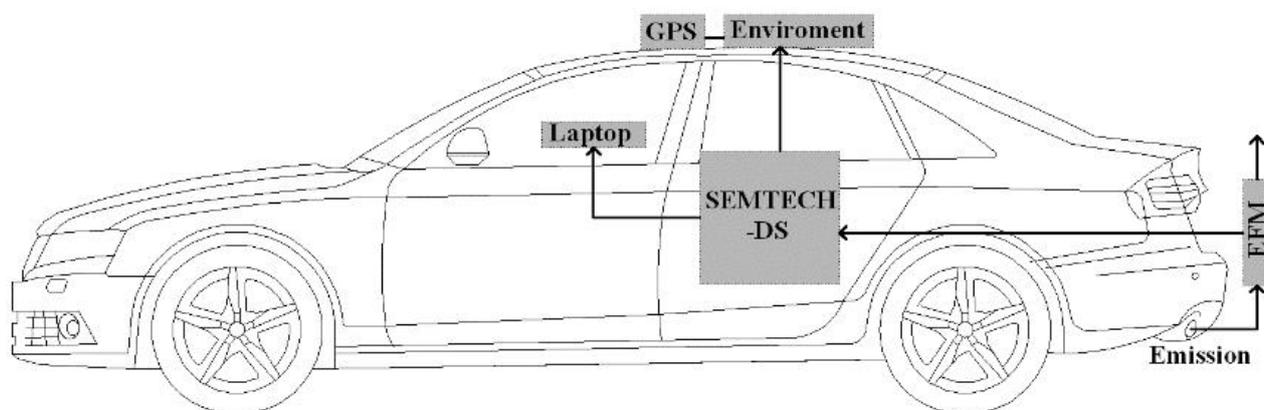


Fig. 1. Sketch of the on-road real driving emissions test system installed in a vehicle.

### 2.2 Test vehicles

At the end of 2016, Lhasa had 1,670 taxis, ~70% being LPG/gasoline dual-fuel and the rest mostly LNG/gasoline dual-fuel, mostly certified to China 4 (Euro 4) emissions standards. Two

LPG/gasoline vehicles and five gasoline vehicles were selected for the investigation in this experiment. The parameters of these vehicles are listed in Table 1. All vehicles were hired from Taxi Company or a local automobile rental company. To obtain the real driving emissions for Lhasa, all tested vehicles were driven by its original driver according to the projected route. As a comparison, two light-duty gasoline vehicles are tested with PEMS in a low-altitude city (Beijing), where the altitude is ~52m, on a similar road type.

Table 1. Test vehicle parameters.

Project	A	B	C	D	E	F
Model year	2015	2014	2012	2016	2009	2011
Odometer/104km	22.2	0.95	63.22	3.78	54.33	30.11
Fuel type	LPG/Gasoline	Gasoline	LPG/Gasoline	Gasoline	Gasoline	Gasoline
Engine displacement/L	1.6	1.6	1.8	2.0	1.6	1.6
Emission standard	Euro4	Euro4	Euro4	Euro4	Euro4	Euro4
Injection type	PFI	PFI	PFI	GDI	PFI	PFI
After-treatment	TWC	TWC	TWC	TWC	TWC	TWC
Intake type	NA	NA	NA	Turbo-charge	NA	NA
Curb weight/kg	1245	1120	1420	1460	1240	1204

Note: PFI, port fuel injection; GDI, gasoline direct injection; TWC, three-way catalysts; NS, naturally Aspirated.

### 2.3 Test cycle

The test route comprised real Lhasa roads, including main roads, collector streets, and national roads, with a total length of ~32 km. The route consisted of ~28.4% main road, ~22.5% collector street, and ~49% national road. Fig. 2 presents the test route map[8]. Experiments were conducted between 12:00-18:00 (Beijing Time) on sunny workdays in October 2016. Air temperature was ~18 °C , humidity ~22%, and wind speed <3 m/s. Before each test, the PEMS was warmed up, calibrated with standard gases, and the vehicle was parked for 6-8 hours. Once the engine started, the PEMS began collecting emissions data. Each test cycle lasted ~1.5 h, averaging ~22.5 km/h. Maximum speed, acceleration, and deceleration were 72.42 km/h, 3.93 m/s<sup>2</sup> , and -4.65 m/s<sup>2</sup> , respectively. The varying driving speeds ensured the test reflected Lhasa's real driving emissions.

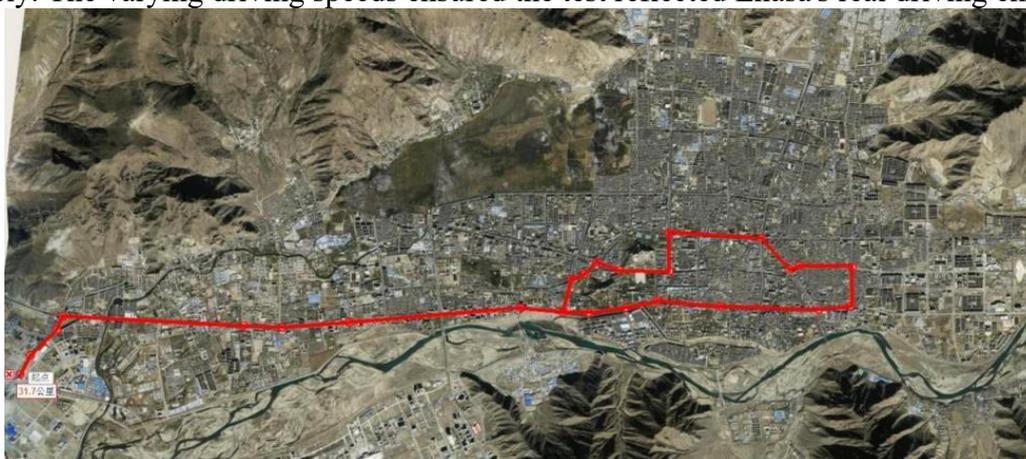


Fig. 2. The map of the on-road test route.

### 3. Results and discussion

#### 3.1 Emission factors for LPG/gasoline and gasoline vehicles

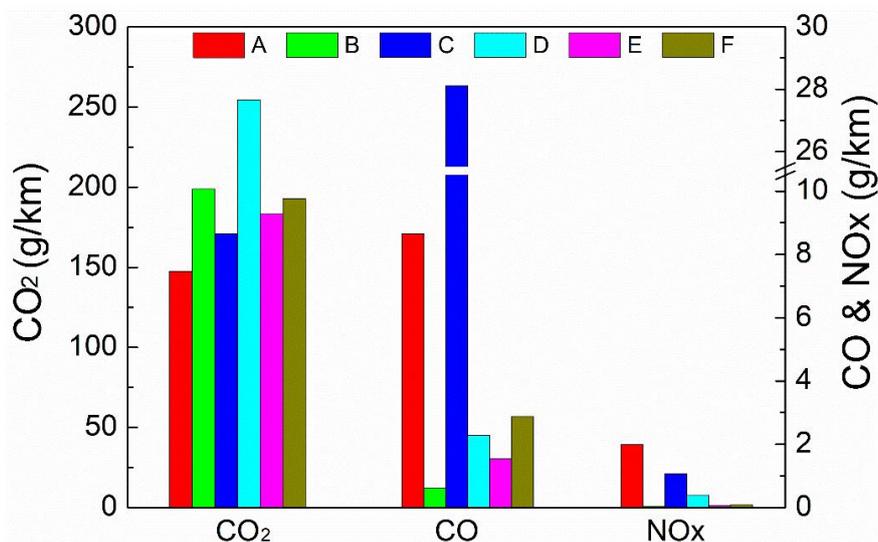


Fig. 3. Emission factors of the test vehicles.

Emission factors, indicating a vehicle's emissions per unit distance, are crucial for emission control strategy development. Fig. 3 presents the emission factors for CO<sub>2</sub>, CO, and NO<sub>x</sub> of the tested vehicles, including cold-start emissions. For CO<sub>2</sub>, LPG/gasoline vehicles (A & C) have lower emission factors (147.7 and 171.0 g/km) than gasoline vehicles (B & D) at high altitudes (198.8 and 254.4 g/km). Low-altitude gasoline vehicles (E & F) show slightly higher CO<sub>2</sub> emission factors than LPG/gasoline vehicles but lower than high-altitude ones. However, LPG/gasoline vehicles exhibit significantly higher average emission factors for CO ( $18.38 \pm 9.22$  g/km) and NO<sub>x</sub> ( $1.53 \pm 0.46$  g/km) than gasoline vehicles in both high-and low-altitude cities. Compared to high-altitude gasoline vehicles, LPG/gasoline vehicles show a 29.7% reduction in CO<sub>2</sub> but increases of 11.6% and 5.99% in CO and NO<sub>x</sub>. Relative to low-altitude gasoline vehicles, they reduce CO<sub>2</sub> by 17% but decrease CO by 51.4% and increase NO<sub>x</sub> by 66.8%. These results stem from factors such as the physicochemical properties and combustion characteristics of LPG and gasoline, engine control, TWC catalytic efficiency, and cold-start emissions. The findings partially align with a Beijing study[9], where LPG/gasoline vehicles had emission factors of 176.9, 2.32, and 0.54 g/km for CO<sub>2</sub>, CO, and NO<sub>x</sub>, representing reductions of 12.6%, 36.8%, and an increase of 37.4% compared to local gasoline vehicles. Reasons for these discrepancies involve air density, weather conditions, road type, TWC catalytic efficiency, and cold-start effects.

In summary, in high-altitude cities, LPG/gasoline vehicles generally have higher traditional gaseous pollutant (CO and NO<sub>x</sub>) emission factors than gasoline vehicles, and both fuel types show different emission characteristics from those in low-altitude areas. When developing emission control strategies for high-altitude cities, specific objectives should be considered for LPG/gasoline and gasoline vehicle development.

#### 3.2 Emissions under varying driving modes

The real driving data collected from the LPG/gasoline- and gasoline-fueled vehicles are analyzed statistically, and the percentage distribution of total driving time and the emissions of C, CO, and NO<sub>x</sub> under various driving modes as references to literature [10], specifically idle, cruise, acceleration, and deceleration are listed in Table 3. The definition of driving modes are listed in Table 2.

Table 2. Definitions of Driving Modes.

Driving mode	Definition
Idle	Speed = 0 km/h, $-0.1 \text{ m/s}^2 < a^* < 0.1 \text{ m/s}^2$
Cruise	Speed > 0 km/h, $-0.1 \text{ m/s}^2 < a < 0.1 \text{ m/s}^2$
Acceleration	Speed > 0 km/h, $a^* \geq 0.1 \text{ m/s}^2$
Deceleration	Speed > 0 km/h, $a \leq -0.1 \text{ m/s}^2$

\*a is defined as the transient acceleration of the vehicle,  $\text{m/s}^2$

Table 3. Emissions Ratios under Various Driving Modes (unit: %).

	Idle	Cruise	Acceleration	Deceleration	Idle	Cruise	Acceleration	Deceleration
	A				B			
Time	21.62	30.79	26.28	21.31	22.72	15.78	34.48	27.02
CO <sub>2</sub>	10.01	35.88	40.56	13.55	16.53	15.23	51.21	17.02
CO	21.45	30.16	26.56	21.84	15.94	13.68	46.34	24.04
NOx	3.36	38.22	47.54	10.88	14.79	16.97	49.81	18.42
	C				D			
Time	27.81	15.01	30.93	26.25	25.85	11.12	33.29	29.74
CO <sub>2</sub>	16.51	17.06	46.60	19.82	13.12	11.44	53.64	21.80
CO	9.46	16.42	51.41	22.71	4.68	14.72	38.85	41.75
NOx	2.05	15.36	65.26	17.32	2.36	7.71	74.01	15.93
	E				F			
Time	19.88	25.51	27.27	27.34	25.03	21.44	28.07	25.46
CO <sub>2</sub>	11.49	28.65	38.83	21.04	16.20	25.95	39.34	18.51
CO	10.08	24.81	41.43	23.69	5.07	17.66	64.75	12.51
NOx	5.32	21.44	57.48	15.75	4.96	22.51	54.97	17.56

Because the distribution of driving modes is significantly influenced by the behavior of the driver, the specific distribution of LPG/gasoline and gasoline vehicles will not be compared in this section, while the contribution of various driving modes to vehicle emission will be analyzed. As shown in Table 2, the idle mode of all vehicles (A, B, C, D, E, and F) takes up 21.62%, 22.72%, 27.81%, 25.85%, 19.88%, and 25.03%, separately, which means almost a quarter of the total driving time is wasted on waiting in line or stopping at red lights. Although the contribution ratio of the idle mode for emissions is not the highest, the emission factor could be considered to be infinite as the result of the vehicle not moving. Besides, both the city size and vehicle ownership in Lhasa are much smaller than in Beijing, while Lhasa's idle time ratio is even higher than Beijing's, which indicates that the traffic situation in Lhasa still needs improving. It is one way improve traffic conditions might be to optimize the phase time of traffic signals to reduce idle time.

Many previous studies have shown that the accelerating mode aggravates the vehicle's emissions [11-13]. In the present study, the accelerating mode occupies more than a quarter, even up to one-third of the total test time. Taking vehicle C as an example, the proportion of the accelerating mode is 30.93%, while it contributes 46.6%, 51.41%, and 65.26% of CO<sub>2</sub>, CO, and NOx, emissions. On the other hand, the cruise mode, which occupies 15.01% of the total test time, contributes 17.06%, 16.42%, and 15.36% of emissions. This trend is similar to that identified in previous investigations [9]. Therefore, improving the phase time of traffic signals, and regulating the driving habits of drivers to reduce the proportion of time spent accelerating, and reducing idle time would contribute to reductions in emissions.

### 3.3 Influence of speed on emissions

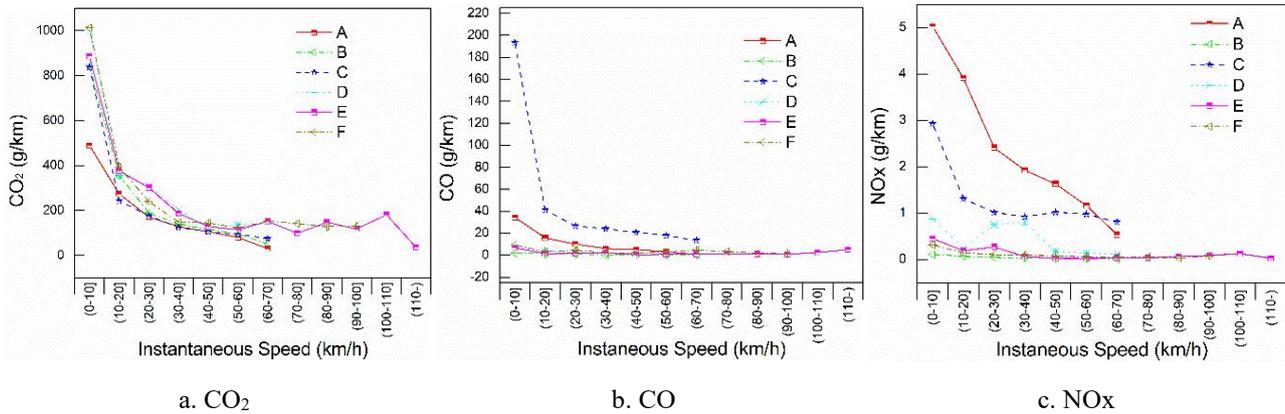


Fig. 4. Emissions under various speeds.

Fig. 4 illustrates the relationship between emission factors and vehicle speed for tested vehicles fueled by LPG/gasoline and gasoline in a high-altitude city. Generally, the emission factors of CO<sub>2</sub>, CO, and NOx decrease rapidly at first and then slowly as speed increases, except for vehicle D's NOx emissions, which rise from 20-40 km/h. These trends are consistent with prior studies [9, 12]. LPG/gasoline vehicles have lower CO<sub>2</sub> emission factors than gasoline vehicles across most speeds but higher CO and NOx emission factors, especially at low speeds. Notably, vehicle B's CO and NOx emissions are ultra-low at high altitudes, similar to vehicles E and F at low altitudes. This may be due to the precise match between modern vehicle control and TWC catalytic conversion. The fluctuation in vehicle D's NOx emission factor may be attributed to two factors. First, the turbo-charged engine in vehicle D can cause high NOx emissions. The severe surging raises exhaust temperature quickly, even producing visible flames during acceleration at 20-40 km/h. Second, compared to naturally aspirated engines in vehicles A/B/C, the TGDI engine in vehicle D has a higher thermal load, shortening the cold-start warm-up process and reducing emissions. In conclusion, increasing vehicle average speed, enhancing engine control, and improving after-treatment catalytic conversion efficiency are effective ways to reduce vehicle emissions in high-altitude areas.

### 3.4 Impacts of acceleration on emissions

During the experiments in Lhasa, most of vehicle speed were distributed in the range of 0-60 km/h, with acceleration generally between -1 m/s<sup>2</sup> to 1 m/s<sup>2</sup>, so, the vehicle speed are divided speed into “v<20 km/h”, “20 km/h ≤ v < 40 km/h”, and “v ≥ 40 km”, and the acceleration are divided into 7 intervals with a step of 0.4m/s<sup>2</sup>, 21 bins in total, as shown in Table 4. Fig. 5 shows the emission rates of vehicles fueled with LPG/gasoline and gasoline in Lhasa and gasoline vehicles in Beijing as a function of acceleration.

Table 4. Bins definitions of Speed-Acceleration

Bins	Speed- Acceleration (km/h, m/s <sup>2</sup> )	Bins	Speed- Acceleration (km/h, m/s <sup>2</sup> )	Bins	Speed- Acceleration (km/h, m/s <sup>2</sup> )
1	v < 20 , a < -1	8	20 ≤ v < 40, a < -1	15	v ≥ 40, a < -1
2	v < 20, -1 ≤ a < -0.6	9	20 ≤ v < 40, -1 ≤ a < -0.6	16	v ≥ 40, -1 ≤ a < -0.6
3	v < 20, -0.6 ≤ a < -0.2	10	20 ≤ v < 40, -0.6 ≤ a < -0.2	17	v ≥ 40, -0.6 ≤ a < -0.2
4	v < 20, -0.2 ≤ a < 0.2	11	20 ≤ v < 40, -0.2 ≤ a < 0.2	18	v ≥ 40, -0.2 ≤ a < 0.2
5	v < 20, 0.2 ≤ a < 0.6	12	20 ≤ v < 40, 0.2 ≤ a < 0.6	19	v ≥ 40, 0.2 ≤ a < 0.6
6	v < 20, 0.6 ≤ a < 1	13	20 ≤ v < 40, 0.6 ≤ a < 1	20	v ≥ 40, 0.6 ≤ a < 1
7	v < 20, a ≥ 1	14	20 ≤ v < 40, a ≥ 1	21	v ≥ 40, a ≥ 1

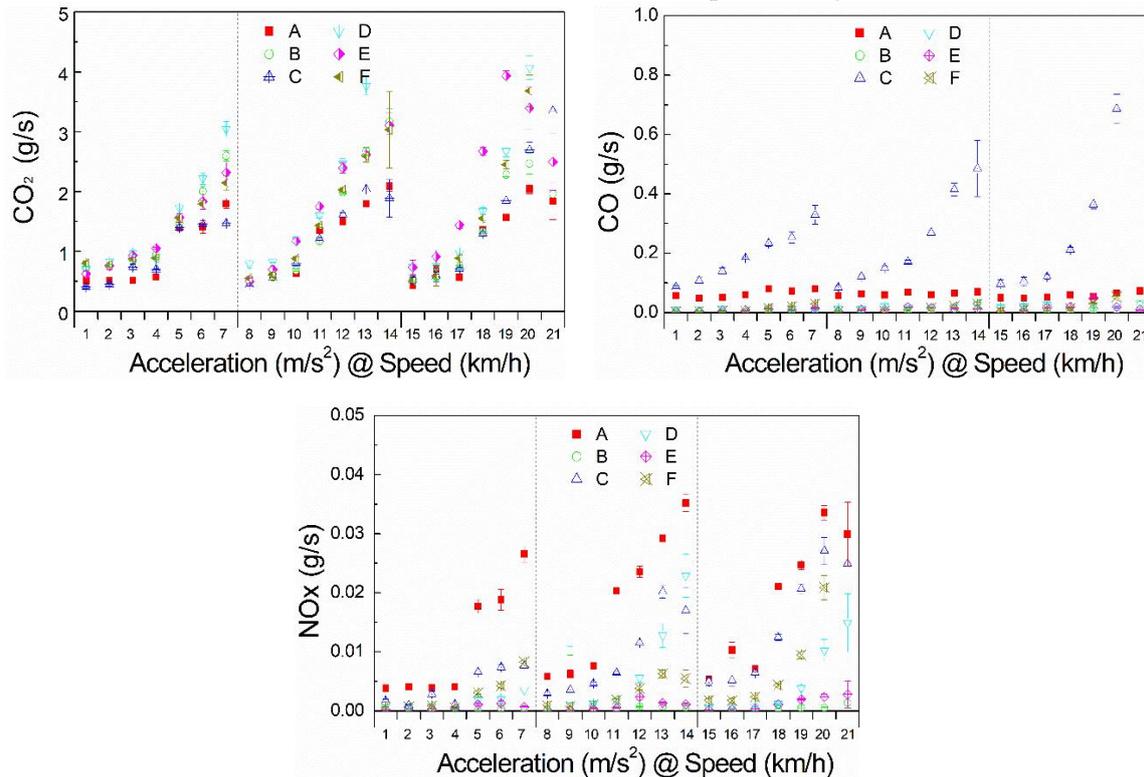


Fig. 5. Emission rates as a function of acceleration.

As shown in Fig. 5, the emissions of CO<sub>2</sub>, CO, and NO<sub>x</sub> for all tested vehicles increase with acceleration. LPG/gasoline vehicles generally have higher CO and NO<sub>x</sub> emission rates than gasoline vehicles, while their CO<sub>2</sub> emission rates are lower. When acceleration is below 0 m/s<sup>2</sup>, the gaseous emission rates of both fuel types are low and change little, except for CO emissions from vehicle C at speeds below 20 km/h. Thereafter, most emission factors increase with acceleration. Gasoline vehicles (B, D, E, F) show ultra-low CO and NO<sub>x</sub> emissions across most acceleration ranges, except for NO<sub>x</sub> emissions from the TGDI vehicle (D). These findings align with previous studies[12]. Under low-speed conditions with frequent stops and accelerations, vehicles emit large amounts of CO and NO<sub>x</sub>, especially during quick stops when the remaining LPG mixture in cylinders is too lean to burn completely, leading to high CO emissions. The emission differences between vehicles A and C may stem from vehicle A's high mileage, which accelerates TWC aging and reduces catalytic efficiency.

#### 4. Conclusions

This study analyzed the on-road real driving emissions of LPG/gasoline- and gasoline-fueled vehicles in a high-altitude city and gasoline vehicles in a low-altitude city using PEMS, drawing the following conclusions:

(1) The average emission factors of CO<sub>2</sub>, CO, and NO<sub>x</sub> for LPG/gasoline vehicles are  $159.22 \pm 11.81$ ,  $18.38 \pm 9.22$ , and  $1.53 \pm 0.46$  g/km. For high-altitude gasoline vehicles, they are  $226.64 \pm 27.80$ ,  $1.46 \pm 0.83$ , and  $0.22 \pm 0.17$  g/km. For low-altitude gasoline vehicles, the factors are  $188.01 \pm 4.82$ ,  $2.21 \pm 0.67$ , and  $0.07 \pm 0.003$  g/km. Except for CO<sub>2</sub>, LPG/gasoline vehicles emit more CO and NO<sub>x</sub> than gasoline vehicles in both high-and low-altitude cities.

(2) Vehicle emission factors are closely related to driving mode, which is influenced by driver behavior and traffic conditions. Idle and acceleration modes significantly affect CO and NO<sub>x</sub> emissions. In high-altitude tests, these modes account for about 24.5% and 31.2% of total testing time, with higher emissions than low-altitude vehicles (22.5% and 27.7%).

(3) Vehicle emission factors generally decrease as speed increases. Under acceleration  $<0 \text{ m/s}^2$ , emission factors slightly decrease with increasing acceleration, then show an increasing trend as acceleration continues to rise.

Compared to gasoline vehicles, LPG/gasoline vehicles generally emit more CO and NO<sub>x</sub> in both high-and low-altitude cities. Notably, Euro 4 gasoline vehicles with low odometer readings exhibit ultra-low gaseous pollutant emissions, even lower than some low-altitude vehicles. To mitigate the impact of vehicle emissions on high-altitude urban air pollution, policymakers should focus on real-driving emissions and consider improving traffic conditions and regulating driving behavior.

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