# Research on RDE performance for in-use vehicles especially at high altitude conditions in China

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**Keywords:** RDE, In-use vehicle, High altitude conditions.

**Abstract.** The real driving emissions (RDE) of an in-use gasoline an in use diesel light-duty (LD) vehicle , both are SUV type, are studied based on portable emission measurement system (PEMS). The gasoline vehicle complying with emission standard of China 6 with a mileage of about 50000 km, and the diesel vehicle in this study is complying with emission standard of China 5 with a mileage of about 130000 km for there are hardly any China 6 diesel vehicles in-use in major city. Special attentions are paid on their emission behaviors at high altitude conditions (1300 to 3000 m above sea level). It is observed that the RDE test approach is still feasible for revealing in-use real driving emissions at extremely high altitudes (>1300 m, which is beyond the upper limit of extended altitude conditions according to the Euro 6 regulation). The results reveals that for in-use China 6 gasoline vehicle, the efficient three way catalyst (TWC) is capable of handling NOx, CO emission sufficiently, accompany with port fuel injection that guarantees the RDE test results (NOx, PN, CO) fulfill the China 6 emissions standards (which are 35 mg/km, 6E11 #/km and 500 mg/km respectively). And for China 5 in-use diesel vehicle, EGR as the only NOx control means is not sufficient which brings extremely high real driving NOx emission, with the maximum value exceeds about 3.7 and 23.2 times of the China 5 and China 6 NOx emission limits, but on the other hand, the PN emission is only about 1% of the China 6 PN standard value for the usage of DPF.

## 1 Introduction

The emission limits for cars have been progressively tightened in the past 25 years. Take the emission regulation of light-duty vehicle as an example, the emission limits of HC, CO and NOx for type I test of Euro 5 standard is only about 50%, 56% and 60% of the

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limiting values of Euro 3 standard. The corresponding emission limits of Euro 6 (b) standard is 500, 50 and 35 mg/km respectively, which is approximately 40%-50% more stringent than the Euro 5 standard [1].

Despite the severe emission limits, several key pollutants of vehicles, especially NOx, have failed to deliver real-world improvements of reducing the actual on-road emissions [2]. The emissions for typical driving conditions, especially diesel vehicles, are deliberately left much higher than promised or tested [3], the NOx emission is approximately 10 times higher in extreme conditions such as air-conditioning or sudden acceleration [4]. Rubino studied the real-world emission behavior of light-duty (LD) vehicles with respect to their emissions on conventional chassis dynamometer by the CO2 window-based method and revealed that the NOx concentrations are several times higher during real driving regimes which are far beyond the scope of type approval test cycle [5, 6]. The outclassed NOx emission of on-road conditions than type approval test consists with the study of Vojtisek-Lom, who cumulated the exhaust emissions of LD diesel vehicles by portable emission measurement system (PEMS), further found that the PM emissions were also considerably higher at full load, especially at low rpm [7]. Weiss conducted a comprehensive on-road emissions test of LD vehicles by using the EMROAD method, which is a CO2 window - based data processing method developed for extracting and processing the raw data recorded by PEMS [8], and found that the NOx emissions of gasoline vehicles as well as CO and total hydrocarbon emissions of both diesel and gasoline vehicles generally remain below the respective emission limits, by contrast, NOx emissions of modern Euro 5 diesel vehicles, exceed emission limits by 320±90% [9]. Hu used the vehicle specific power (VSP)-bin method, which can normalize the driving conditions in an integrated way that better correlates the instantaneous power demand on the engine per unit vehicle mass with emission rates, to calculate the emission behavior of 16 diesel taxies drove on different roads in Macao with PEMS, and revealed that diesel cars with specific emission control devices (such as EGR + DOC) usually penalize fuel economy, meanwhile with significantly higher NO2 emissions and NO2/NOx ratios than the other diesel cars [10]. Carslaw analyzed the remote sensing data and found that the real NOx emission have not decreased for the past 15-20 years even for Euro 5 vehicles and the current type approval test is inadequate to ensure the real-world emissions decrease in line with emission limits [11]. Based on the statistic of ADAC, AEC, JRC and TOI, the real-world NOx emission of diesel passenger cars are 400-500 mg/km (5-6 times of the Euro 5 limit), while the CO, THC, and PM real world test results do not exceed the type approval limits [12].

One reason for the current vehicle emission contradiction is that obsolete tests or cycle beating techniques have been used by carmakers leading to levels of car emission many times higher on the road than in laboratory tests (e.g. the Volkswagen emissions scandal in 2015) [13]. Another reason is that the conditions under which type approvals usually take place are associated only to a limited area of engine operating range, incomparably a smaller operating scope than driving under real-world conditions [14], this will lead the engineer calibrate only for specific inspections other than the whole engine working range. Industry experts believe that the solution for this contradiction is to calibrate the engines based on actual driving emission data, limits the emissions not only during the type approval tests [15], but also over the entire operating range [16, 17].

In 2017, the European Union introduced testing in real-world conditions called Real Driving Emissions (RDE), using PEMS in addition to laboratory tests, with the actual limits use 110% conformity factor (abbreviated as CF, which represents the difference between the laboratory test and real-world conditions, 110% means CF=2.1) in 2017, and 50% (CF=1.5) in 2019 [18]. By referring to European experiences, RDE test is also introduced in China 6 regulation, with some amendments according to big geographical and traffic condition differences between Europe and China, one of the most important changes is that we further extend the requirements of altitude from 1300 m to 2400 m for the altitude of European countries is generally less than 700 m, while over 1/3 (9 out of 23) provinces of China are above 1500 m altitude.

This paper mainly focused on real driving emissions of in-use vehicles, special attentions are paid on the emission behaviors at high altitude and low temperature environmental conditions.

## 2 RDE test and apparatus introduction

Generally, the China 6 regulation follows the standard RDE test method of Euro 6 regulation, with some adjustments: 1) the emission of THC, CH4, NMHC is not included for the calibration gas H2 is regarded as dangerous cargo which is forbidden to be carried on road in China; 2) there are differences in conformity factor and implementation time between China 6 and Euro 6 regulation, which can be referred to Table 1; 3) considering the apparent data processing difference between power-bin method and chassis dynamometer in-use method, the EMROAD method is recommended in China 6 regulation; 4) the extended altitude is 700~1300 m in Euro 6 regulation, while in China 6 regulation further extended altitude, which is 1300~2400 m, is add by considering the actual geographical conditions in China.

As defined in China 6 legislation, the RDE test should be carried out under the following demands: 1) the test duration should between 5400 and 7200 seconds; 2) the urban, rural and motorway conditions are classified by vehicle speed, which is in the range of < 60 km/h, 60-90 km/h, and > 90 km/h ; 3) the mileage of each condition shall not be less than 16 km, while the total distance performed under urban, rural and motorway conditions should be 34%, 33% and 33% respectively, which allows a deviation of ± 10% but the percentage of urban condition shall not be less than 29%.

**Table 1.** The difference of conformity factor and implementation time between China 6 and Euro 6 regulation.

| Regulation | | Conformity Factor (CF) | Implementation time |
|---|---|---|---|
| Euro 6 | | Submit data only | 2016.4.1 |
| | | 2.1 | 2017.9.1 |
| | | 1.5 | 2019.9.1 |
| China 6 | (a) | Submit data only | 2020.1.1 |
| | (b) | 2.1 | 2023.1.1 |

The test apparatus is presented in Figure 1, a portable AVL M.O.V.E system was used for the measurement of exhaust emissions from vehicles, specifically carbon monoxide, carbon dioxide, nitrogen oxides and particle number emissions. The installation status of test apparatus in vehicle for RDE tests is presented in Figure 2.

**Fig. 1.** The PEMS apparatus.

In terms of bench-marking and quality control, zero-span checks were performed before and after each measurement. Post-processing plausibility checks were made on all data, focusing on CO2, to ensure that the data collected were realistic.

## 3 Results and analysis of RDE tests

### 3.1 Vehicle and test conditions

The purpose of this paper is to verify the real driving emissions of in-use vehicles, especially at high altitude and low temperature environmental conditions, therefore, the RDE tests were carried out in 5 regions with altitude above 1300 m and 1 more 0 m altitude region for comparison. The detailed environmental conditions are shown in Table 2.

**Table 2.** Environmental conditions of RDE tests.

| Altitude (m) | Temperature (℃) |
|---|---|
| 0 | 15/30 |
| 1300 | 15/30 |
| 1900 | 0/15/20/25/30 |
| 2200 | 0 |
| 2400 | 0/15/20 |
| 3000 | 0 |

Vehicle 1 is naturally aspirated equipped with a port fuel injection (PFI) 2.7L gasoline engine and a three way catalytic (TWC) converter, vehicle 2 is turbo charged equipped with a 2.0L diesel engine and a diesel particulate filter (DPF). The detailed vehicle parameters can be referred to Table 3.

**Fig. 2.** Installation statuses of test apparatus in vehicle 1 for RDE tests.

**Table 3.** Vehicle parameters.

| Vehicle | Fuel | Fuel supply | Air supply | After treatment |
|---|---|---|---|---|
| Vehicle 1 | gasoline | PFI | naturally aspirated | TWC |
| Vehicle 2 | diesel | DI | Turbo charged | DPF |

## 3.2 PEMS verification test

According to legislation, the PMES verification tests were carried out first before RDE test on Chassis Dynamometers under WLTC cycle, the PEMS is in series connected to the Chassis Dynamometer test system as shown in Figure 3, and the emission differences between Chassis Dynamometer test and PEMS test are shown in Table 4. As can be seen in Table 4 that the PEMS detected CO2, CO and NOx emissions show good agreements with the Chassis Dynamometers test results, all meet the regulation allowable deviations. The PN emissions differ considerably, but the corresponding data is in the same quantity rank and the allowable deviation of PN is not specified by regulation.

**Fig. 3.** The Installation statues of PEMS verification test of vehicle 2. PEMS is in series connected to the Chassis Dynamometers system, the test cycle is WLTC cycle.

### 3.3 The influence of altitudes on real driving emissions

Figure 4 shows the real driving emissions (CO2, CO, NOx and PN) of vehicle 1 at different altitudes varying from 0-2400 m with an approximately constant environmental temperature of 15 ℃. It is easily speculated that the PN emission should not be a problem as the fuel is port injected which provided a tremendous uniformity mixture state, on the other hand, the CO and NOx emission can be restrained for the usage of TWC which will very likely results in very low levels of these two gaseous emissions, additionally, as the cold start is excluded in emission statistics according to the regulation, the real driving emissions of vehicle 1 have great possibilities to fulfill the China 6 emission limits even with the conformity factor of 2.1 not counted. It is observed in Figure 4 that there is no obvious regularity of CO emission in real driving conditions as the altitudes varied from 0-2400 m, but all the CO emissions are around 200 mg/km, which below the China 6 limiting value of 500 mg/km, the maximum conformity factor of CO is 0.498, which means there are still 50% allowance of CO emission comparing to the limiting value. Figure 4 also reveals that the NOx emission showed a downward trend with the increase of altitude as the lower oxygen concentration generally suppress the combustion temperatures , the maximum conformity factor of NOx is 0.628, implying more than 37% allowance to the NOx limiting value. The PN emission also showed a downward trend with the increase of altitude, which shows a maximum conformity factor of 0.633 with more than 36% allowance to the China 6 PN limiting value.

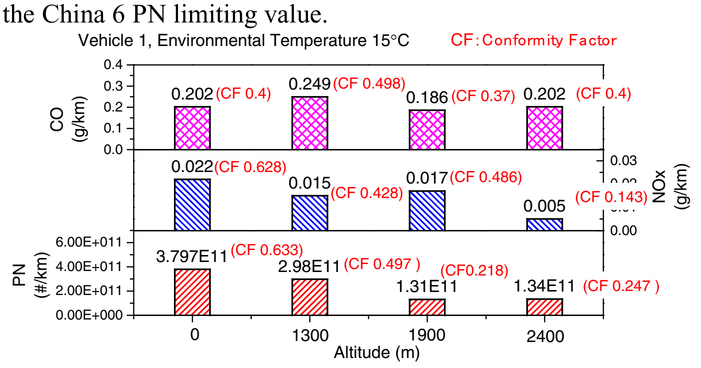


**Fig. 4.** The real driving emissions of vehicle 1 at different altitudes varying from 0-2400 m with an approximately constant environmental temperature of 15 ℃.

Figure 5 shows the real driving emissions of vehicle 2 at 0 ℃ environmental temperature with different altitudes varying from 1900-3000 m. The results in Figure 5 reveal that for the tested diesel vehicle, the CO, NOx and PN emission didn't change significantly as the altitude rises from 1900 to 2200 m, after that, it increases tremendously at the altitude of 3000 m, which may due to the deterioration of combustion caused by low oxygen concentration at high altitude regions. All CO emissions meet the China 5 or China 6 regulation (both are 500 mg/km for CI vehicle), with the maximum conformity factor of 0.204 showing nearly 80% allowance to the limiting value. Due to the usage of DPF, the PN emission is quite small, which is approximately two orders of magnitude lower than the China 5 or China 6 PN limiting value (both are 6E11 #/km for CI vehicle). The NOx emission of vehicle 2 is quite high for EGR as the only NOx control means is obviously not sufficient in real driving conditions. the extremely high real driving NOx emission of vehicle 2 exceeds about 4-4.5 times and 19-21 times refer to the 180 mg/km of China 5 and 35 mg/km of China 6 emission limit respectively. Figure 5 shows that the RDE test method is an effective mean revealing the actual emission behavior in real world not only in type approval conditions but also in extreme altitude conditions in China.

**Table 4.** The WLTC emission differences between Chassis Dynamometer test and PEMS test.

| Vehicle # | Means of WLTC emission measurement | CO2 emission factor (g/km) | CO emission factor (g/km) | NOx emission factor (g/km) | PN emission factor (#/km) |
|---|---|---|---|---|---|
| Vehicle 1 | Chassis Dynamometer Test | 272.421 | 0.76 | 0.0145 | 3.09E+11 |
| | PEMS Test | 273.899 | 0.71 | 0.0141 | 8.10E+11 |
| | Deviation | 0.54% | 6.58% | 2.76% | 61.85% |
| Vehicle 2 | Chassis Dynamometer Test | 180.92 | 0.026 | 0.384 | 2.19E+09 |
| | PEMS Test | 190.14 | 0.027 | 0.375 | 6.18E+09 |
| | Deviation | 5.09% | 3.84% | 2.34% | 64.56% |
| Regulation allowable deviation | | ±10g/km or 10% | ±150mg/km or 15% | ±15mg/km or 15% | -- |

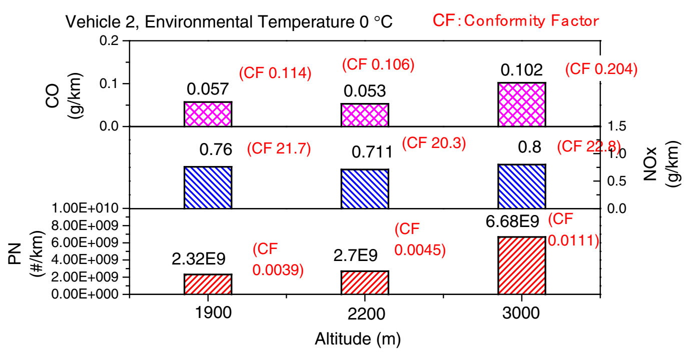


**Fig. 5.** The real driving emissions of vehicle 2 at different altitudes varying from 1900-3000 m with an approximately constant environmental temperature of 0 ℃.

## 3.4 The influence of environmental temperatures on real driving emissions

Figure 6 shows the real driving emissions of vehicle 1 at different environmental temperatures varying from 0-30 ℃ with a constant altitude of 1900 m. It is observed in Figure 6 that there is no obvious regularity of CO, NOx and PN emission in real driving conditions as the temperature varied from 0-30 ℃. All the emissions are below the China 6 limiting values, the maximum conformity factor of CO, NOx and PN emission are 0.372, 0.486 and 0.218 respectively.

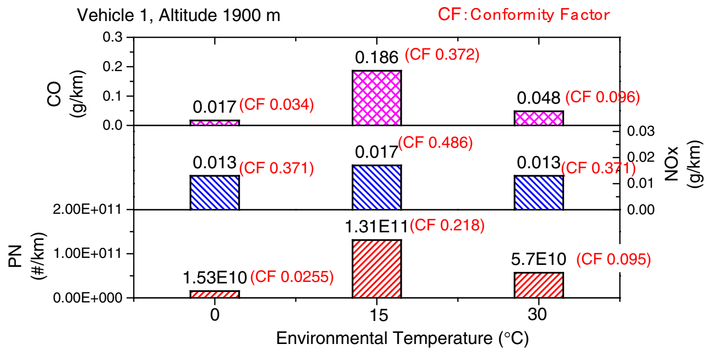


**Fig. 6.** The real driving emissions of vehicle 1 at different environmental temperatures varying from 0-30 ℃ with a constant altitude of 1900 m.

Figure 7 shows the real driving emissions of vehicle 2 at 1900 m altitude with different environmental temperatures varying from 0-30 ℃. The results in Figure 7 reveal that for the tested diesel vehicle, the CO, NOx and PN emission increases first as the temperature rises from 0 to 15 ℃, after that, the change of emissions are not obvious. The CO and PN emissions are below the China 5 or China 6 limiting values, the maximum conformity factor are 0.146 and 0.0086 respectively. The insufficient of EGR in controlling of NOx emission brings extremely high real driving NOx emission, with the maximum value exceeds about 4.6 and 23.2 times of the China 5 and China 6 NOx emission limits.

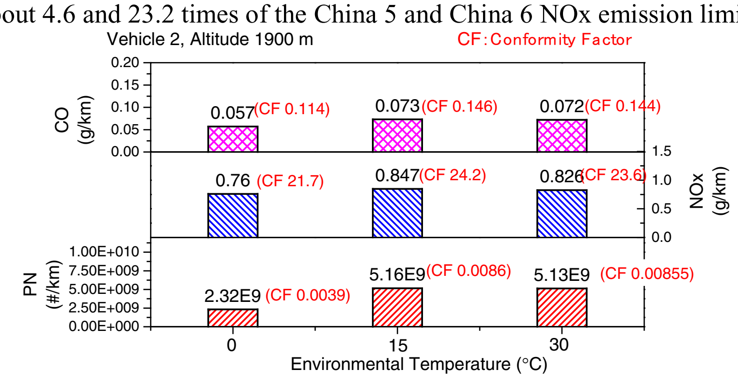


**Fig. 7.** The real driving emissions of vehicle 2 at different environmental temperatures varying from 0-30 ℃ with a constant altitude of 1900 m.

### 3.5 The influence of cold and hot starts on real driving emissions

Figure 8 shows the EMROAD calculated emission differences between two RDE tests of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperature, one with cold start and the other with hot start. The results in Figure 8 reveal that as the cold start is excluded in emission statistics according to the regulation, the EMROAD calculated emission differences between cold start and hot start are quite small, the hot start test has almost the same CO emissions and 23% lower NOx and PN emissions comparing to the cold start test.

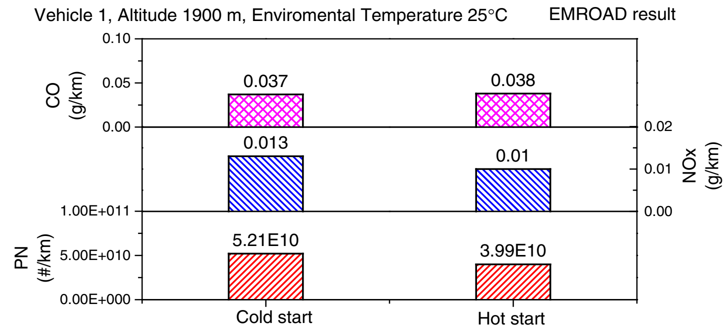


**Fig. 8.** The EMROAD calculated emission differences between cold start and hot start RDE tests of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperatures.

As the engine cold start is one of the most significant pollutant emission procedures, the integral vehicle emissions should be quite different between cold and hot start RDE tests other than the EMROAD method has presented. Figure 9 revealed the transient emission of CO, NOx and PN during a cold start RDE test of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperature. It is shown in Figure 9 that apparent peaks of CO, NOx and PN emission can be observed at cold start period while the engine coolant temperature is below 70 ℃, the peaks of emissions generated is many times higher than their corresponding emissions occurred during urban, rural and motorway driving conditions, and the integral CO, NOx and PN emissions of cold start period account for more than 90%, 25% and 65% respectively of the corresponding total emissions during the whole RDE test. Figure 10 shows the integral emission differences between two RDE tests of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperature, one with cold start and the other with hot start. The results in Figure 10 reveal that there exist great differences in integral vehicle emissions between cold and hot start, and the cold start test emits 68.4% more CO, 38.4% more NOx and 75% more PN than the hot start test.

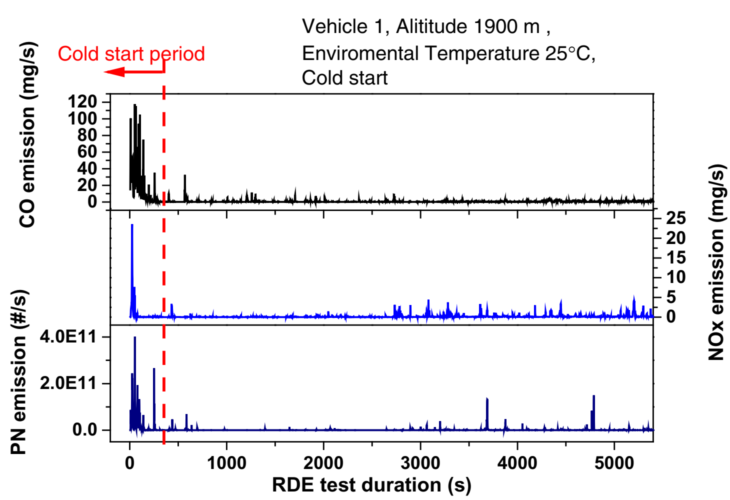


**Fig. 9.** The transient emission of CO, NOx and PN during a RDE test of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperature.

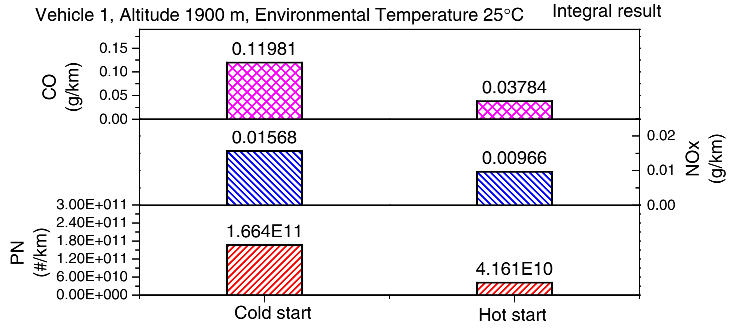


**Fig. 10.** The integral emission differences between cold start and hot start RDE tests of vehicle 1 at 1900 m altitude and 25 ℃ environmental temperature.

The main purpose of introducing RDE tests is to detect the vehicle emission level in real driving conditions, promoting technological innovation to control the air pollution emissions of cars, vans and trucks. As the cold start is indispensable in normal vehicle usage and as shown in Figure 9 that great amount of pollutants were generated in cold start stage resulting in significant differences between hot and cold start integral emissions, in order to reflect the true level of emissions better, the RDE test should consider adding cold start emissions at an appropriate time in the future.

### 3.6 The repeatability of RDE tests

Three repetitive RDE tests were implemented on vehicle 1 under the same altitude of 1900 m, the same environmental temperature of 15 ℃ and the same test route, and the emission differences are shown in Figure 11. It is revealed in Figure 11 that the RDE tests have poor repeatability and there exist huge differences in emissions between each individual test. Table 5 gathered the statistics of the repetitive RDE test results' deviation with the average value, showing that the maximum deviation of CO, NOx and PN emission to their counterpart average values could be 99.5%, 84.5% and 57.6% respectively. This means that even though the test conditions and routes are carefully controlled, the RDE test results are still lack of repeatability for they are likely affected by driving habits, road conditions, climate conditions and other factors.

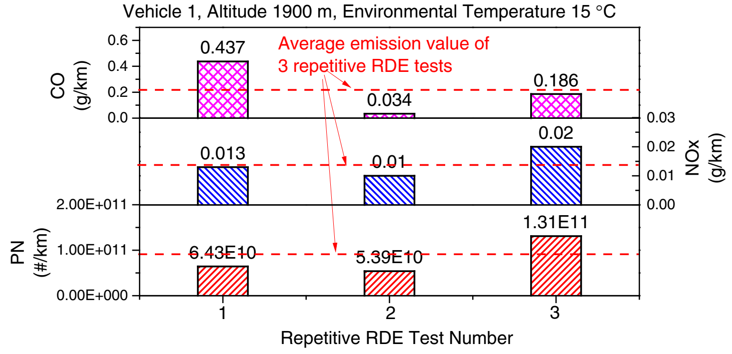


**Fig. 11.** The emission differences between 3 repetitive RDE tests of vehicle 1 under the same altitude of 1900 m, the same environmental temperature of 15 ℃, and the same test route.

**Table 5.** The deviation of repetitive RDE test results with the average value.

| Test Number | Emission deviation with the average value % | | |
|---|---|---|---|
| | CO | NOx | PN |
| 1 | + 99.5 | - 9.1 | - 22.6 |
| 2 | - 84.5 | - 30.1 | - 35.1 |
| 3 | - 15.1 | + 39.9 | + 57.6 |

### 3.7 Conformity Factor statistics of RDE tests at different altitudes and environmental temperatures

The statistics of the Conformity Factor of RDE tests at different altitudes and environmental temperatures are shown in Table 6, which reveals that the PN emissions of both vehicle 1 and vehicle 2 are under China 5 or China 6 limit values, with quite large margins are still preserved. The maximum CF of PN emission of vehicle 1 and vehicle 2 are 0.478 and 0.47 respectively, both have more than 50% allowance to the PN limiting value.

The NOx emissions of vehicle 1 fulfill the China 6 emissions standards with the maximum CF of 0.86, while for vehicle 2, as EGR is the only NOx control means, which is obviously not sufficient that brings extremely high real driving NOx emission, with the CF varies from 3.5 to 4.7 and from 18.2 to 24.2 for China 5 and China 6 limits respectively, meaning that the maximum NOx emission exceeds about and 3.7 and 23.2 times of the China5 and China 6 emission limits.

## 4 Conclusions

This paper mainly focused on the real on-road emissions behaviors of in-use gasoline and diesel vehicles, especially at high altitude conditions. It is observed that the RDE test approach is still feasible for revealing in-use real driving emissions at extreme conditions, and the following conclusions were obtained:

1) The RDE test method can still be used as an important means to detect the actual vehicle emission in the further extended altitude conditions in China, which can support the manufactories developing more environment-friendly vehicles.

2) For China 6 port fuel injection gasoline LD vehicle, the efficient TWC is capable of handling NOx, CO emission sufficiently, which guarantees the RDE test results fulfill the China 6 emissions standards.

3) For China 5 in-use diesel vehicle, EGR as the only NOx control means is not sufficient which brings extremely high real driving NOx emission, with the maximum value exceeds about 3.7 and 23.2 times of the China 5 and China 6 NOx emission limits, but on the other hand, the PN emission is only about 1% of the China 6 PN standard value for the usage of DPF.

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**Table 6.** The Conformity Factor of RDE tests at different altitudes and environmental temperatures.

| Vehicle | Altitude (m) | Temperature (℃) | CF (Conformity Factor) | | |
|---|---|---|---|---|---|
| | | | CO | NOx | PN |
| Vehicle 1 | 0 | 15 | 0.40 | 0.57 | 0.633 |

| | | | | | |
|---|---|---|---|---|---|
| | | 30 | 0.16 | 0.86 | 0.298 |
| | 1300 | 15 | 0.50 | 0.29 | 0.500 |
| | | 30 | 0.50 | 0.57 | 0.141 |
| | 1900 | 0 | 0.04 | 0.29 | 0.030 |
| | | 15 | 0.38 | 0.57 | 0.218 |
| | | 20 | 0.88 | 0.29 | 0.107 |
| | | 25 | 0.10 | 0.29 | 0.095 |
| | | 30 | 0.12 | 0.57 | 0.045 |
| | 2400 | 0 | 0.2 | 0.57 | 0.120 |
| | | 20 | 0.66 | 0.57 | 0.478 |
| | 3000 | 0 | 0.22 | 0.29 | 0.130 |
| Vehicle 2 | 1300 | 15 | 0.08 | 22.28 | 0.006 |
| | | 30 | 0.18 | 21.42 | 0.005 |
| | 1900 | 0 | 0.12 | 21.71 | 0.004 |
| | | 15 | 0.14 | 24.28 | 0.009 |
| | | 25 | 0.14 | 23.71 | 0.009 |
| | 2400 | 15 | 0.4 | 24.28 | 0.001 |
| | 3000 | 0 | 0.2 | 22.85 | 0.011 |

Abbreviations

| | |
|---|---|
| **RDE** | Real driving emission. |
| **LD** | Light duty. |
| **PEMS** | Portable emission measurement system. |
| **PFI** | Port fuel injection. |
| **TWC** | Three way catalyst. |
| **VSP** | Vehicle specific power. |
| **CF** | Conformity factor. |
| **DPF** | Diesel particulate filter. |
| **WLTC** | Worldwide Harmonized Light Vehicles Test Cycle. |
| **EGR** | Exhaust Gas Recirculation. |
| **DI** | Direct injection. |

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